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REVIEW

The Anthropocene: conceptual and historical perspectives

By Will Steffen[1,*], Jacques Grinevald[2], Paul Crutzen[3] and John McNeill[4]

[1] *Climate Change Institute, The Australian National University, Canberra, ACT 0200, Australia*
[2] *Graduate Institute of International and Development Studies and University of Geneva, Geneva, Switzerland*
[3] *Max Planck Institute for Chemistry, 55128 Mainz, Germany*
[4] *School of Foreign Service, Georgetown University, Washington, DC 20057, USA*

The human imprint on the global environment has now become so large and active that it rivals some of the great forces of Nature in its impact on the functioning of the Earth system. Although global-scale human influence on the environment has been recognized since the 1800s, the term *Anthropocene*, introduced about a decade ago, has only recently become widely, but informally, used in the global change research community. However, the term has yet to be accepted formally as a new geological epoch or era in Earth history. In this paper, we put forward the case for formally recognizing the Anthropocene as a new epoch in Earth history, arguing that the advent of the Industrial Revolution around 1800 provides a logical start date for the new epoch. We then explore recent trends in the evolution of the Anthropocene as humanity proceeds into the twenty-first century, focusing on the profound changes to our relationship with the rest of the living world and on early attempts and proposals for managing our relationship with the large geophysical cycles that drive the Earth's climate system.

Keywords: Anthropocene; global change; planetary boundaries; Industrial Revolution; geo-engineering

1. Introduction

Climate change has brought into sharp focus the capability of contemporary human civilization to influence the environment at the scale of the Earth as a single, evolving planetary system. Following the discovery of the ozone hole over Antarctica, with its undeniably anthropogenic cause, the realization that the emission of large quantities of a colourless, odourless gas such as carbon dioxide (CO_2) can affect the energy balance at the Earth's surface has reinforced the concern that human activity can adversely affect the broad range of ecosystem

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*Author for correspondence (will.steffen@anu.edu.au).

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services that support human (and other) life [1,2] and could eventually lead to a 'crisis in the biosphere' ([3], cited in Grinevald [4]). But climate change is only the tip of the iceberg. In addition to the carbon cycle, humans are (i) significantly altering several other biogeochemical, or element cycles, such as nitrogen, phosphorus and sulphur, that are fundamental to life on the Earth; (ii) strongly modifying the terrestrial water cycle by intercepting river flow from uplands to the sea and, through land-cover change, altering the water vapour flow from the land to the atmosphere; and (iii) likely driving the sixth major extinction event in Earth history [5]. Taken together, these trends are strong evidence that humankind, our own species, has become so large and active that it now rivals some of the great forces of Nature in its impact on the functioning of the Earth system.

The concept of the *Anthropocene*, proposed by one of us (P.J.C.) about a decade ago [6,7], was introduced to capture this quantitative shift in the relationship between humans and the global environment. The term Anthropocene suggests: (i) that the Earth is now moving out of its current geological epoch, called the Holocene and (ii) that human activity is largely responsible for this exit from the Holocene, that is, that humankind has become a global geological force in its own right. Since its introduction, the term Anthropocene has become widely accepted in the global change research community, and is now occasionally mentioned in articles in popular media on climate change or other global environmental issues. However, the term remains an informal one. This situation may change as an Anthropocene Working Group has recently been formed as part of the Subcommission on Quaternary Stratigraphy to consider whether the term should be formally recognized as a new epoch in the Earth's history [8].

2. Antecedents of the Anthropocene concept

The term Anthropocene may seem a neologism in scientific terminology. However, the idea of an epoch of the natural history of the Earth, driven by humankind, notably 'civilized Man', is not completely new and was mooted long before the rising awareness of the global environment in the 1970s, triggered, among others, by NASA's *Earthrise* photography and the Club of Rome's 1972 report on *Limits to Growth* [9]. Biologist Eugene F. Stoermer wrote [4, p. 243]: 'I began using the term "anthropocene" in the 1980s, but never formalized it until Paul contacted me'. About this time other authors were exploring the concept of the Anthropocene, although not using the term (e.g. [10]). More curiously, a popular book about *Global Warming*, published in 1992 by Andrew C. Revkin, contained the following prophetic words: 'Perhaps earth scientists of the future will name this new post-Holocene period for its causative element—for us. We are entering an age that might someday be referred to as, say, the Anthrocene [sic]. After all, it is a geological age of our own making' [11, p. 55]. Perhaps many readers (e.g. [4]) ignored the minor linguistic difference and have read the new term as Anthro(po)cene!

In fact, before the introduction of the Anthropocene concept [6,7], several historical precedents for this far-reaching idea have been revisited. In retrospect, this line of thought, even before the golden age of Western industrialization and globalization, can be traced back to remarkably prophetic observers and philosophers of Earth history. Following William Clark, the lead author of the IIASA project entitled *Sustainable Development of the Biosphere* [12], Crutzen recognized the early precedent of the 'anthropozoic era' proposed by a noted Italian geologist and Catholic priest [13]. Stoppani was quoted by George Perkins Marsh in the second edition—significantly entitled *The Earth as Modified by Human Action* [14]—of his celebrated *Man and Nature* of 1864 [15]. Another significant early work was *Man as a Geological Agent* [16].

Further development of the concept was interrupted by the two world wars of the twentieth century. Only in 1955, at the Princeton symposium on 'Man's Role in Changing the Face of the Earth' [17] did a remarkable revival of Marsh's theme emerge. Much later, with the symposium entitled *The Earth as Transformed by Human Action* [18], and some other meetings like the seminar organized at the Fundacion César Manrique in Lanzarote [19], did the concept again fully re-emerge.

At all of these academic meetings, references were made to the earlier concept of a transformation of the biosphere into the noösphere, that is, the anthroposphere or the anthropogenic transformation of the Earth system. The term and the notion of the noösphere arose in the Paris of the early 1920s, just after the Great War, and were underpinned by the French publication of the last volume of *La Face de la Terre* by Austrian geologist Eduard Suess (1834–1914), recalling the importance of the notion of the biosphere (coined by Suess [20]). More directly, the concept of the noösphere was the result of the meeting of three prophetic great minds: the Russian geochemist and naturalist Vladimir Vernadsky, creator of biogeochemistry and long neglected father of the science of the biosphere (later called global ecology); and two heterodox Catholic thinkers of evolution, Pierre Teilhard de Chardin, then professor of geology, and his close friend the mathematician-turned-philosopher Edouard Le Roy, Henri Bergson's disciple and successor at the Collège de France. Very little is conserved in the archives about this remarkable troika during the stay of Vernadsky in France from 1922 to 1925. Nevertheless, Vernadsky's teachings at the Sorbonne were published under the title *La Géochimie* [21], in fact the first monograph on biogeochemistry, and, as a follow-up, the now famous book on *The Biosphere* [22,23].

After Teilhard's death in 1955, many people confused the various conceptualizations of the biosphere and the noösphere developed by Teilhard (his disciples or opponents) and Vernadsky (partly assimilated by US ecosystems pioneers following G. E. Hutchinson's Yale scientific school). The Vernadskian revolution was invisible until recently (Grinevald, in the introduction to Vernadsky [22]). The two books of 1927 and 1928 by Le Roy were eclipsed and forgotten (the first partial English translation of his works appeared in Samson & Pitt [24]). Many scholars are ignorant of the old doctrine of the evolution of the biosphere and its transformation by the development of Man's noösphere (including the technosphere and, more recently, the so-called industrial metabolism). The idea of 'Man: a new geological force' was included in Fairfield Osborn's *Our Plundered Planet* [25], quoting in its bibliography the American publication of 'The biosphere and the noösphere' [26].

Both Teilhard and Vernadsky were readers of Suess's *La Face de la Terre* and the celebrated French philosopher Henri Bergson [27]. In his 1907 master book *L'Evolution Créatrice*, Bergson wrote: 'A century has elapsed since the invention of the steam engine, and we are only just beginning to feel the depths of the shock it gave us. . . . In thousands of years, when, seen from the distance, only the broad lines of the present age will still be visible, our wars and our revolutions will count for little, even supposing they are remembered at all; but the steam engine, and the procession of inventions of every kind that accompanied it, will perhaps be spoken of as we speak of the bronze or of the chipped stone of pre-historic times: it will serve to define an age.' (*Creative Evolution*, transl. by Arthur Mitchell, New York, The Modern Library (1911) 1944, p. 153.)

In the chapter 'Carbon and living matter in the earth's crust' of his *Geochemistry*, Vernadsky wrote: 'But in our geologic era, in the psychozoic era—the era of Reason [28, p. 66]—a new geochemical factor of paramount importance appears. During the last 10 000 or 20 000 years, the geochemical influence of agriculture has become unusually intense and diverse. We see a surprising speed in the growth of mankind's geochemical work. We see a more and more pronounced influence of consciousness and collective human reason upon geochemical processes. Man has introduced into the planet's structure a new form of effect upon the exchange of atoms between living matter and inert matter. Formerly, organisms affected the history only of those atoms that were necessary for their respiration, nutrition and proliferation. Man has widened this circle, exerting influence upon elements necessary for technology and for the creation of civilized forms of life. Man acts here not as *homo sapiens*, but as *homo sapiens faber*' [21, p. 342; 23, pp. 219–220]. In the original French text of *La Géochimie*, Bergson's *Evolution Créatrice* is quoted as source of inspiration. The same idea was developed in the second edition, in French, of *La Biosphère* [22]. More recently, James Lovelock, the father of the Gaia hypothesis and a proponent of geophysiological homeostasis, has provided another global conceptual framework for human influence on biogeochemical cycles [29,30].

However, in the beginning of the twentieth century, nobody, except perhaps Vernadsky in the USSR and Henry Adams in the USA, imagined the Great Acceleration of the second phase of the Anthropocene—the post-World War II worldwide industrialization, techno-scientific development, nuclear arms race, population explosion and rapid economic growth. In the interwar period, nobody took seriously the global warming scenario first calculated by Svante Arrhenius [31] in his 1896 fundamental study of greenhouse theory, or by Guy Stewart Callendar [32] in the interwar period. These events occurred before the emergence of our modern planetary ecological conscience.

The diverse notions of noösphere, or similar ideas under different terminology, are, however, not equivalent to the new concept of the Anthropocene, now advocated by the recently elected President of the Geological Society of London for 2010–2012, who wrote in his book: 'The time in which we now live would then, sadly and justly, surely become known as the "Anthropocene". We have received an important message from a warm planet. We can understand it, and we should respond—*as if people mattered*' [33, p. 196].

3. History of the human–environment relationship

The history of interactions between humans and the environment in which they were embedded goes back a very long way, to well before the emergence of fully modern humans to the times of their hominid ancestors. During virtually all of this time, encompassing a few million years, humans and their ancestors influenced their environment in many ways, but always by way of modification of natural ecosystems to gain advantage in gathering the vegetative food sources they required or in aiding the hunt for the animals they hunted. Their knowledge was likely gained by observation and trial-and-error, slowly becoming more effective at subtly modifying their environment but never able to fully transform the ecosystems around them. They certainly could not modify the chemical composition of the atmosphere or the oceans at the global level; that remarkable development would have to wait until the advent of the Industrial Revolution a few centuries ago.

The story begins a few million years ago with the genus *Homo erectus*, which had mastered the art of making stone tools and rudimentary weapons. They later also learned how to control and manipulate fire, a crucial breakthrough that fundamentally altered our relationship with other animals on the planet, none of whom could manipulate fire [34]. Control of fire undoubtedly helped hominids in their hunt for food sources, but it also helped to keep dangerous animals away from the hominid camps at night.

Increasing access to a protein-rich food source paid other dividends for early humans. The shift from a primarily vegetarian diet to an omnivorous diet triggered a fundamental shift in the physical and mental capabilities of early humans, the latter arguably the more important. Brain size grew threefold, to about $1300\,\mathrm{cm}^3$, and gave humans the largest brain-to-body ratio of any animal on the Earth [35]. This subsequently allowed the development of spoken language, and later written language, both facilitating the accumulation of knowledge and social learning from generation to generation. This has ultimately led to a massive—and rapidly increasing—store of knowledge upon which humanity has eventually developed complex civilizations and continues to increase its power to manipulate the environment. No other species now on the Earth or in Earth history comes anywhere near to this capability.

Pre-industrial humans, still a long way from developing the contemporary civilization that we know today, nevertheless showed some early signs of accessing the very energy-intensive fossil fuels on which contemporary civilization is built. About a millennium ago, the first significant human use of fossil fuels—coal—arose during the Song dynasty (960–1279) in China [36,37]. Drawn from mines in the north, the Chinese coal industry, developed primarily to support its iron industry, grew in size through the eleventh century to become equal to the production of the entire European (excluding Russia) coal industry in 1700. While the Chinese coal industry began to lapse into decline in subsequent centuries owing to a variety of reasons, the European coal industry, primarily in England, was beginning its ascent in the thirteenth century. The use of coal grew as did the size of London, and became the fuel of choice in the city because of its high energy density. By the 1600s, the city of London burned around 360 000 tonnes of coal annually [38,39]. However, China and England were the exceptions; the rest of the world relied on wood and charcoal for their primary energy sources. The Chinese and English combustion of coal had no appreciable impact on the atmospheric concentration of CO_2.

Two pre-industrial events have occasionally been cited as heralding the beginning of the Anthropocene. The first was the wave of extinctions of the Pleistocene megafauna. During the last ice age, a number of large mammals in at least four continents—Asia, Australia and the Americas—went extinct [40–42]. Despite the long-standing debate about whether human hunting pressures or climate variability was the ultimate cause of the demise of the megafauna, it seems clear now that humans played a significant role, given the close correlation between the timing of the extinctions and the arrival of humans. Although these extinctions were likely significant for the ecology of these continents over large areas, there is no evidence that they had any appreciable impact on the functioning of the Earth system as a whole.

The second was the advent of agriculture—the so-called Neolithic Revolution—in the early phases of the Holocene. This hypothesis for the beginning of the Anthropocene argues that two agriculture-related events—the clearing of forests and conversion of land to cropping about 8000 years ago and the development of irrigated rice cultivation about 5000 years ago—emitted enough CO_2 and methane (CH_4), respectively, to the atmosphere to prevent the initiation of the next ice age [43]. The hypothesis is that the early forest clearing reversed a downward trend in CO_2 concentration that had been established in the Holocene by increasing CO_2 concentration by 5–10 ppm. A recent model-based analysis claims that these modest increases in greenhouse gas concentrations were enough to trigger natural ocean feedbacks in the climate system strong enough to raise global mean temperature significantly and release additional CO_2 to the atmosphere [44].

On the other hand, there are considerable arguments against the early Anthropocene hypothesis. First, if the very modest increases in greenhouse gas concentrations 5000–8000 years ago drove significant increases in global mean temperature, it would imply that very high global heating would result from the present greenhouse gas concentrations. Furthermore, analyses of the change in solar radiation owing to orbital forcing suggest that the Earth is presently in an unusually long interglacial period and is not due to enter another ice age for at least 10 000 years without any increases in greenhouse gas emissions [45,46]. In addition, the variation of atmospheric CO_2 concentration through the Holocene can be explained by the natural dynamics of the carbon cycle [47,48]. This latter point is buttressed by a recent analysis, using a state-of-the-art dynamic global vegetation model, which shows that CO_2 change owing to land-use change, even assuming double the maximum estimated rate of land-use change in the past, is less than 4 ppm up to 1850, well within the bounds of natural variability [49]. Thus, the early Anthropocene hypothesis does not seem plausible, and does not have widespread support within the research community.

4. The beginning of the Anthropocene

The Industrial Revolution, with its origins in Great Britain in the 1700s, or the thermo-industrial revolution of nineteenth century Western civilization [50], marked the end of agriculture as the most dominant human activity and set the species on a far different trajectory from the one established during most of the Holocene. It was undoubtedly one of the great transitions—and up to now the most significant—in the development of the human enterprise. The underlying reasons for the transition were probably complex and interacting, including resource constraints in some areas, evolving social and political structures that unlocked innovative new thinking, and the beginnings of a new economic order that emphasized markets [51].

One feature stood out in the world that humanity left as it entered the Industrial Revolution; it was a world dominated by a growing energy bottleneck. The primary energy sources were tightly constrained in magnitude and location. They consisted of wind and water moving across the Earth's surface, and, on the biosphere, plants and animals. All of these energy sources are ultimately derived from the flow of energy from the Sun, which drives atmospheric circulation and the hydrological cycle and provides the fundamental energy source for photosynthesis. These processes have inescapable intrinsic inefficiencies; plants use less than 1 per cent of the incoming solar radiation for photosynthesis and animals eating plants obtain only about 10 per cent of the energy stored in the plants. These energy constraints provided a strong bottleneck for the growth of human numbers and activity.

The discovery and exploitation of fossil fuels shattered that bottleneck. Fossil fuels represented a vast energy store of solar energy from the past that had accumulated from tens or hundreds of millions of years of photosynthesis. They were the perfect fuel source—energy-rich, dense, easily transportable and relatively straightforward to access. Human energy use rose sharply. In general, those industrial societies used four or five times as much energy as their agrarian predecessors, who in turn used three or four times as much as our hunting and gathering forebears [52].

Exploiting fossil fuels allowed humanity to undertake new activities and vastly expand and accelerate the existing activities [53]. The most important example of the former is the capability to synthesize reactive nitrogen compounds from unreactive nitrogen in the atmosphere, an energy-intensive process. In essence, this fossil fuel-driven industrial process (the Haber–Bosch process) creates fertilizer out of air. An example of the latter is the rapid increase in the conversion of natural ecosystems, primarily forests, into cropland and grazing areas owing to mechanized clearing technologies [54]. Another example is the increase in the diversion of water from rivers through the construction of large dams.

The result of these and other energy-dependent processes and activities was a significant increase in the human enterprise and its imprint on the environment. Between 1800 and 2000, the human population grew from about one billion to six billion, while energy use grew by about 40-fold and economic production by 50-fold [55]. The fraction of the land surface devoted to intensive human activity rose from about 10 to about 25–30% [56]. The imprint on the environment was also evident in the atmosphere, in the rise of the greenhouse gases CO_2, CH_4 and nitrous oxide (N_2O). Carbon dioxide, in particular, is directly linked to the rise of energy use in the industrial era as it is an inevitable outcome of the combustion of fossil fuels.

Although the atmospheric CO_2 concentration provides a very useful indicator to track the evolution of the Anthropocene [57], it is not particularly useful for identifying a beginning date for the Anthropocene because natural sinks of carbon in the oceans and on land dampened and delayed the imprint of the early industrial period on the atmosphere. For example, atmospheric CO_2 concentration was 277 ppm (by volume) in 1750, 279 ppm in 1775, 283 ppm in 1800 and 284 ppm in 1825 [58], all of which lie within the range of Holocene variability of 260–285 ppm [59]. Only by 1850 did the CO_2 concentration (285 ppm) reach the upper limit of natural Holocene variability and by 1900 it had climbed to 296 ppm [58], just high enough to show a discernible human influence beyond natural variability. Since the mid-twentieth century, the rising concentration and isotopic composition of CO_2 in the atmosphere have been measured directly with great accuracy [60], and has shown an unmistakable human imprint.

So when did the Anthropocene actually start? It is difficult to put a precise date on a transition that occurred at different times and rates in different places, but it is clear that in 1750, the Industrial Revolution had barely begun but by 1850 it had almost completely transformed England and had spread to many other countries in Europe and across the Atlantic to North America. We thus suggest that the year AD 1800 could reasonably be chosen as the beginning of the Anthropocene. Note that we have used a Christian calendar date to mark the beginning of the Anthropocene, rather than the ‘before present (BP)’ date that is normally used to mark events earlier in the Holocene. Studies of the Holocene, especially those quoting radiocarbon dates, often use BP although that ‘present’ is defined as a rapidly receding 1950. We use the standard Christian calendar here both for familiarity and also for the importance of near-historical events and dates in our analysis. It is striking, however, that the radiocarbon ‘present’ date is very close to the beginning of both the nuclear age and the Great Acceleration, which comprise one of the several candidates for a beginning-of-Anthropocene date.

5. The Great Acceleration

The human enterprise switched gears after World War II. Although the imprint of human activity on the global environment was, by the mid-twentieth century, clearly discernible beyond the pattern of Holocene variability in several important ways, the rate at which that imprint was growing increased sharply at mid-century. The change was so dramatic that the 1945 to 2000+ period has been called the Great Acceleration [61].

Figure 1 gives a visual representation of the Great Acceleration. As shown in figure 1*a*, which displays several indicators of the development of human enterprise from the beginning of the Industrial Revolution to the beginning of the new millennium, every indicator of human activity underwent a sharp increase in rate around 1950 [5,55]. For example, population increased from 3 to 6 billion in just 50 years, while the leap in economic activity was even more dramatic—a rise of 15-fold over that period. The consumption of petroleum grew by a factor of 3.5 since 1960. Some of the indicators were virtually 0 at the beginning of the Great Acceleration but exploded soon after the end of World War II. The number of motor vehicles rose from only 40 million at the end of the war to about 700 million by 1996, and continues to rise steadily. The post-war period has also seen the rapid expansion of international travel, electronic communication and economic connectivity, all from very low or non-existent bases.

One of the most dramatic trends of the past half-century has been the widespread abandonment of the farm and the village for a life in the city. Over half of the human population—over 3 billion people—now live in urban areas, with the fraction continuing to rise. Migration to cities usually brings with it rising expectations and eventually rising incomes, which in turn brings an increase in consumption, forming yet another driver for the Great Acceleration.

The imprint of the burgeoning human enterprise on the Earth system is unmistakable, as shown in figure 1*b*. Not all of the 12 global environmental indicators show the same, sharp change in slope around 1950 owing to lags and buffering effects in complex natural systems, but the Earth system has clearly moved outside the envelope of Holocene variability. The rise in atmospheric greenhouse gas concentrations is well documented [1], but there are many more equally significant changes to the global environment. Conversion of natural ecosystems to human-dominated landscapes has been pervasive around the world [2]; the increase in reactive nitrogen in the environment, arising from human fixation of atmospheric nitrogen for fertilizer, has been dramatic [62]; and the world is likely entering its sixth great extinction event and the first caused by a biological species [63].

The onset of the Great Acceleration may well have been delayed by a half-century or so, interrupted by two world wars and the Great Depression. The embryo of the phenomenon was clearly evident in the 1870–1914 period. The rates of both population and economic growth began to rise above their earlier levels. The Industrial Revolution gathered pace also, and spread rapidly from its base in England and the Low Countries across other parts of Europe and to North America, Russia and Japan. The seeds for the post-World War II explosion in mobility were planted with the invention of the automobile and the aeroplane. Globalization began in earnest with the integration of the outputs of mines and plantations in Australia, South Africa and Chile into an emerging global economy. But the acceleration of these trends was shattered by World War I and the disruptions of the decades that followed.

What finally triggered the Great Acceleration after the end of World War II? This war undoubtedly drove the final collapse of the remaining pre-industrial European institutions that contributed to the depression and, indeed, to the Great War itself. But many other factors also played an important role [55,61]. New international institutions—the so-called Bretton Woods institutions—were formed to aid economic recovery and fuel renewed economic growth. Led by the USA, the world moved towards a system built around neo-liberal economic principles, characterized by more open trade and capital flows. The post-World War II economy integrated rapidly, with growth rates reaching their highest values ever in the 1950–1973 period.

Other factors also contributed to the Great Acceleration. The war produced a cadre of scientists and technologists, as well as a spectrum of new technologies (most of which depended on the cheap energy provided by fossil fuels), that could then be turned towards the civil economy. Partnerships among government, industry and academia became common, further driving innovation and growth. More and more public goods were converted into commodities and placed into the market economy, and the growth imperative rapidly became a core societal value that drove both the socio-economic and the political spheres.

Environmental problems received little attention during much of the Great Acceleration. When local environmental stresses, such as urban air pollution or the fouling of waterways, or regional environmental problems, such as

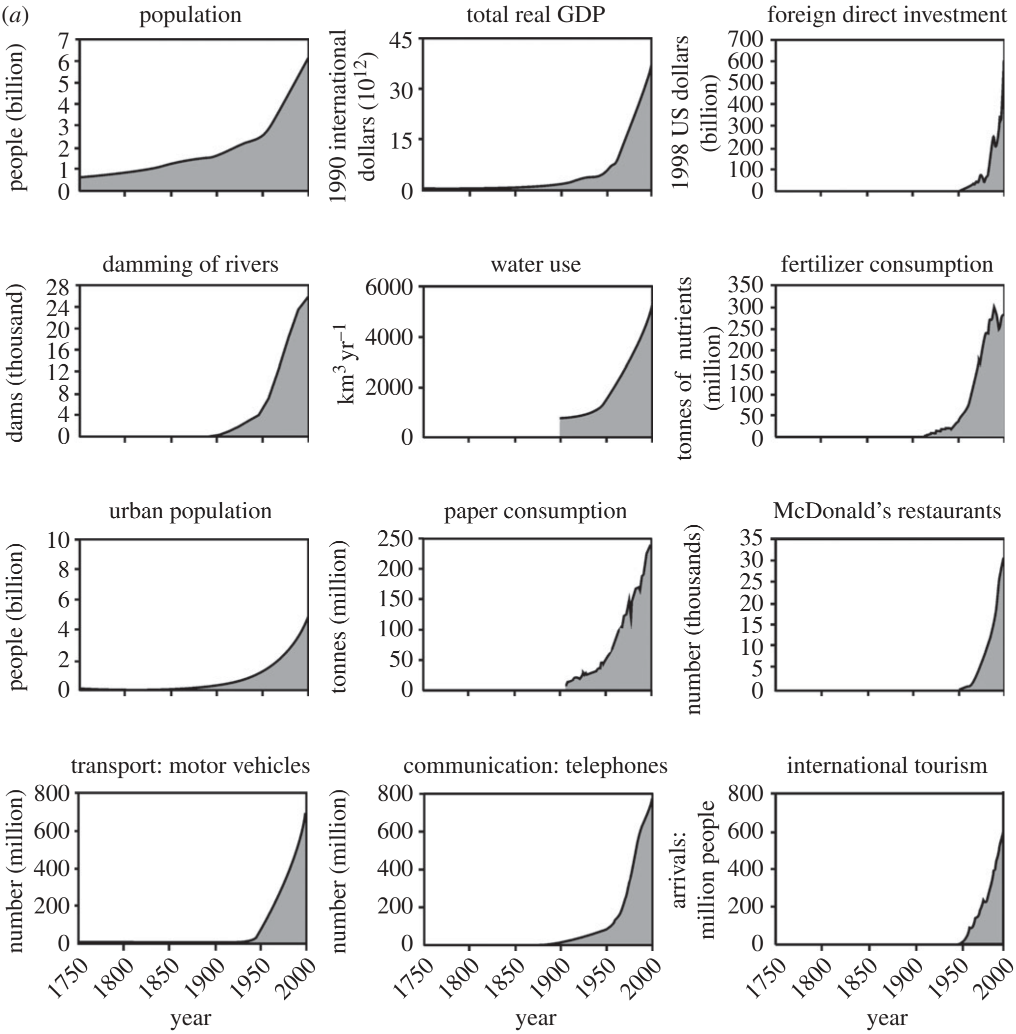

Figure 1. (*a*) The increasing rates of change in human activity since the beginning of the Industrial Revolution. Significant increases in rates of change occur around the1950s in each case and illustrate how the past 50 years have been a period of dramatic and unprecedented change in human history. From Steffen *et al.* [5], including references to the individual databases on which the individual figures are based. (*b*) Global scale changes in the Earth system as a result of the dramatic increase in human activity: (i) atmospheric CO_2 concentration; (ii) atmospheric N_2O concentration; (iii) atmospheric CH_4 concentration; (iv) percentage total column ozone loss over Antarctica, using the average annual total column ozone, 330, as a base; (v) Northern Hemisphere average surface temperature anomalies; (vi) natural disasters after 1900 resulting in more than 10 people killed or more than 100 people affected; (vii) percentage of global fisheries either fully exploited, overfished or collapsed; (viii) annual shrimp production as a proxy for coastal zone alteration; (ix) model-calculated partitioning of the human-induced nitrogen perturbation fluxes in the global coastal margin for the period since 1850; (x) loss of tropical rainforest and woodland, as estimated for tropical Africa, Latin America and South and Southeast Asia; (xi) amount of land converted to pasture and cropland; and (xii) mathematically calculated rate of extinction. Adapted from Steffen *et al.* [5], including references to the individual databases on which the individual figures are based.

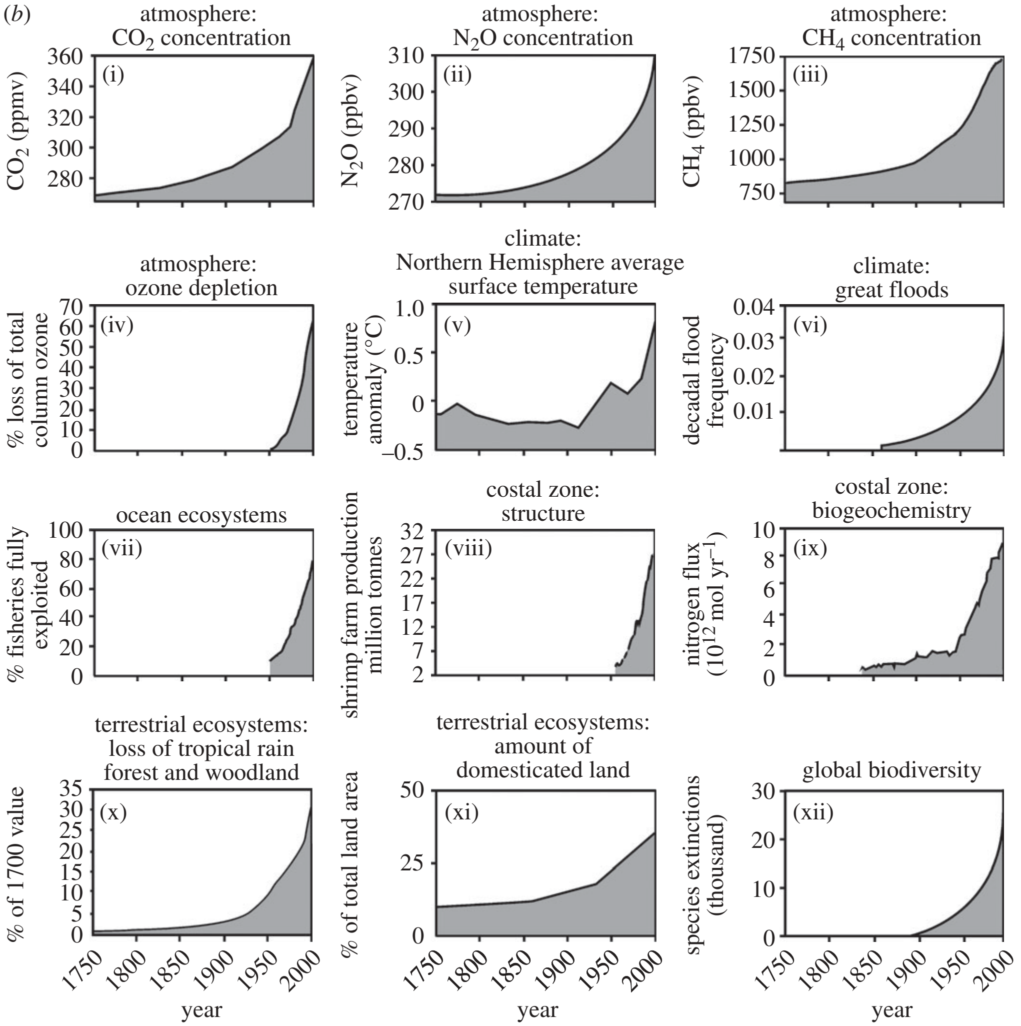

Figure 1. (*Continued.*)

the acid rain episode in northern Europe and eastern North America arose, they were sometimes ameliorated, but this action was largely confined to the wealthy countries of Europe, North America and Japan. The emerging global environmental problems were largely ignored. During the Great Acceleration, the atmospheric CO_2 concentration grew by an astounding 58 ppm, from 311 ppm in 1950 to 369 ppm in 2000, almost entirely owing to the activities of the OECD countries. The implications of these emissions for the climate did not attract widespread attention until the 1990s, and the cautious scientific community did not declare, with any degree of confidence, that the climate was indeed warming and that human activities were the likely cause until 2001 [64].

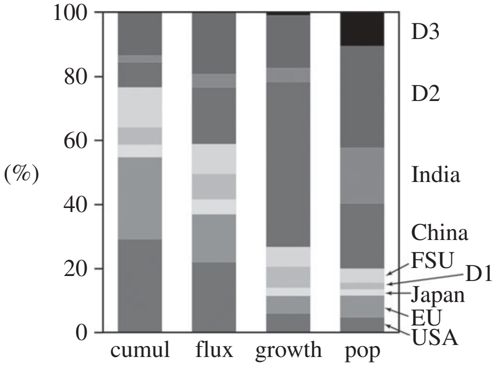

Figure 2. Relative contributions of nine regions to cumulative global emissions (1751–2004), the global emission flux for 2004, global emissions growth rate (5-year smoothed for 2000–2004) and global population (2004). FSU, Former Soviet Union countries; D1, developed countries except the USA, the EU and Japan; D2, developing countries except China and India; D3, least-developed countries. Adapted from Raupach *et al.* [65], which includes references to the individual databases on which the figure is based.

6. The Anthropocene in the twenty-first century

As the first decade of the twenty-first century comes to a close, many of the trends established during the Great Acceleration have continued, but the Anthropocene has also taken some new directions. One of the most prominent of these has been the rapid development trajectories that have emerged in some of the world's largest developing countries, most prominently China but also India, Brazil, South Africa and Indonesia. While it is clear that the Great Acceleration of the 1945–2000 period was almost entirely driven by the OECD countries, representing a small fraction of the world's population, the Great Acceleration of the twenty-first century has become much more democratic.

Figure 2, based on data through 2004, clearly shows the rapidly changing pattern of human emissions of CO_2 [65]. From a long-term perspective, developing countries have accounted for only about 20 per cent of the total, cumulative emissions since 1751, but contain about 80 per cent of the world's population. The world's poorest countries, with a combined population of about 800 million people, have contributed less than 1 per cent of the cumulative CO_2 emissions since the beginning of the Industrial Revolution. However, the most recent data in the figure show the dramatic changes over the past decade. For 2004, the emissions from developing countries had grown to over 40 per cent of the world total, and the emissions growth rate, based on a 5-year smoothed average for the 2000–2004 period, show that emissions from China and India have grown much more rapidly than those of the OECD countries and the former Soviet Union.

The global carbon budget for 2008 shows these trends even more sharply [66]. By 2008, coal had become the largest fossil-fuel source of CO_2 emissions, with over 90 per cent of the growth in coal use coming from China and India. China has now become the world's largest emitter of CO_2, and India has overtaken Russia as the third largest emitter. However, about 25 per cent of the growth in emissions over the last decade from developing countries was owing to the increase of international trade in goods and services produced in these developing countries but consumed in the developed world.

Despite the enormous economic growth rates achieved by China and India over the last decade, it is undoubtedly clear that resource constraints will prevent these and other developing countries from precisely following the post-1950 trajectories of the OECD countries. The most well-known of these potential constraints is the so-called 'peak oil' issue [4,67]. Nevertheless, China, in particular, has continued to achieve a sustained economic growth rate that has eclipsed that of the post-1950 era in the OECD countries.

The concept of peak oil is, in fact, more complex than is often appreciated. Technically speaking, peak oil refers to the maximum rate of the production of oil in any area under consideration, recognizing that it is a finite natural resource, subject to depletion [68,69]. It can thus refer to a single oil field or to global oil production as a whole, the latter being the more commonly understood scale of interest. In general, oil production is expected to rise to a maximum and then slowly decline. At the global scale, however, the ability to locate and access new sources of oil is an important term in the peak oil equation. But peak oil often implicitly (and incorrectly) refers to the ability of the production of oil to keep up with the demand. Ultimately, it is indeed the supply–demand relationship that is of most concern from the perspective of economic development; that is, supply will need to keep pace with demand if the large developing countries are to repeat the pathway followed by the OECD countries in their post-World War II economic explosion, when oil was plentiful and inexpensive.

What, then, are the prospects for the availability of oil beyond 2010? In terms of demand, an increase of about 2–3% yr^{-1} has been observed through the first decade of the twenty-first century, mainly owing to increasing demand in China and India. The International Energy Agency forecasts that production will need to increase by a further 26 per cent by 2030 to keep up with the demand [67]. The prospects of achieving this level of increased production in just two decades at prices that are affordable in the developing world seem highly unlikely. A recent, thorough assessment of the peak oil issue [67] came to the conclusions that (i) the timing of a peak for global oil production is relatively insensitive to assumptions about the size of the resource and (ii) the date of peak production is estimated to lie between 2009 and 2031, with a significant risk of a peak before 2020 (figure 3).

Much less well known is the possibility that the world is close to 'peak phosphorus' [70]. Phosphorus is a key element, along with nitrogen, in the fertilizers that have played a central role the rapid increase in agricultural production achieved during the Great Acceleration. The demand for fertilizer will grow as the world population continues to increase to the middle of the century at least and as diets change with the rapid development of China, India and other large developing countries. However, using a Hubbert-type analysis for phosphorus, the production of phosphorus is likely to peak at 25–30 Mt P per annum around 2030, well before the demand is likely to peak [70]. Without careful management of phosphorus production and distribution in an equitable and long-term manner, a deterioration of food security in some parts of the world, as well as diminishing supplies of petroleum, could slow the Great Acceleration significantly in the near future. The production of biofuels could exacerbate the situation.

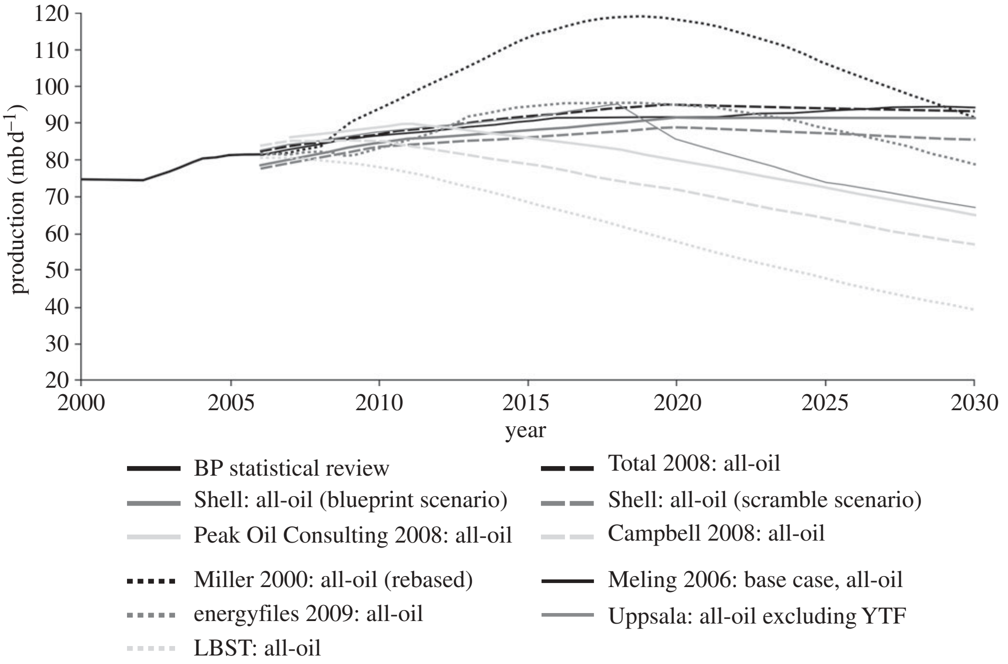

Figure 3. Forecasts for the peaking of the global production of conventional oil. The forecasts range from 2009 to 2031 (adapted from Sorrell *et al.* [67], which also includes references to the individual lines in the graph).

Perhaps one of the most controversial twists of the Anthropocene in the twenty-first century is the accelerating drive not only to understand the molecular and genetic basis of life, but to synthesize life itself. The announcement in May 2010 that a team led by J. Craig Venter had built a genome from its chemical constituents and used it to make synthetic life marks a dramatic step towards that goal [71]. The research effort, costing US$ 40 million and employing 20 people working for a decade, resulted in the creation of a bacterial chromosome, which was then transferred into a bacterium where it replaced the original DNA. With the new, artificially produced chromosome in place, the bacterial cell began replicating to produce a new set of proteins [72]. A team led by Venter was one of the two teams to first map the complete human genome, a feat that was announced in 2001 [73,74].

These latest steps towards building synthetic life are ultimately based on a longer history of research on the origin of life. The research goes back to 1952, just at the beginning of stage 2 of the Anthropocene—the Great Acceleration—when chemists Stanley Miller and Harold Urey performed a classic experiment that showed that the organic molecules that form the building blocks of life could be formed from simple inorganic molecules in the primitive Earth atmosphere [75,76]. They mixed methane, water vapour, ammonia, hydrogen and CO_2 in a closed container; when an electric current was discharged through the mixture, complex organic molecules, including amino acids, carbohydrates and nucleic acids, were formed.

Ironically, while humanity may be on the verge of creating new forms of life, it has failed to slow the recent decline in the Earth's existing biological diversity [77]. A synthesis of 31 indicators associated with biodiversity change during 1970–2010 shows no significant reductions in the rate of decline of biodiversity during that period. Despite some notable achievements towards reversing biodiversity loss, for example, an increase in protected areas globally to 12 per cent of the terrestrial surface and the declaration of new protected areas aimed at conserving key biodiversity areas [78,79], the overall trend continues to be one of the decline in 8 out of 10 indicators of the state of biodiversity, including declines in the populations of vertebrates [80], the extent of forest cover [81,82] and the condition of coral reefs.

The study has also examined trends in (i) the drivers of change to biodiversity, such as ecological footprint, nitrogen deposition, numbers of alien species, overexploitation and climate impacts and (ii) human responses to biodiversity decline, such as extent of protected areas, management of invasive alien species and sustainable forest management (figure 4; [15]). All of the indicators of human pressure on biodiversity show increases over the past several decades, with none showing a significant reduction. Humanity has responded to the decline in biodiversity with an increase in a range of conservation actions (figure 4*c*), but the level of response has not been sufficient to significantly affect the rate of biodiversity decline and, in fact, the rate of increase in response activity has slowed over the most recent decade.

Steffen *et al.* [57] argued that humanity is now entering stage 3 of the Anthropocene based on the growing awareness of human impact on the environment at the global scale and the first attempts to build global governance systems to manage humanity's relationship with the Earth system. The Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC) are examples of such attempts. However, the results from these two attempts at global governance have been disappointing. Emissions of CO_2 continue to rise unabated, while, as noted above, the human-driven decline in Earth's biodiversity shows no signs of being slowed or arrested.

Failure to build effective global governance systems is perhaps not surprising. Many characteristics of the Anthropocene are largely outside the range of past experience from an environmental governance perspective [83,84]. For example, time lags in the Earth system can be formidable; decisions made over the next decade or two could commit future societies to metres of sea-level rise centuries into the future. Irreversibility is also a common feature; loss of species cannot be reversed if society after the fact decides they might be valuable or worth preserving. Equity issues are often magnified in the Anthropocene. The strong difference between the wealthy countries that are most responsible for the additional greenhouse gases in the atmosphere and the poorest countries that are likely to suffer the most severe impacts of climate change is a classic example. Finally, the sheer complexity of the Earth system functioning, for example, the likelihood of tipping elements in large sub-systems of the planet [85], presents a bewildering array of problems to policymakers.

Given the nature of the problems arising in the Anthropocene, it is little wonder that political leaders, policymakers and managers are struggling to find effective global solutions. There are, however, some innovative approaches

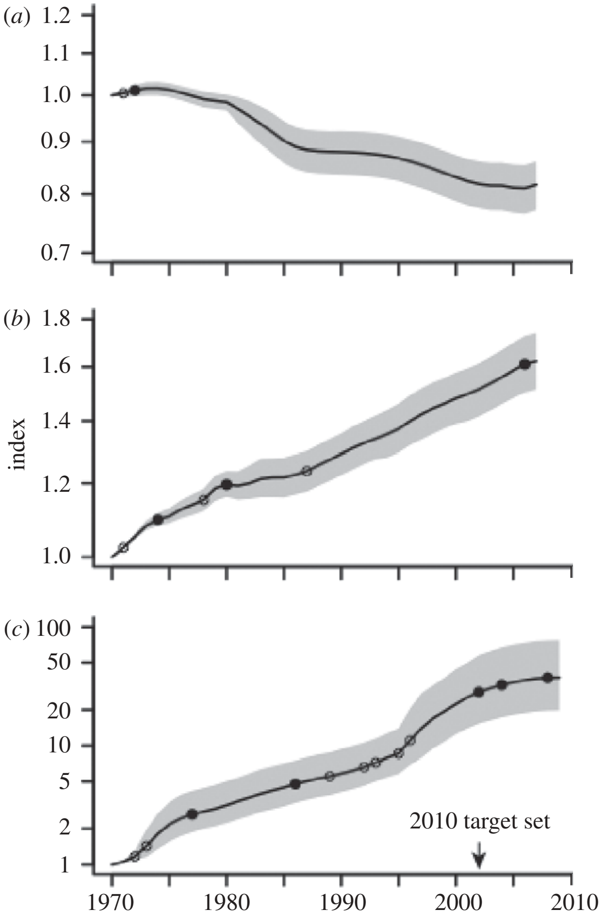

Figure 4. Aggregated indices of (*a*) the state of biodiversity, (*b*) the human pressures on biodiversity, and (*c*) the human responses to biodiversity decline. Shading shows the 95% CI, and significant positive/upward (open circles) and negative/downward (closed circles) inflections are indicated. Adapted from Butchart *et al.* [76], which also includes details on the methodology and the indices used in the aggregation.

that offer hope. Active adaptive management has proven effective in dealing with complexity and uncertainty at smaller levels [86–88] and might also be effective at the global level. Multi-level and polycentric governance systems show promise of bridging the gap between global problems and local impacts and solutions [89–91]. An additional—and very essential—challenge is to build early warning systems for changes in the Earth system functioning, so that policymakers can respond in time. The GEOSS (Global Observation System of Systems), designed to achieve comprehensive, coordinated and sustained observations of the state of the planet to support enhanced prediction of the Earth system behaviour (www.earthobservations.org), will be a key element in any early warning system. Finally, the governance community will need to greatly enhance its capacity to assimilate new information commensurate with humanity's exploding capability to gather both biophysical and socio-economic data and to analyse, interpret and model complex system dynamics [84].

The urgency of getting effective global governance systems in place was highlighted by the Copenhagen climate conference in December 2009, where attempts to reduce greenhouse emissions fell far short of expectations. The prospects for the immediate future do not look any brighter, given the need to turn around the rising levels of global emissions and the need for very deep and rapid cuts to emissions thereafter if what many consider to be 'dangerous' climate change is to be avoided [92,93]. Given this situation, considerable discussion is now turning towards the feasibility of deploying various climate- or geo-engineering approaches to cool the surface of the Earth [94–96] and, dependent on their outcome, possibly to be followed, step-by-step, by atmospheric tests. A major review of geo-engineering has been published by the Royal Society (2009). Only recently a taboo topic, geo-engineering has rapidly become a serious research topic and *in situ* tests may subsequently be undertaken if the research shows promising approaches.

Perhaps the most widely discussed geo-engineering approach is based on artificially adding aerosols (microscopic particles suspended in air) into the stratosphere ([97] and reintroduced by Crutzen [98]). Aerosols can originate naturally—for example, from wildfires, dust storms or volcanic eruptions—or from human activities such as fossil fuel and biomass combustion. Aerosols generally act to cool the climate by scattering back into space some of the incoming solar radiation. The effect is enhanced as some of these particles also act as nuclei around which water vapour condenses and forms clouds, affecting cloud brightness (albedo) and precipitation. The geo-engineering approach based on this phenomenon is to deliberately enhance sulphate particle concentrations in the atmosphere and thus cool the planet, offsetting a fraction of the anthropogenic increase in greenhouse gas warming. The cooling effect is most efficient if the sulphate particles are produced in the stratosphere, where they remain for one to two years.

Near the ground, the cooling effect of sulphur particles comes at a substantial price as they act as pollutants affecting human health. According to the World Health Organization, sulphur particles lead to more than 500 000 premature deaths per year worldwide [99]. Through acid precipitation ('acid rain') and deposition, SO_2 and sulphates also cause various kinds of ecological damage, particularly in freshwater bodies. This creates a dilemma for environmental policymakers, because emission reductions of SO_2, and also most anthropogenic organic aerosols, for health and ecological considerations, add to global warming and associated negative consequences, such as sea level rise. According to model calculations by Brasseur & Roeckner [100], complete improvement in air quality could lead to a global average surface air temperature increase by 0.8°C on most continents and 4°C in the Arctic.

Needless to say, the possibility of adverse environmental side effects must be fully researched before countermeasures to greenhouse warming are attempted. Among negative side effects, those on stratospheric ozone are obvious from an atmospheric chemical perspective. Recent model calculations by Tilmes *et al.* [101] indicate a delay by several decades in the recovery of the ozone hole.

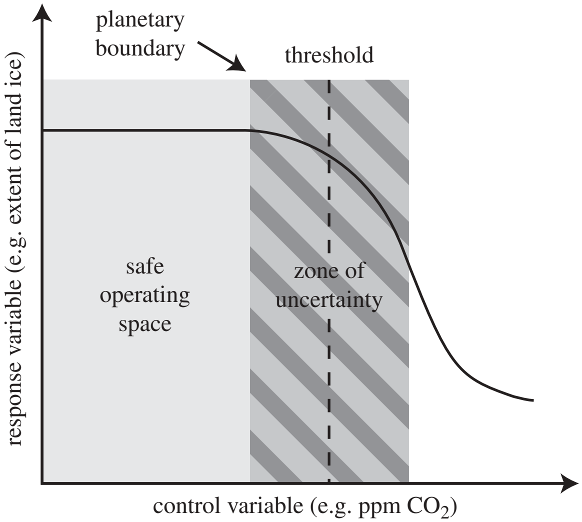

Figure 5. Conceptual description of planetary boundaries. The boundary is designed to avoid the crossing of a critical continental-to-global threshold in an Earth system process. Insufficient knowledge and the dynamic nature of the threshold generate a zone of uncertainty about its precise position, which informs the determination of where to place the boundary. Adapted from Rockström *et al.* [108].

There are at least two additional, potentially serious problems. First, should measures to limit CO_2 emissions prove unsuccessful, growing uptake of CO_2 will lead to acidification of the upper ocean waters, leading to dissolution of calcifying organisms [102]. Second, the effect of enhanced sulphur particle concentration in the stratosphere on precipitation regimes around the world, and hence on the water resources required to support human activities, may also be serious. Reducing incoming energy (sunlight) to the Earth's surface will no doubt lower global average temperature but it will also affect the global hydrological cycle. For example, the eruption of Mt Pinatubo in 1991, which produced a large volume of sulphur particles that were injected into the stratosphere, lowered global average temperature for a few years and led to increases in the incidence of drought and substantial decreases in global stream flow [103]. Data for the twentieth century as a whole show that volcanic eruptions caused detectable decreases in global land precipitation [104,105].

There is no doubt that, if geo-engineering is to play a significant role in preventing the climate system to warm beyond the '2°C guardrail' [106], much more scientific research is required. Even more importantly, legal, ethical and societal issues, not to mention the challenges of global governance described earlier, will need to be thoroughly explored and solved before deliberate human modification of the climate system can be undertaken. Building trust among international political leaders of many different cultures and perspectives, and with the general public, would be required to make any large-scale climate modification acceptable, even if it would appear scientifically advantageous. Ultimately, the near inevitability of unforeseen consequences should give humanity pause for serious reflection before embarking on any geo-engineering approaches.

A strongly contrasting approach—in many ways the antithesis of geo-engineering—is the planetary boundaries concept introduced by Rockström and colleagues [107,108]. The approach recognizes the severe risks associated with trying to deliberately manipulate the Earth system to counteract deleterious human influences, given the lack of knowledge of the functioning of the Earth system and the possibility of abrupt and/or irreversible changes, some of them very difficult to anticipate, when complex systems are perturbed. The planetary boundaries approach is thus explicitly based on returning the Earth system to the Holocene domain, the environmental envelope within which contemporary civilization has developed and thrived.

The set of planetary boundaries defines the 'safe operating space' for humanity with respect to the Earth system, and are based on a small number of sub-systems or processes, many of which exhibit abrupt change behaviour when critical thresholds are crossed. The approach is shown conceptually in figure 5. Control variables are defined for each sub-system or process, and, where possible, thresholds are identified in relation to the control variable. Thresholds are intrinsic features of the Earth system, and exist independent of human actions or desires. The boundaries themselves, on the other hand, are values of the control variable set at a 'safe' distance from the threshold, 'safe' being a value judgement based on how societies deal with risk and uncertainty.

Rockström *et al.* [107,108] suggest that nine planetary boundaries comprise the set that defines the safe operating space for humanity. Table 1 sets out the nine global sub-systems or processes, their control variables (parameters), the suggested planetary boundaries and the current position along the control variable compared with the pre-industrial (pre-Anthropocene) value. According to this analysis, three of the boundaries—those for climate change, rate of biodiversity loss and the nitrogen cycle—have already been transgressed. That is, in these cases humanity has already driven the Earth system out of the Holocene domain. Several of the processes—for example, change in land use and global freshwater use—do not have well-defined thresholds but rather could undermine the resilience of the Earth system as a whole.

The planetary boundaries concept is a further development in the unfolding stage 3 of the Anthropocene. Up to now, attempts at conceptualizing a global approach to managing humanity's relationship with the environment have focused either on individual sub-systems or processes in isolation—climate, biodiversity, stratospheric ozone—or on simple cause–effect approaches to deliberately manipulating the Earth system, that is, geo-engineering. Planetary boundaries take the next step, by considering the Earth system as a single, integrated complex system and by identifying a stability domain that offers a safe operating space in which humanity can pursue its further development and evolution.

7. Societal implications of the Anthropocene concept

Up to now the concept of the Anthropocene has been confined almost entirely to the research community. How will it be perceived by the public at large and by political or private sector leaders? If the debate about the reality of anthropogenic climate change is any indication, the Anthropocene will be a very difficult concept

Table 1. The planetary boundaries (adapted from Rockström *et al.* [107], which also includes the individual references for the data presented in the table). Those rows shaded in grey represent processes for which the proposed boundaries have already been transgressed. Boundaries for processes in dark grey have been crossed.

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 m^{-2})	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 phosphorus cycle)	amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
phosphorus 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 ($km^3\,yr^{-1}$)	4000	2600	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 of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof	to be determined		

for many people to accept. The rise of climate scepticism is increasingly being recognized, not as a scientific debate about evidence and explanation, but rather a normative debate deeply skewed by beliefs and values and occasionally by cynical self-interest [109].

Climate scepticism, or more appropriately the denial of contemporary climate change and/or its human causes, is, in many cases, a classic example of ‘cognitive dissonance’; that is, when facts that challenge a deeply held belief are presented, the believer clings even more strongly to his or her beliefs and may begin to proselytize fervently to others despite the mounting evidence that contradicts the belief [110]. This response may become even more pronounced for the Anthropocene, when the notion of human 'progress' or the place of humanity in the natural world is directly challenged. In fact, the belief systems and assumptions that underpin neo-classical economic thinking, which in turn has been a major driver of the Great Acceleration [61], are directly challenged by the concept of the Anthropocene.

Humanity has faced significant challenges to its belief systems from science in the past. One of the most prominent examples in the recent past is the theory of evolution, first postulated by Charles Darwin, which directly challenged the narrative of Christianity (and many other religions) about the origin of humans. The notion, subsequently strengthened by further scientific research, that we are 'just' another ape and not a special creation 'above' the rest of nature shook the society of Darwin's time, and still causes tension and conflict in some parts of the world.

The concept of the Anthropocene, as it becomes more well known in the general public, could well drive a similar reaction to that which Darwin elicited [111]. Can human activity really be significant enough to drive the Earth into a new geological epoch? There is one very significant difference, however, between the two ideas, Darwinian evolution and the Anthropocene. Darwin's insights into our origins provoked outrage, anger and disbelief but did not threaten the material existence of society of the time. The ultimate drivers of the Anthropocene, on the other hand, if they continue unabated through this century, may well threaten the viability of contemporary civilization and perhaps even the future existence of *Homo sapiens*.

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