CSIRO PUBLISHING

Environ. Chem. **2013**, *10*, 269–280
http://dx.doi.org/10.1071/EN13061

Rowland Tribute

Perspectives on our planet in the Anthropocene

Jonathan Williams[A,B] *and Paul J. Crutzen*[A]

[A]Max Planck Institute for Chemistry, D-55128 Mainz, Germany.
[B]Corresponding author. Email: jonathan.williams@mpic.de

Environmental context. The term Anthropocene has been proposed as a name for the present geological epoch in recognition of the recent rise of humans to being a geophysical force of planetary importance. This paper provides an overview of humanity's global impact in terms of population, energy and food demands, climate, air and ocean pollution, biodiversity and erosion, before giving a perspective on our collective future in the Anthropocene.

Abstract. Within the last 70 years (an average person's lifetime), the human population has more than tripled. Our energy, food and space demands as well as the associated waste products have affected the Earth to such an extent that humanity may be considered a geophysical force in its own right. As a result it has been proposed to name the current epoch the 'Anthropocene'. Here we draw on a broad range of references to provide an overview of these changes in terms of population, energy and food demands, climate, air and ocean pollution, biodiversity and erosion. The challenges for the future in the Anthropocene are highlighted. We hope that in the future, the 'Anthropocene' will not only be characterised by continued human plundering of the Earth's resources and dumping of excessive amounts of waste products in the environment, but also by vastly improved technology and management, wise use of the Earth's resources, control of the human and domestic animal population, and overall careful manipulation and restoration of the natural environment.

This paper is the first in a series of annual invited papers commemorating Professor Sherwood (Sherry) Rowland, Nobel laureate and founding Board Member of *Environmental Chemistry*.

Received 19 March 2013, accepted 27 May 2013, published online 20 August 2013

Introduction

Approximately 100 000 years ago several groups of hominid species roamed the savannah regions of Africa and Asia. They had evolved over the preceding 7–13 million years from tree-dwelling apes that made a transition to the then fast expanding grassland areas. Of these hominid tribes *Homo sapiens* proved the most successful, spreading across the continents of Europe, Australia, North America and finally South America so that by 12 000 years ago they had achieved a global presence and a population estimated at ~5 million.[1] The earliest *Homo sapiens* were part of a flourishing savannah ecosystem, hunting and gathering their food while themselves being prey to other species. They had harnessed fire,[2] and may have developed superior communication to other homonids.[3,4] However, there was little indication that this particular terrestrial species would surge in numbers to the 7 billion it is today. The global human population increased slowly at first reaching an estimated 300 million by 1 AD and up to 1.6 billion by 1900.

It is over the second half of the last century that the population growth has become truly startling, a period that is known as the Great Acceleration.[5] Sherwood Rowland, to whom this paper is dedicated, was born in 1927 when the

Prof. Jonathan Williams is an atmospheric chemist. He completed his B.Sc. and Ph.D. at the University of East Anglia, England, and after working as a postdoctoral researcher at the NOAA Aeronomy laboratory in Boulder, USA, he became a research group leader at the Max Planck Institute for Chemistry, Germany, with a focus on the investigation of the chemistry of volatile organic compounds (VOCs) in the atmosphere. He has participated in many international field campaigns on aircraft, ships and at ground stations. He is editor on several journals and recently co-authored the textbook The Atmospheric Chemist's Companion.

Born in 1933 in Amsterdam, Prof. Paul J. Crutzen was trained as a civil engineer and worked with the Bridge Construction Bureau of the City of Amsterdam. In 1959 he joined Stockholm University (MISU) to study meteorology and atmospheric chemistry. His research has been especially concerned with the natural and anthropogenically disturbed photochemistry of ozone in the stratosphere and troposphere. Thereby he identified the importance of nitrogen oxides emitted by fossil fuel and biomass burning, especially in the tropics, as important sources of air pollution with potential impacts on ozone and Earth climate. He served as Director of Research at the National Center of Atmospheric Research in Boulder, Colorado, 1977–80, and thereafter, until his retirement in 2000, at the Max Planck Institute for Chemistry in Mainz. Until April 2008 he did part-time research at the University of California, San Diego, Scripps Institution of Oceanography. In 1995 he received the Nobel Prize for Chemistry for his work on atmospheric ozone.

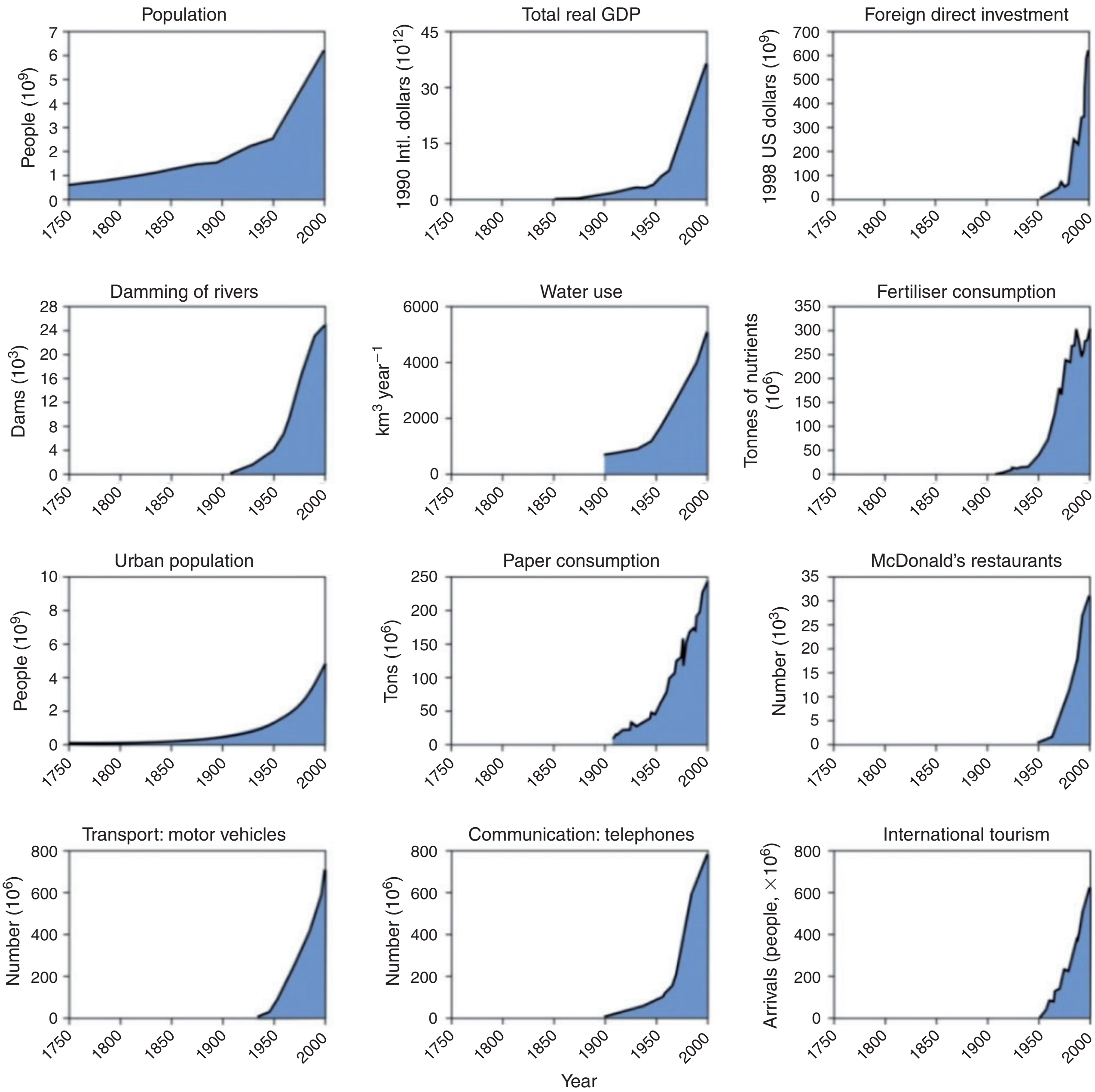

Fig. 1. Strongly changing parameters in the Anthropocene from Steffen et al.[8] (reproduced with permission).

population was 2 billion. Within his lifetime he witnessed a population doubling in 1974 (4 billion), when he published his seminal paper on ozone destruction by chlorofluorocarbons (CFCs) (see Molina and Rowland[6]), and a tripling (6 billion) in 1999, shortly after he received the Nobel prize for chemistry. At the 6-billion mark *Homo sapiens* had exceeded by 100 times the biomass of any prehuman large species that has existed on land and growth continues today at ~1.2 % per year globally so that over 230 000 people are born every day.[7] Of the estimated 110 billion *Homo sapiens* that have ever lived, ~6 % are alive today and 50 % of the present population live in cities. Humankind has now inhabited or visited almost all places on Earth, and has even set foot on the moon.

Current predictions suggest that the global population will reach 8–10 billion by 2050 and will have increased in average age. Human fecundity and related consumption of the Earth's resources has brought about profound changes relative to the pre-human planet.[8] So much so that it has been proposed that the current epoch should be named the 'Anthropocene',[9–13] to recognise that *Homo sapiens* have risen to become a significant geophysical force in their own right,[14] ('Anthropo-' meaning human and '-cene' meaning new). Fig. 1 shows how since 1950 the population and selected anthropogenic activities or indices have increased, in many cases so much that natural processes are exceeded. In the remainder of this short review paper we highlight several key global issues linked to the Anthropocene. Particular focus is placed on the atmosphere and changes in composition, chemistry and climate. We conclude the paper with a perspective on our collective future in the Anthropocene.

Energy and food

To sustain the burgeoning global population of humankind requires prodigious quantities of energy and food. Providing these has had a profound effect on the environment and many of

Fig. 2. Light sources at night, powered by fossil fuels (figure courtesy of Globaia, www.globaia.org, reproduced with permission).

the long established elemental cycles on Earth. Currently most man-made energy is derived from the fossil fuels coal, oil and gas, which are limited resources. They provide the 15 terawatts (15×10^{12} J s^{-1}, ~500 EJ year^{-1}) of power consumed on average by humans at present.[15] This is comparable to the Earth's internal heat production by radioactive decay. It is primarily fossil fuels that illuminate the dark side of the Earth in the image shown in Fig. 2. Importantly, only ~5 % (in 2004) of this energy is derived from sustainable (non-fossil fuel type) sources.[16] Without fossil fuel use in agriculture for planting, harvesting and fertiliser production the human population would have remained between 2 billion and 3 billion.[17] In other words, technological advances powered with fossil fuel have thus far saved us from the crisis predicted by Thomas Malthus in which the linear increase in food production ultimately fails the exponentially increasing population. Industrial agricultural activities have grown dramatically in number and efficiency especially since the Second World War, the so-called 'Great Acceleration', see Fig. 1. Although the main activity thus far has been in the developed world, the developing countries are following rapidly, especially in Asia.

The rapid spread of western consumptional culture in the post-war period known as the Great Acceleration was fuelled by plenty of cheap energy and likely catalysed by increased international financial co-operation as well as improved transportation and communication. Although before 1940 international trade was still related to colonialism, in the second half of the 20th century post-colonial and globalised commercial structures have taken over. Progress in medicine, particularly with antibiotics, has served to increase life expectancy and thereby population. Demand for food and energy has been the main driver of environmental change, modifying land cover and releasing waste products into the air and water. There are now some 20 billion farm animals worldwide, equating to approximately double the human biomass and the total terrestrial large vertebrate biomass is now approximately one order of magnitude above pre-human levels.[18] Industrial output increased 40 times during the past century; energy use 16 times and almost 50 % of the land surface has been transformed by human action, primarily for food and energy production. Most natural fisheries are fully or over-exploited. Today some 10 % of the Earth's surface, an area equivalent to South America, is now used for human food production. Genetically engineered crops and animals can serve to intensify food production but remain controversial. Fertilisers and pesticides are applied copiously, but inefficiently, to permit the intensification of agricultural production. Application is, however, globally uneven with some areas badly needing phosphates for fertilising whereas in other regions too intensive application has led to runoff and eutrophication of the waterways. The usage of phosphorous is particularly important as global reserves of this essential element are finite and dwindling. The problem has been neglected for a long time and if phosphorous is not recycled we may be heading for catastrophe.[19]

Changes resulting from increasing industrial output are not just quantitative in nature. There are qualitative alterations as well. Industry has introduced many thousands of newly synthesised compounds into the environment. Some of them are toxic, carcinogenic or mutagenic. Some of these molecules made by the chemical industry are remarkably hard for the environment to degrade (e.g. Dieldrin) so they will persist over decades. Even some non-toxic chemicals can show deleterious effects, such as the almost inert CFCs, which were shown by Rowland et al. to have caused the ozone hole.[20]

Currently the anthropogenic energy demand is satisfied primarily by finite carbon-based fuels (coal, oil and gas) that were derived from solar energy, sometimes termed 'fossilised sunlight.' With peak oil imminent (or even past), more sustainable energy and also element sources must be sought in order to maintain the population and food supply.[21] Presently, however, coal seam gas and shale oil are being increasingly exploited. Ultimately direct sunlight capture as an energy source would be highly desirable for the future with support from geothermal, wind and hydropower. One interesting future technology vision involves coupling solar energy sources to desalination plants (to provide water), to agriculture and to settlements.[22] This holistic solution to water, energy and food production would serve to expand farmable land in desert regions and create a new modular, energy-focussed societal structure, see Fig. 3.

Recently, food and energy have become more closely linked through the production of biofuel. Fuel ethanol production from corn has proven very profitable in the United States and now the grain harvest is in demand as a primary foodstuff, for raising meat products, and for use as a fuel for combustion. As a result grain prices have risen abruptly and in the last decade the world food price index has doubled. If the price of oil increases, pressure will rise to convert additional land from food to fuel production. In other parts of the world biofuel production has expanded at the cost of tropical forest (e.g. palm oil production in Indonesia and sugarcane in Brazil).[23] Such changes expose the global population in the Anthropocene to potential food shortages and to biodiversity losses.[21] Yet currently between 30 and 50 % (or 1.2×10^9 and 2×10^9 Mg) of all food produced is wasted and never reaches a human stomach.[24]

Greenhouse gas emissions

The exploitation of fossil fuels for energy has resulted in emission of carbon dioxide to the atmosphere. There it can affect the Earth's climate by absorbing outgoing infrared radiation. The extent and potential climatic effect of recent CO_2 releases may be gauged through direct comparison to pre-human CO_2

Fig. 3. Combined electricity, freshwater, crops and living quarters (from Cleary[18], reproduced with permission).

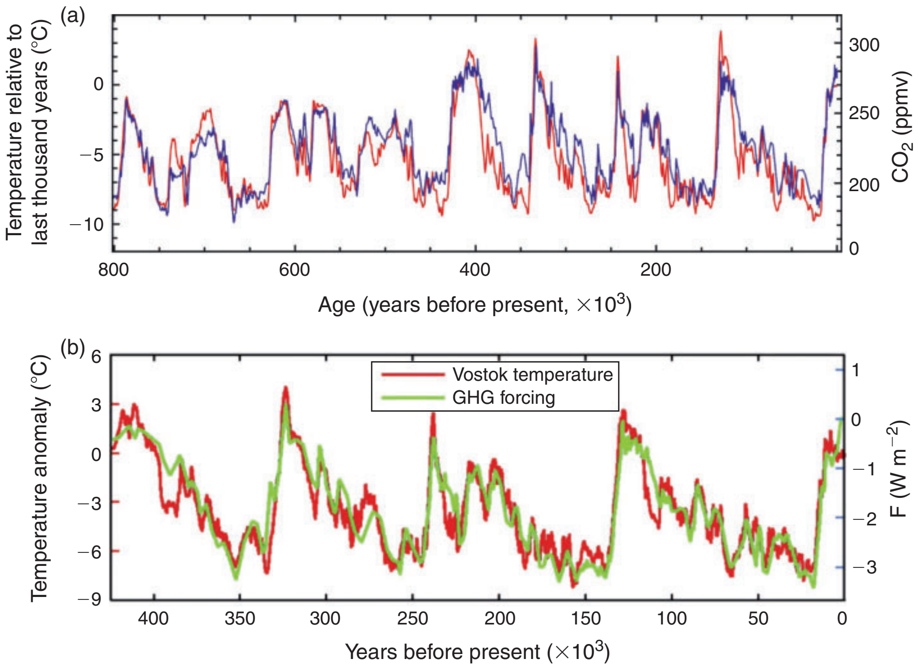

Fig. 4. (a) CO_2 from Lüthi et al.[25] and temperature data from Jouzel et al.[26] (b) Greenhouse gas forcing (GHG) (F) and Vostok temperature. The Antarctic temperature (left scale) is from Vostok ice core measurements (Vimeux et al.[21]) and global climate forcing (right scale) is due to CO_2, CH_4 and N_2O levels (Hansen et al.[22]). All images reproduced with permission.

levels (over the past 800 000 years) that can be derived from measurement of gas trapped in ice cores. Within this timespan, periodic glaciations of the northern hemisphere have occurred approximately every 100 000 years, apparently paced by the natural variation in the Earth's elliptical orbit around the sun, which affects ocean temperature and its capacity to absorb CO_2. In the course of such glaciations, CO_2 concentrations fall by ~100 ppm (μmol mol^{-1}), lower CO_2 causes lower radiative forcing and hence lower global temperatures,[25,26] see Fig. 4a. The long-term stability of the correlations of greenhouse gas forcing (combining CO_2, N_2O and CH_4 forcings) and the Vostok ice core-derived temperature clearly shows that we cannot escape a vicious cycle.[27,28] An increase in greenhouse gas concentration is unequivocally related to the increase in temperature.[27,28] The same 100 ppm change in CO_2 observed in a glacial–interglacial transition has occurred recently and much more rapidly between 1958 and 2010.[29,30] Over the past 800 000 years CO_2 has remained in the range of 172–300 ppm,[25] but now in 2013 it has reached 400 ppm and may even reach over 1000 ppm in the year 2100.[31] Fossil fuels are being used at a

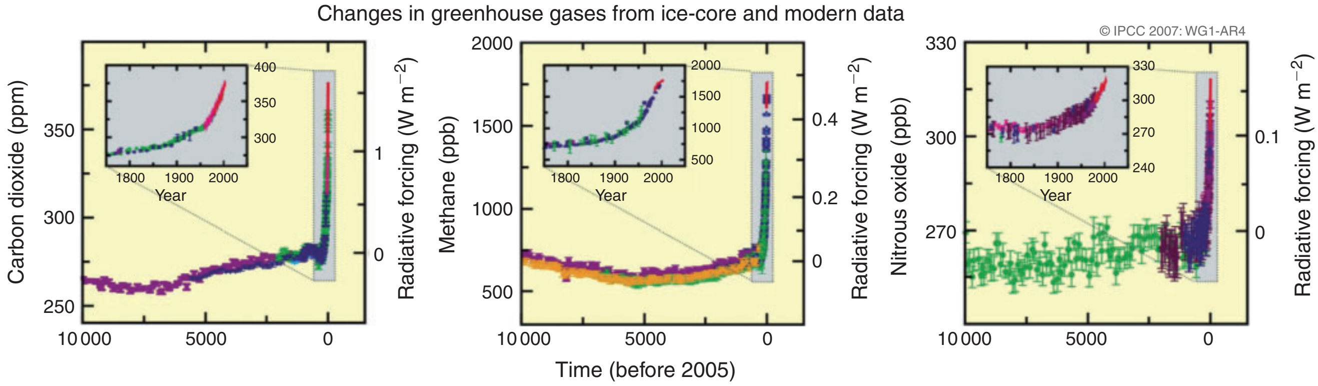

Fig. 5. Changes in CO_2, N_2O and CH_4 concentrations from ice cores and modern data. (Reproduction of fig. SPM.1 from the IPCC 2007 report,[34] with permission.)

prodigious rate and we are likely to have used up this valuable resource in a matter of centuries. It is worth noting that fossil fuels form only very slowly over millions of years. Annual coal consumption today is some 300 000 times the rate it accumulates.[32]

Presently, it seems likely that much of the estimated 4×10^9 Mg of fossil fuel carbon reserve will be released to the atmosphere as CO_2 over the coming century. Regrettably, the least efficient of the fossil fuels, namely coal, is set to become the main energy source in 2017. Although approximately half the CO_2 is being taken up by the ocean and the terrestrial biosphere, most will enter the atmosphere and persist there for extended time periods, comparable to those associated with nuclear waste,[33] providing a long-term enhancement in the Earth's radiative forcing even if we stopped emitting tomorrow.

CO_2 is not the only rapidly increasing greenhouse gas resulting from human activity. Levels of N_2O and CH_4, which are respectively 300 and 25 times more potent as greenhouse gases than CO_2 on a per-molecule basis, have increased significantly. From 1800 to present the methane concentration has surged from 800 to 1800 ppbv, whereas N_2O has increased from 272 to 310 ppb, see Fig. 5.[34]

Sherwood Rowland was one of the first to identify these changes in CH_4 as anthropogenic and to track the global concentration.[35,36] Anthropogenic emissions of methane from mining, ruminants, rice agriculture and biomass burning are now more than double the natural emissions from wetlands and termites. Strong additional methane emissions may result from the projected transition of the boreal permafrost to wetland, and see the recent changes in northern hemisphere snowcover, see Fig. 6. The pace of the climate change going on in the Arctic is on the order of two to three times as fast as in the rest of the world.[34]

The invention of the Haber–Bosch Process allowed humans to generate reactive nitrogen for intensifying agriculture. This nitrification was previously the preserve of a few evolutionarily adapted bacteria that replenished soil nitrogen when fields lay fallow. The anthropogenic input of reactive nitrogen to soil now exceeds the natural input.[37] Yet only a small fraction of the applied fertiliser (20–30 %) is actually taken up by plants. Much is lost into the atmosphere producing phytotoxic ozone or washed in to rivers causing eutrophication. An important side effect of this latter process is the production of N_2O, the greenhouse gas and source of NO in the stratosphere.[38]

In short, the provision of food and energy for the human population over the past 200 years has inadvertently elicited rapid increases in the global concentrations of long lived greenhouse gases on scales normally associated with 100 000 year climate cycles. Carbon dioxide, methane and nitrous oxide show a sharp increase in the modern period. If we look at the changes of temperature, of sea level and the northern hemisphere snow cover, we recognise that the correlation with greenhouse gas emissions exists and that this correlation can be explained by modelling, experiment and theory, see Figs 5 and 6.[34]

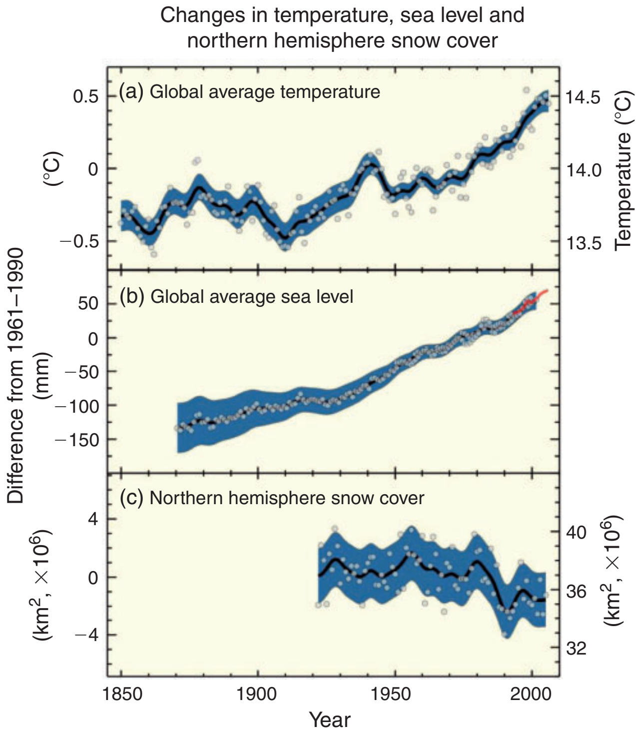

Fig. 6. Changes in temperature, sea level and northern hemisphere snow cover from 1850 to 2005. (Reproduction of fig. SPM3 from the IPCC 2007 report,[34] with permission.)

The iconic table of radiative forcing contributions provided in the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report shows the many different ways in which radiative forcing is influenced by human activities, see Fig. 7. It shows the calculated global mean radiative forcing caused by atmospheric gases and particles. Especially

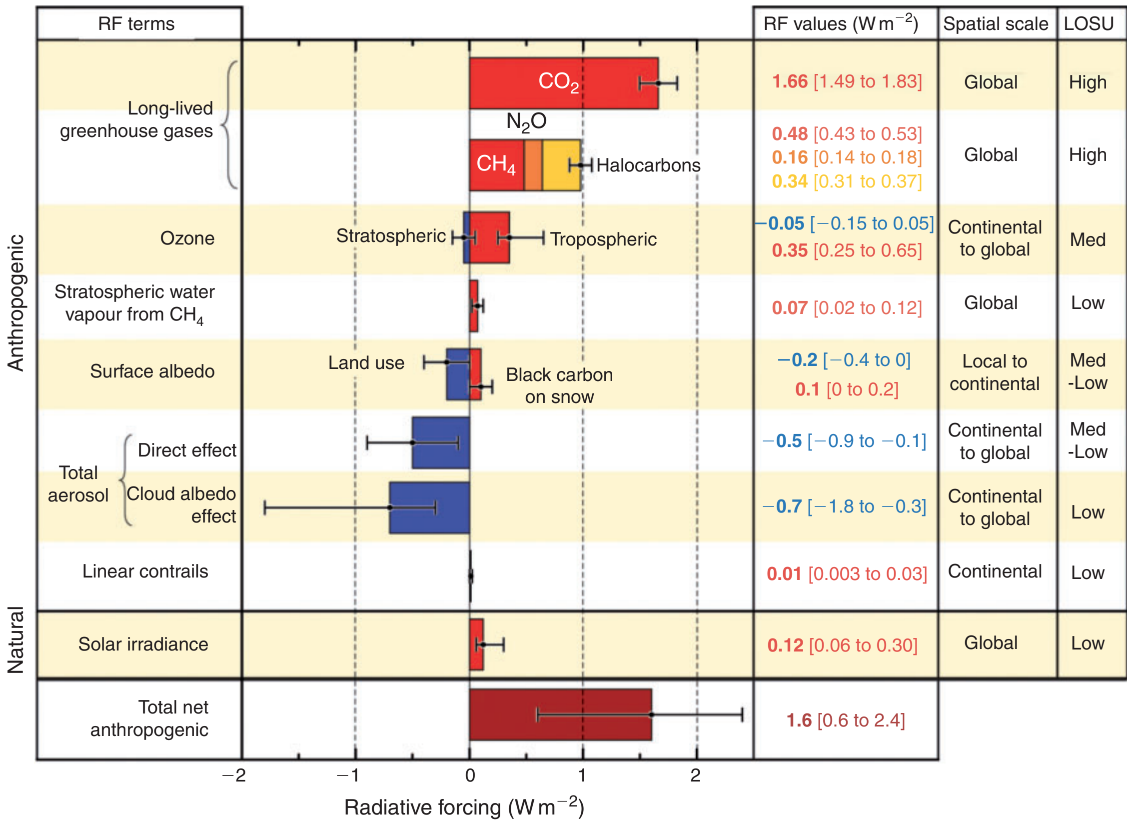

Fig. 7. Summary of radiative forcings, with spatial scale and level of scientific understanding (LOSU). (Reproduction of fig. SPM.2 from the IPCC 2007 report,[34] with permission.) (RF, radiative forcing; LOSU, level of scientific understanding.)

noteworthy here is that the level of scientific uncertainty (LOSU) is great. We simply do not know much about the consequences of our actions. This applies especially to the increased albedo effect. This backscattering of solar radiation from the surface of particles and clouds in the atmosphere is largely cooling, with the exception of black carbon. The complexity of the albedo assessment can be appreciated by considering that low altitude cumulous clouds have a cooling effect (by reflecting incoming sunlight), whereas higher level cirrus clouds warm the atmosphere (by absorbing outgoing infrared). However, the warming of the Earth's atmosphere is an evident phenomenon. Observations of air and ocean temperatures, on snow and ice cover and the rising global sea level are clear and unambiguous. Average global surface temperatures are expected to rise between 1.1 and 6.4 °C by the year 2100 depending on emission scenarios.[34] Conservative estimates of sea level rise are between 19 and 58 cm in the same period.

From Fig. 7 it can be deduced that cleaning the lower atmosphere of reflective particulate air pollution will warm the troposphere, enhancing the greenhouse effect. The opposite is the case when particles are added to the upper atmosphere. In order to stabilise concentrations of carbon dioxide and nitrous oxide at current levels, reductions in emissions of 60 % in the case of carbon dioxide and 70–80 % in the case of nitrous oxide have to be met. Yet the emissions still continue to increase. The conditions for the long-term stabilisation of methane are not clear yet, in particular due to the unknown effects of the thawing of permafrost.

There are two lessons to be learned from the discussion above: we have to reduce the emissions of greenhouse gases. In addition, we may choose to actively engage in counter-measures and if that is done deliberately, the effect can be termed geoengineering.[39] Such projects are both political and scientific in character requiring a new approach involving science and politics. Many, including the authors of this review, hold that geoengineering approaches should be attempted only as a last resort and that emission reduction is the only ultimate solution. However, if warming occurs much faster than predicted, geoengineering may need to be considered, perhaps first regionally in the more rapidly warming polar regions. A study by the Royal Society has investigated the efficacy of injecting very large amounts of sulfur into the stratosphere, approximately ~1–2 Tg of sulfur per year.[39,40] This very drastic action has to be followed up in the long-term, for the cooling to be effective. Due to the large uncertainties involved, we propose to study the resulting albedo scheme but only consider deployment if climate change becomes dramatic. Too many questions are still unresolved. Among them are the particle effects on longwave radiation, ozone loss and cirrus effects. Above all geoengineering must not question our determination to reduce emissions of greenhouse gases. In a few cases active anthropogenic intervention has resulted in a stabilisation or even reduction of atmospheric constituents. One example is the banning of CFCs through the Montreal protocol, which has achieved the required reduction. CFCs are a non-negligible part of the overall increase of greenhouse gases.

Ozone

Fig. 8a shows polar stratospheric clouds (PSCs) also called mother-of-pearl clouds.[41] They are very beautiful and damaging at the same time. At very low temperatures (<−75 °C) in the stratosphere the ice-particles forming PSCs play a large role

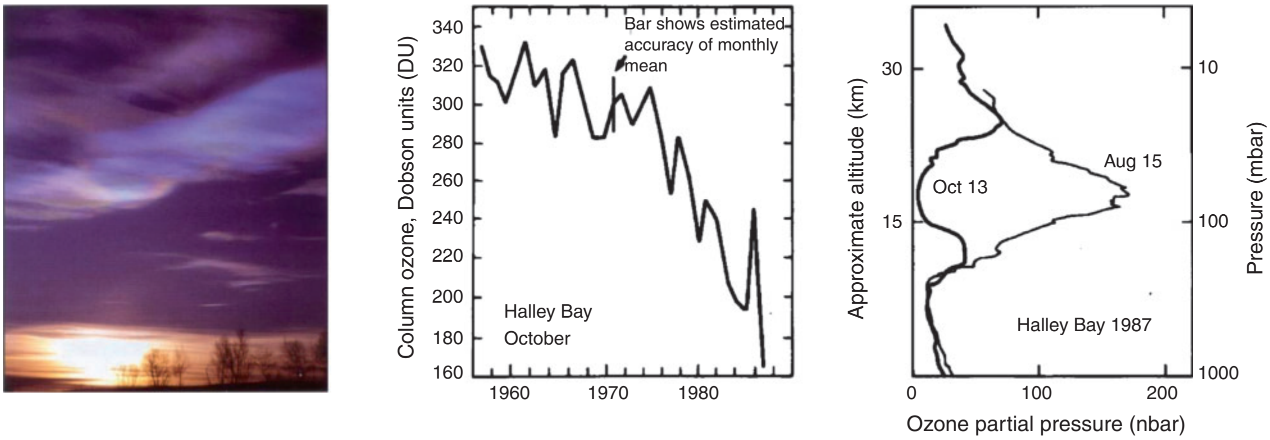

Fig. 8. A polar stratospheric cloud (from Fahey and Hegglin[41]), the decline of column ozone since 1953 (from Farman et al.[42]) and the vertical profile of the ozone hole (from Hofmann et al.[43]).

in ozone depletion. This is so because on the surface of the particles chlorine and bromine are converted into highly reactive catalytic forms, effecting the destruction of ozone. At high altitudes (~40 km) ozone loss occurs in the absence of these ice clouds by gas phase reactions. The effect of human activity was revealed when dramatic changes in ozone concentration were observed in spring time at high altitudes (12–25 km) (see Fig. 8b,c[42,43]) in the Antarctic where it was least expected. It took time to explain it scientifically and it clearly had a life-threatening dimension for humankind on earth. Sherwood Rowland was a key figure in this process.[6,44,45] Once the cause was determined in the 1980s, the CFC gases were banned from production. Nevertheless it will take several decades to heal the ozone hole.[46] It is a sobering thought that if the ozone-destroying chlorine would chemically behave like the closely related element bromine (or the refrigerants chosen for industrial production would have contained bromine instead of chlorine as was nearly the case), we would not just see the ozone hole in Antarctic spring; rather, we would experience it as a year-round and global effect. It was just luck and not our scientific intelligence, helping us out of a potential global catastrophe. This we know now because the effects of halogens on the ozone layer have been studied intensively for 40 years. But there are many more scientific riddles waiting. We do not know the effects of the many toxic and carcinogenic substances that we release day by day into the environment, so a precautionary approach is advisable. Scientists and engineers need to work with society to develop a sustainable future.

Although ozone is desirable in the stratosphere, ozone in the lower troposphere (0–15 km) is harmful to both humans and plants. By using our atmosphere as a convenient space to dump waste gases (nitrogen oxides and hydrocarbons), we have created optimal conditions for the formation of photochemical ozone and the fouling of our planetary nest. As an oxidant, ozone can directly damage lung tissue when inhaled. It has also been shown to dramatically reduce crop yields by damaging leaf tissue, with losses being calculated in the order of billions of dollars.[47] Background ozone is rising in many regions of the troposphere (e.g. Lelieveld et al.[48]) affecting both natural and anthropogenic ecosystems. Although ozone is harmful physiologically, some is necessary in the lower atmosphere to produce hydroxyl (OH) radicals. These highly reactive OH radical species result from ozone photolysis and, as the primary initiators of atmospheric oxidation, they effectively limit the concentrations of potentially toxic compounds (e.g. carbon monoxide) and greenhouse gases (e.g. methane).

The oceans and freshwater

The ocean and the atmosphere exchange massive quantities of CO_2 as part of the global carbon cycle. However, since the Industrial Revolution a significant anthropogenic CO_2 flux from fossil fuel usage has been added to the natural flux, leading to the increases in atmospheric mixing ratios discussed above. Between 2000 and 2008 some 26 % of this anthropogenic CO_2 was absorbed by the ocean and a similar amount by the terrestrial biosphere,[49] in effect providing a degree of mitigation to climatic change. The downside of the uptake by the ocean is that it is thereby acidified (pH is lowered)[50] alongside other marine climate change effects such as temperature, circulation, stratification, nutrient input and oxygen content, with potentially wide ranging biological species redistribution.[51] Marine organisms will have to respond to increasing temperature and acidification acting together. Generally they will be forced poleward with warming, but equatorward with increased acidification as cooler waters towards the poles take up more CO_2 and have lower pH. Between pre-industrial time and the 1990s the pH has decreased from 8.2 to 8.1 and may reach 7.8 by 2100.[52] Note that because pH is a log scale a difference of 0.4 equates to the ocean being 2.5 times more acidic. It is important to note that the buffering capacity of the ocean decreases as the ocean absorbs more CO_2 meaning that the ocean will take up less and less CO_2 as the seawater pH falls. Again it is the rate of this process that is cause for alarm,[53] for although the world's oceans have been more acidic in the past,[54] erstwhile changes have generally occurred over many millions of years allowing ecosystems time to adapt. At particular threat today from ocean acidification are the calcifying phytoplankton (e.g. coccolithophores), molluscs and coral reefs.[53,55] Although there is some evidence of tolerant marine species and indications that primary production and nitrogen fixation may increase with acidification, ocean communities are set to change abruptly with poorly understood effects on the marine food web.

Increasing population, industrial activity and climate warming will also affect freshwater in the Anthropocene. Water use has increased 9-fold during the past century to 600 m^3 per capita per year; 65 % for irrigation, 25 % for industry and ~10 % for households,[56] see also Fig. 1. It is worth reflecting that it takes 20 000 L of water to grow 1 kg of coffee, 11 000 L of water to make a ‘Quarter Pounder’, 5000 L of water to make 1 kg of cheese, whereas 1 kg of grain requires 1000 L[56] Over the past century tens of millions of people have been displaced through issues of water supply.[57] Some have had their homes flooded to make dams; still more have moved when local water resources were exhausted by overpumping. China, India and the United States, the world’s main grain producers, are all currently withdrawing water for irrigation from their underground aquifers at rates faster than they can be replenished so that watertables are falling markedly. When watertables descend too far, the overlying agriculture collapses and desertification begins, ultimately resulting in dust storms that erode and scatter the precious fertile topsoil to leave a largely barren scrubland. Incidences of major dust storms have been increasing dramatically over the past decade, severely affecting air quality in major cities and sometimes affecting neighbouring states.[21]

Although extensive infrastructures for water supply have been constructed, more than 1 billion people worldwide still lack access to safe drinking water. Climate change and associated changes in temperature and weather patterns will further alter freshwater distribution. Disputes between states may arise as water resources change.[58] For example, Pakistan is reliant on the flow of water from the Indus, which flows first through India and this has long been identified as potential cause for conflict. Similar tensions could develop between Egypt and Sudan and Ethiopia upstream of the Nile, particularly because wealthy nations are now acquiring land in these regions and developing water-intensive agriculture.[17] Likewise Turkey, which controls the headwaters of the Tigris and Euphrates, will affect Iraq and Syria through its proposed development of hydropower dams. More efficient usage of current resources is gradually being implemented worldwide. The largest domestic use of potable water, namely toilet flushing, has been made markedly more efficient. Likewise innovation in the form of drip irrigation and microsprinkers have improved agricultural irrigation, and recycling and process refining have reduced industrial demand.[57]

Man the eroder

Human actions have also had a deep effect on geological features. Human-caused erosion by crop tillage and land uses for grazing and construction exceeds natural erosion by 15 times. Sediment erosion rates have increased by more than an order of magnitude by human activities.[59] Conversely, because of human activities, the transport of sediments to the coastal zone (i.e. river deltas) has greatly decreased due to the construction of large dams.[60] The extent to which humans are modifying the Earth’s surface chemistry has been examined recently by comparing total anthropogenic fluxes of 77 elements with their natural counterparts Anthropogenic fluxes of up to 62 elements were found to surpass their corresponding natural fluxes.[61,62] Again the rate of anthropogenic change relative to the natural is striking. Take as an example the Grand Canyon, which cuts through a 1.8-km depth of rock spanning an age of 1.5 billion years. The last 6000 years, the time over which *Homo sapiens* have proliferated over the globe, are represented by only the uppermost millimetre of the depth profile.[63] Although nature has taken millions of years to carve out such a feature humans can excavate to equivalent depths in just a couple of years (e.g. Bingham Canyon copper mine 1.2 km deep, 4 km wide). Likewise constructions equivalent to small mountains can be completed in a few years (e.g. Burj Dubai, 829 m). In a sense humans have developed the powers of a latter-day superhero, diverting rivers, tunnelling through or flattening mountains, clearing forests or creating islands. The construction of the Palm Islands will add 520 km of beaches to the city of Dubai, United Arab Emirates, and displace more than 3 Gt of rock, sand and limestone.

It is interesting to consider what legacy we may leave in the rock,[63] even if we were to be removed from the Earth tomorrow.[64] Whether lasting traces of our existence will exist in the future rock record will be a factor in the decision whether to name the coming epoch ‘The Anthropocene.’ In our view anthropogenic rock assemblies should be identifiable 1 million years from now. Buried bones and pollen will reveal the extent of people, animals and plants. In geologically favourable locations concrete will remain in the strata, and rock-bound cavities will remain where iron objects have rusted or been dissolved away. Humankind’s changes to the carbon cycle will also be recorded isotopically in the sediments.[65]

Biodiversity

The expansion of humanity has come at the expense of other species and of biodiversity as a whole.[66] Fossil remains indicate that the colonising of each continent by *Homo sapiens* coincided with the local extinction of most megafauna species.[67] With increasing population humanity has appropriated natural habitats for both living space and food production. Further pressure has been exerted on existing ecosystems as their larger, slower and tastier components are exploited. Between 1700 and 2000, the terrestrial biosphere made the transition from mostly wild to mostly anthropogenic, passing the 50 % mark early in the 20th century.[68] At present, and ever more in the future, the form and process of terrestrial ecosystems in most biomes will be predominantly anthropogenic, the product of land use and other direct human interactions with ecosystems.[68] A lamentable legacy of human proliferation is that other animal species, that have taken millions of years to evolve, are rapidly becoming extinct. The natural rate of extinction in the absence of humans is thought to be one species per million per year. Currently the extinction rate is thought to be 100–1000 times this value.[66,69,70] There have been five main extinctions in the Earth’s 4.6 billion year history in which significant fractions (>50 %) of the existing genera have been lost. Such events are easily identified in geological strata where numerous and diverse fossil species abruptly give way to a few species types and then in turn, over some millions of years, to a diversity of new species assemblages. These transitions are used to delineate geological segments of time such as between the Permian and Triassic periods (250 million years ago), which was the most severe extinction of all. By 2050 it is estimated that 3.5 % of avifauna will be extinct and greater losses still are expected in mammals and freshwater fishes, which have to contend with increasing eutrophication caused by inefficient fertiliser usage. Still new species are being discovered and it is a tragedy to think that many species will become extinct before they can be examined and learned from. It is a sobering thought that if the current rates of extinction continue, then in 200–300 years the overall loss of species will be equivalent to that experienced in previous mass extinctions.[71] It may well be that we now live in the age of the sixth mass extinction in the history of earth,[72] the first to be caused by a species and not a geological event.[66] Because natural marine food resources have peaked (fisheries are fully or over-exploited),[73] it is expected that mostly terrestrial ecosystems will be used to feed and clothe the rising human population. Although aquaculture is expanding rapidly, this practice also has a significant ecological effect.[74] Land conversion is expected at the further cost of biodiversity, particularly in the tropical forests. The net change in forest area in the period 2000–2010 is estimated at -5.2×10^6 ha year^{-1} (an area approximately the size of Costa Rica), down from -8.3×10^6 ha year^{-1} in the period 1990–2000.[75] Much of the present agricultural crop harvest is used to feed animals and so a reduction in our dietary reliance on animal protein would increase the food available overall and decrease emissions of many of the aforementioned greenhouse gases. The average US citizen consumes 120 kg of meat per year and if the considerable populations of developing countries increase their consumption of meat, the pressure increases to develop further agricultural land, with accelerated loss of biodiversity.

In 1997 the natural environment was estimated by a team of economists and scientists to provide humanity with ecosystem services equivalent to $33 trillion. Such services include regulation of atmosphere and climate, purification of fresh water, formation of soil, detoxification of waste, pollination of crops and production of biofuel, lumber and fodder.[66] This valuation of the Earth's ecosystem was nearly twice the gross world product at the time ($18 trillion). Since 1997 the global world product (GWP) has increased while the ecosystem services have shrunk, a diverging trend that cannot continue if sustainability is to be achieved. The immense value of a biodiverse ecosystem is particularly perceptible in pharmaceutical development. Bioprospecting natural molecules developed by plants over millions of years has proven both effective and lucrative to medicine. All manner of revolutionary drugs including antibiotics, analgesics and antidepressents have been developed through study or adaption of natural products. Humankind must recognise and protect the resources proffered by natural ecosystems if we are to prosper in the Anthropocene.

The Anthropocene

From the preceding discussion it can be discerned that we are presently emerging from the Holocene, covering the past 10 000 to 12 000 years, into a new planetary epoch heavily affected by humankind's activities – the Anthropocene. The name Holocene (meaning recent whole) appears to have been proposed by Sir Charles Lyell in 1833 and it was adopted by the International Geological Congress in Bologna in 1885. Around this time several scientists recognised in print that humankind had become a significant geological, morphological and climatological force. In 1864, G. P. Marsh published a book entitled 'Man and Nature', which has been more recently reprinted under the title 'The Earth as Modified by Human Action'.[76] Stoppani in 1873 identified humankind's activities as a 'new telluric force which in power and universality may be compared with the greater forces of Earth',[77] and even spoke of an anthropozoic era. The great geologist V. I. Vernadsky noted in 1926 the increasing power of humankind as part of the biosphere,[78] as shown by the following excerpt 'the direction in which the processes of evolution must proceed, namely towards increasing consciousness and thought, and forms having greater and greater influence on their surroundings'. The Jesuit P. Teilhard de Chardin and E. Le Roy in 1924 coined the term 'noösphere', the world of thought, to mark the growing role played by humankind's brainpower and technological talents in shaping its own future and environment. This concept has been recently reworked into the concept of a technosphere.[79] Although humankind's significant environmental effect on a regional scale has long been recognised, the introduction of 'The Anthropocene' in 2000 as a global concept[9–11] has struck a chord with the zeitgeist. It is clear to most that for the immediate future a planetary anthropogenic effect will be felt regardless of any measures we will take. In view of this it is entirely appropriate in our view to name a new geological epoch, the Anthropocene, to take into account the large and permanent planetary effect of humankind.

At the time of writing there are well over 200 scientific articles published in 27 separate countries containing the word 'Anthropocene' in either title or abstract according to the Thomson Reuters Web of Science (date of search: 7 December 2012). The word has been taken as a theme for symposia (e.g. Haus der Kulturen der Welt-Berlin), for podcast series (e.g. Stanford University, generation Anthropocene) conferences and for research grant themes. Elsevier has launched a journal named *Anthropocene*. The use of the word 'Anthropocene' in the English language literature has been increasing exponentially since 2002 (n-gram, frequency of usage over time in Google Books, made 24 January 2013), whereas the trend of 'Gaia' usage is decreasing.[80] If the term 'Anthropocene' is officially accepted as the name of the emerging epoch then the word will emerge into modern everyday parlance. For this acceptance, there is gathering momentum in both geological quarters[81,82] and in general popularity. Before 2003, the term 'Anthropocene' yielded 416 web hits on Google but by 2013 that number had increased to over 2 370 000. Although the term 'Anthropocene' is not as well known as 'global warming' (~176 000 000 web hits *v.* with two out of three people polled knowing of it in 2008), the Anthropocene can be considered a more useful paradigm-defining term encompassing all human effects.[82]

The exact starting date for the Anthropocene, or where to place the 'golden spike', has been debated extensively. Some argue the most fitting start time to be the late 1700s, which coincides with the invention of the steam engine (by James Watt in 1784), which propelled the industrial revolution, with the first detectable rises in methane measureable in ice cores.[83] Alternatively, the stable carbon isotope signature, which changes sharply at c. 1850 with the rise of fossil fuel usage (Suess effect), has been suggested. Others contend the beginning of the Great Acceleration in the 1950s would be more suitable,[84] and this coincides with atomic weapon tests (late 1950s early 1960s) that have left a traceable global radioactivity signal (e.g. iodine 129, half-life 15.7 million years). In our view, the longevity of this signal makes it an attractive choice for geological demarcation. Much earlier dates have also been proposed, such as some 8000 years ago when detectable anthropogenic changes such as widespread forest clearance began,[85] or even 40 000 years ago when terraforming through use of fire began.[86] To a geologist investigating the remains of the human race 100 million years from now it will be of little import in which century the Anthropocene began, but rather how long humankind's dominion lasted and the effect it has had on the course of biological evolution. The extended warm period following the most recent ice age has permitted *Homo sapiens* to flourish. Yet through our actions we have initiated planetary scale changes at unprecedented rates, changes that will be preserved in the geological record of the planet for hundreds of millions of years.

Will we prosper in this new time of rapid change? By the end of this century it is likely that global temperatures will have increased by 1.1–6.4 °C, coral reefs will be severely damaged or destroyed and significant parts of the Greenland and West Antarctic–Antarctic Peninsula icecaps will be beginning to melt.[34] We may share the implicit optimism that human brain power will solve the challenging problems in front of us. However, the rapid quantitative expansion of humankind eats up much of our scientific and technical accomplishments. Technological solutions are not the whole answer. Even limitless energy would, given the current global mindset, simply allow for further devastation of the environment. Moreover humankind is the only species to have produced weapons of mass destruction. It is especially frightening that what has happened so far has been caused by only a part of the world's population. The wealthiest nations have had a planetary effect (e.g. in terms of climate gas emission, land-use and fossil fuel consumption) far greater than their proportion of the global population.

The Anthropocene has heralded a new age of interconnectivity, communication and availability of information. Knowledge of the planet's current state can be accessed from reliable sources globally in milliseconds. This is in stark contrast to the situation only 100 years ago when such information was confined to small groups of experts and public engagement was poor. Such improvements in information access and technology should help us work to a global consensus on sustainability, which in our view will be essential for concerted action. Dissemination of accurate information in all media can serve to educate, convince, confront or to cajole the planetary public. Multidisciplinary co-operation will be required to address the planet's anthropogenic ailments. Research and invention must be combined effectively with politics to exit the old paradigm of 'truth speaking to power' and to enter a more unified discourse taking into account present interests, power relationships and locked-in behavioural patterns. Moreover, a restructuring of the global governance system has been recently recommended, involving both public and private sectors, to mitigate and adapt to Earth system transformation at the scale and speed now required.[87] It is interesting to reflect that key to the success of early *Homo sapiens* was the ability to communicate with language, a clear evolutionary advantage when used to warn others of danger. Perhaps today's fast-growing communication network will serve a similar purpose, and may help us restrain the largest geophysical force we can control,[88] namely ourselves. Hopefully, in the future, the 'Anthropocene' will not only be characterised by continued human plundering of the Earth's resources and dumping of excessive amounts of waste products in the environment, but also by vastly improved technology and management, wise use of the Earth's resources, control of the human and domestic animal population and overall careful manipulation and restoration of the natural environment.

References

[1] I. Tattersall, J. H. Schwartz, Evolution of the genus *Homo*. *Annu. Rev. Earth Planet. Sci.* **2009**, *37*, 67. doi:10.1146/ANNUREV.EARTH.031208.100202

[2] S. R. James, Hominid use of fire in the lower and middle Pleistocene. *Curr. Anthropol.* **1989**, *30*, 1. doi:10.1086/203705

[3] M. Musso, A. Moro, V. Glauche, M. Rijntjes, J. Reichenbach, C. Büchel, C. Weiller, Broca's area and the language instinct. *Nat. Neurosci.* **2003**, *6*, 774. doi:10.1038/NN1077

[4] W. Enard, M. Przeworski, S. E. Fisher, C. S. Lai, V. Wiebe, T. Kitano, A. P. Monaco, S. Pääbo, Molecular evolution of FOXP2, a gene involved in speech and language. *Nature* **2002**, *418*, 869. doi:10.1038/NATURE01025

[5] W. Steffen, P. J. Crutzen, J. R. McNeill, The Anthropocene: are humans now overwhelming the great forces of nature? *Ambio* **2007**, *36*, 614. doi:10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2

[6] M. J. Molina, F. S. Rowland, Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone. *Nature* **1974**, *249*, 810. doi:10.1038/249810A0

[7] J. Cohen, Human population: the next half century. *Science* **2003**, *302*, 1172. doi:10.1126/SCIENCE.1088665

[8] W. Steffen, R. A. Sanderson, P. D. Tyson, J. Jäger, P. A. Matson, B. Moore III, F. Oldfield, K. Richardson, H.-J. Schellnhuber, B. L. Turner, R. J. Wasson, *Global Change and the Earth System: A Planet under Pressure Series: Global Change – The IGBP Series*, 1st edn **2004** (Springer: Berlin).

[9] P. J. Crutzen, Geology of mankind. *Nature* **2002**, *415*, 23. doi:10.1038/415023A

[10] P. J. Crutzen, The 'Anthropocene'. *J. Phys. IV France* **2002**, *12*, 1. doi:10.1051/JP4:20020447

[11] P. J. Crutzen, E. F. Stoermer, The Anthropocene. *Glob. Change Newsl.* **2000**, *41*, 17.

[12] P. J. Crutzen, W. Steffen, How long have we been in the Anthropocene era? *Clim. Change* **2003**, *61*, 251. doi:10.1023/B:CLIM.0000004708.74871.62

[13] J. Zalasiewicz, M. Williams, A. G. Smith, T. L. Barry, A. L. Coe, P. R. Bown, P. Brenchley, D. Cantrill, A. Gale, P. Gibbard, F. J. Gregory, M. W. Hounslow, A. C. Kerr, P. Pearson, R. Knox, J. Powell, C. Waters, J. Marshall, M. Oates, P. Rawson, P. Stone, Are we now living in the Anthropocene? *GSA Today* **2008**, *18*, 4. doi:10.1130/GSAT01802A.1

[14] P. M. Vitousek, H. A. Mooney, J. Lubchenco, J. M. Melillo, Human domination of earth's ecosystems. *Science* **1997**, *277*, 494. doi:10.1126/SCIENCE.277.5325.494

[15] *BP Statistical Review of World Energy June 2012* **2012**. Available at http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2012.pdf [Verified 17 July 2013].

[16] J. Chow, R. J. Kopp, P. R. Portney, Energy resources and global development. *Science* **2003**, *302*, 1528. doi:10.1126/SCIENCE.1091939

[17] T. Lenton, A. Watson, *Revolutions that Made the Earth* **2011** (Oxford University Press: Oxford, UK).

[18] A. D. Barnosky, Megafauna biomass tradeoff as a driver of Quaternary and future extinctions. *Proc. Natl Acad. Sci. USA* **2008**, *105*, 11 543. doi:10.1073/PNAS.0801918105

[19] D. Cordell, J.-O. Drangert, S. White, The story of phosphorus: global food security and food for thought. *Glob. Environ. Change* **2009**, *19*, 292. doi:10.1016/J.GLOENVCHA.2008.10.009

[20] F.S Rowland, Stratospheric ozone depletion. *Phil. Trans. R. Soc. B* **2006**, *361*, *1469*, 769. doi:10.1098/RSTB.2005.1783

[21] L. R. Brown, *Full Planet, Empty Plates: The New Geopolitics of Food Scarcity* **2012** (W. W. Norton & Co.: New York).

[22] D. Clery, Greenhouse – power plant hybrid set to make Jordan's desert bloom. *Science* **2011**, *331*, 136. doi:10.1126/SCIENCE.331.6014.136

[23] D. M. Lapola, R. Schaldacha, J. Alcamoa, A. Bondeaud, J. Kocha, C. Koelkinga, J. A. Priess, Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc. Natl Acad. Sci. USA* **2010**, *107*, 3388. doi:10.1073/PNAS.0907318107

[24] *Global Food, Waste Not, Want Not* **2013** (Institute of Mechanical Engineers: London). Available at http://www.imeche.org/knowledge/themes/environment/global-food [Verified 2 August 2013].

[25] D. Lüthi, M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, T. F. Stocker, High-resolution carbon dioxide concentration record 650 000–800 000 years before present. *Nature* **2008**, *453*, 379. doi:10.1038/NATURE06949

[26] J. Jouzel, V. Masson-Delmotte, O. Cattani, G. Dreyfus, S. Falourd, G. Hoffmann, B. Minster, J. Nouet, J. M. Barnola, J. Chappellaz, H. Fischer, J. C. Gallet, S. Johnsen, M. Leuenberger, L. Loulergue, D. Luethi, H. Oerter, F. Parrenin, G. Raisbeck, D. Raynaud, A. Schilt, J. Schwander, E. Selmo, R. Souchez, R. Spahni, B. Stauffer, J. P. Steffensen, B. Stenni, T. F. Stocker, J. L. Tison, M. Werner, E. W. Wolff, Orbital and millennial Antarctic climate variability over

the last 800 000 years. *Science* **2007**, *317*, 793. doi:10.1126/SCIENCE.1141038

[27] F. Vimeux, K. M. Cuffey, J. Jouzel, New insights into southern hemisphere temperature changes from Vostok ice cores using deuterium excess correction. *Earth Planet. Sci. Lett.* **2002**, *203*, 829. doi:10.1016/S0012-821X(02)00950-0

[28] J. Hansen, M. Sato, P. Kharecha, G. Russell, D. W. Lea, M. Siddall, Climate change and trace gases. *Phil. Trans. R. Soc. A* **2007**, *365*, 1925. doi:10.1098/RSTA.2007.2052

[29] C. D. Keeling, R. B. Bacastow, A. E. Bainbridge, C. A. Ekdahl, P. R. Guenther, L. S. Waterman, Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus* **1976**, *28*, 538. doi:10.1111/J.2153-3490.1976.TB00701.X

[30] K. W. Thoning, P. P. Tans, W. D. Komhyr, Atmospheric carbon dioxide at Mauna Loa Observatory 2. Analysis of the NOAA GMCC data, 1974–1985. *J. Geophys. Res.* **1989**, *94*, 8549. doi:10.1029/JD094ID06P08549

[31] G.-K. Plattner, F. Joos, T. F. Stocker, O. Marchal, Feedback mechanisms and sensitivities of ocean carbon uptake under global warming. *Tellus* **2001**, *53B*, 564.

[32] C. H. Langmuir, W. Broecker, *How to Build a Habitable Planet* **2012** (Princeton University Press: Princeton, NJ).

[33] D. Archer, M. Eby, V. Brovkin, A. Ridgwell, L. Cao, U. Mikolajewicz, K. Caldeira, K. Matsumoto, G. Munhoven, A. Montenegro, K. Tokos, Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Plant. Sci.* **2009**, *37*, 117.

[34] IPCC, Summary for policymakers, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M.Tignor, H. L. Miller) pp. 1–18 **2007** (Cambridge University Press: Cambridge, UK, and New York).

[35] D. R. Blake, F. S. Rowland, Continuing worldwide increase in tropospheric methane 1978–1987. *Science* **1988**, *239*, 1129. doi:10.1126/SCIENCE.239.4844.1129

[36] D. R. Blake, F. S. Rowland, Worldwide increase in tropospheric methane 1978–1983. *J. Atmos. Chem.* **1986**, *4*, 43. doi:10.1007/BF00053772

[37] N. Gruber, J. N. Galloway, An earth system perspective of the global nitrogen cycle. *Nature* **2008**, *451*, 293. doi:10.1038/NATURE06592

[38] P. J. Crutzen, The role of NO and NO_2 in the chemistry of the troposphere and stratosphere. *Annu. Rev. Earth Planet. Sci.* **1979**, *7*, 443. doi:10.1146/ANNUREV.EA.07.050179.002303

[39] P. J. Crutzen, Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change* **2006**, *77*, 211. doi:10.1007/S10584-006-9101-Y

[40] *Geoengineering the climate: science, governance and uncertainty, RS Policy document 10/09, RS1636* **2009** (Royal Society: London).

[41] D. W. Fahey, M. I. Hegglin, *Twenty Questions and Answers about the Ozone Layer: 2010 Update*. *Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project, Report number 52* **2011** (World Meteorological Organization: Geneva, Switzerland). [Reprinted from *Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project, report number 52* **2011** (World Meteorological Organization: Geneva, Switzerland)].

[42] J. C. Farman, B. G. Gardiner, J. D. Shanklin. *Nature* **1985**, *315*, 207. doi:10.1038/315207A0

[43] D. J. Hofmann, S. J. Oltmans, J. M. Harris, B. J. Johnson, J. A. Lathrop, Ten years of ozonesonde measurements at the south pole: implications for recovery of springtime Antarctic ozone. *J. Geophys. Res.* **1997**, *102*(D7), 8931. doi:10.1029/96JD03749

[44] F. S. Rowland, J. E. Spencer, M. J. Molina, Stratospheric formation and photolysis of chlorine nitrate. *J. Phys. Chem.* **1976**, *80*, 2711. doi:10.1021/J100565A019

[45] S. Solomon, R. Garcia, F. S. Rowland, D. J. Wuebbles, On the depletion of Antarctic ozone. *Nature* **1986**, *321*, 755. doi:10.1038/321755A0

[46] IPCC, *IPCC/TEAP Special Report. Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons* **2005** (Cambridge University Press: Cambridge, UK).

[47] H. Akimoto, Global air quality and pollution. *Science* **2003**, *302*, 1716. doi:10.1126/SCIENCE.1092666

[48] J. Lelieveld, J. van Aardenne, H. Fischer, M. de Reus, J. Williams, P. Winkler, Increasing ozone over the Atlantic Ocean. *Science* **2004**, *304*, 1483. doi:10.1126/SCIENCE.1096777

[49] C. Le Quéré, C. Rödenbeck, E. T. Buitenhuis, T. J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett, M. Heimann, Saturation of the Southern Ocean CO_2 sink due to recent climate change. *Science* **2007**, *316*, 1735. doi:10.1126/SCIENCE.1136188

[50] K. Caldeira, M. E. Wickett, Anthropogenic carbon and ocean pH. *Nature* **2003**, *425*, 365. doi:10.1038/425365A

[51] S. C. Doney, M. Ruckelshaus, J. E. Duffy, J. P. Barry, F. Chan, C. A. English, H. M. Galindo, J. M. Grebmeier, A. B. Hollowed, N. Knowlton, J. Polovina, N. N. Rabalais, W. J. Sydeman, L. D. Talley, Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.* **2012**, *4*, 11. doi:10.1146/ANNUREV-MARINE-041911-111611

[52] J. P. Gattuso, L. Hansson, *Ocean Acidification* **2011** (Oxford University Press: Oxford, UK).

[53] O. Hoegh-Guldberg, P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, M. E. Hatziolos, Coral reefs under rapid climate change and ocean acidification. *Science* **2007**, *318*, 1737. doi:10.1126/SCIENCE.1152509

[54] B. Hönisch, A. Ridgwell, D. N. Schmidt, E. Thomas, S. J. Gibbs, A. Sluijs, R. Zeebe, L. Kump, R. C. Martindale, S. E. Greene, W. Kiessling, J. Ries, J. C. Zachos, D. L. Royer, S. Barker, T. M. Marchitto Jr, R. Moyer, C. Pelejero, P. Ziveri, G. L. Foster, B. Williams, The geological record of ocean acidification. *Science* **2012**, *335*, 1058. doi:10.1126/SCIENCE.1208277

[55] U. Riebesell, I. Zondervan, B. Rost, P. D. Tortell, R. E. Zeebe, F. M. M. Morel, Reduced calcification in marine plankton in response to increased atmospheric CO_2. *Nature* **2000**, *407*, 634.

[56] F. Pearce, Earth: the parched planet. *New Sci.* **2006**, *2006*, *2540.*

[57] P. H. Gleick, Global freshwater resources: Soft-path solutions for the 21st century. *Science* **2003**, *302*, 1524. doi:10.1126/SCIENCE.1089967

[58] J. Burke, M. Moench, *Groundwater and Society: Resources, Tensions, Opportunities* **2000** (United Nations: New York).

[59] B. H. Wilkinson, Humans as geological agents. *Geology* **2005**, *33*, 161. doi:10.1130/G21108.1

[60] J. P. M. Syvitski, A. Kettner, Sediment flux and the anthropocene. *Phil. Trans. R. Soc. A* **2011**, *369*, 957. doi:10.1098/RSTA.2010.0329

[61] I. S. Sen, B. Peucker-Ehrenbrink, Anthropogenic disturbance of element cycles at the earth's surface. *Environ. Sci. Technol.* **2012**, *46*, 8601. doi:10.1021/ES301261X

[62] R. J. Klee, T. E. Graedel, Elemental cycles: a status report on human or natural dominance. *Annu. Rev. Environ. Resour.* **2004**, *29*, 69. doi:10.1146/ANNUREV.ENERGY.29.042203.104034

[63] J. Zalasiewicz, *The Earth After Us: What Legacy will Humans Leave in the Rocks?* **2008** (Oxford University Press: Oxford, UK).

[64] A. Weisman, *The World Without Us* **2008** (Virgin Books: Croydon, UK).

[65] S. Al-Rousan, J. Pätzold, S. Al-Moghrabi, G. Wefer, Invasion of anthropogenic CO_2 recorded in planktonic foraminifera from the northern Gulf of Aquaba. *Int. J. Earth Sci.* **2004**, *93*, 1066. doi:10.1007/S00531-004-0433-4

[66] E. O. Wilson, *The Future of Life* **2003** (Vintage Press: London, UK).

[67] A.D. Barnosky, Megafauna biomass tradeoff as a driver of Quaternary and future extinctions. *Proc. Natl Acad. Sci. USA* **2008**, *105*, 11 543. doi:10.1073/PNAS.0801918105

[68] E. C. Ellis, K. K. Goldewijk, S. Siebert, D. Lightman, N. Ramankutty, Anthropogenic transformation of the biomes, 1700 to 2000. *Glob. Ecol. Biogeogr.* **2010**, *19*, 589.

[69] J. H. Lawton, R. M. May, *Extinction Rates* **2005** (Oxford University Press: Oxford, UK).

[70] Millennium Ecosystem Assessment, *Living Beyond Our Means: Natural Assets and Human Well-being* (Ed. R. T. Watson, A.H. Zakri) **2005** (World Resources Institute: Washington, DC).

[71] C. D. Thomas, A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. T. Peterson, O. L. Phillips, S. E. Williams, Extinction risk from climate change. *Nature* **2004**, *427*, 145. doi:10.1038/NATURE02121

[72] A. D. Barnosky, N. Matzke, S. Tomiya, G. O. U. Wogan, B. Swartz, T. B. Quental, C. Marshall, J. L. McGuire, E. L. Lindsey, K. C. Maguire, B. Mersey, E. A. Ferrer, Has the Earth's sixth mass extinction already arrived? *Nature* **2011**, *471*, 51. doi:10.1038/NATURE09678

[73] D. Pauly, J. Alder, E. Bennett, V. Christensen, P. Tyedmers, R. Watson, The future for fisheries. *Science* **2003**, *302*, 1359. doi:10.1126/SCIENCE.1088667

[74] J. Williams, P. J. Crutzen, Nitrous oxide from aquaculture. *Nat. Geosci.* **2010**, *3*, 143. doi:10.1038/NGEO804

[75] FAO, JRC. *Global forest land-use change 1990–2005, FAO Forestry Paper number 169* (Eds E. J. Lindquist, R. D'Annunzio, A. Gerrand, K. MacDicken, F. Achard, R. Beuchle, A. Brink, H. D. Eva, P. Mayaux, J. San-Miguel-Ayanz, H.-J. Stibig) **2012** (Food and Agriculture Organization of the United Nations and European Commission Joint Research Centre: Rome).

[76] G. P. Marsh, *The Earth as Modified by Human Action* **1965** (Belnap Press, Harvard University Press: Cambridge, MA).

[77] W. C. Clark, *Sustainable Development of the Biosphere* (Eds W. C. Clark, R. E. Munn) **1986** (Cambridge University Press: Cambridge, UK).

[78] V. I. Vernadsky, *The Biosphere* **1998** (Copernicus, Springer: New York). [Translated and annotated version from the original of 1926].

[79] P. K. Haff, Technology and human purpose: the problem of solids transport on the Earth's surface. *Earth Syst. Dynam.* **2012**, *3*, 149. doi:10.5194/ESD-3-149-2012

[80] J.-B. Michel, Y. K. Shen, A. Presser Aiden, A. Veres, M. K. Gray, The Google Books Team, J. P. Pickett, D. Hoiberg, D. Clancy, P. Norvig, J. Orwant, S. Pinker, M. A. Nowak, E. Lieberman Aiden, Quantitative analysis of culture using millions of digitized books. *Science* **2011**, *331*, 176. doi:10.1126/SCIENCE.1199644

[81] J. P. M. Syvitski, Anthropocene: an epoch of our making. *Glob. Change* **2012**, *78*, 12.

[82] J. Zalasiewicz, M. Williams, A. Haywood, M. Ellis, The Anthropocene: a new epoch of geological time? *Phil. Trans. R. Soc.* **2011**, *369*, 835. doi:DOI:10.1098/RSTA.2010.0339

[83] R. T. Watson, H. Rodhe, H. Oescher, U. Siegenthaler, Greenhouse gases and aerosols, in *Climate Change. The IPCC Scientific Assessment* (Eds J. T. Houghton, G. J. Jenkins, J. J. Ephraums) **1990**, pp. 5–40 (Cambridge University Press: New York).

[84] W. Steffen, J. Grinevald, P. Crutzen, J. McNeill, The Anthropocene: conceptual and historical perspectives. *Phil. Trans. R. Soc.* **2011**, *369*, 842. doi:10.1098/RSTA.2010.0327

[85] W. D. Ruddiman, The anthropogenic greenhouse era began thousands of years ago. *Clim. Change* **2003**, *61*, 261. doi:10.1023/B:CLIM.0000004577.17928.FA

[86] S. J. Gale, P. G. Hoare, The stratigraphic status of the Anthropocene. *Holocene* **2012**, *22*, 1491. doi:10.1177/0959683612449764

[87] F. Biermann, K. Abbott, S. Andresen, K. Bäckstrand, S. Bernstein, M. M. Betsill, H. Bulkeley, B. Cashore, J. Clapp, C. Folke, A. Gupta, J. Gupta, P. M. Haas, A. Jordan, N. Kanie, T. Kluvánková-Oravská, L. Lebel, D. Liverman, J. Meadowcroft, R. B. Mitchell, P. Newell, S. Oberthür, L. Olsson, P. Pattberg, R. Sánchez-Rodríguez, H. Schroeder, A. Underdal, S. Camargo Vieira, C. Vogel, O. R. Young, A. Brock, R. Zondervan, Navigating the Anthropocene: improving earth system governance. *Science* **2012**, *335*, 1306. doi:10.1126/SCIENCE.1217255

[88] S. R. Palumbi, Humans as the world's greatest force. *Science* **2001**, *293*, 1786. doi:10.1126/SCIENCE.293.5536.1786