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Volume 1 Number 1 April 2014

Contents

Editorial

Research articles

Perspectives and controversies

Short communication

Review

Editorial

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The Anthropocene Review: Its significance, implications and the rationale for a new transdisciplinary journal

**Frank Oldfield,[1] Anthony D Barnosky,[2]
John Dearing,[3] Marina Fischer-Kowalski,[4]
John McNeill,[5] Will Steffen[6] and Jan Zalasiewicz[7]**

Abstract

Human activities now play a major, integral and ever-increasing role in the functioning of the Earth System. This fact lies at the heart of the notion of the Anthropocene. Documenting, understanding and responding to the present and future challenges posed by the recent, dramatic changes in the relationship between humans and their environment thus becomes an imperative for human society. This editorial presents the rationale for engaging with the Anthropocene across a wide range of disciplines from engineering and environmental science to the social sciences and humanities. This essentially transdisciplinary engagement requires the establishment of a new journal, *The Anthropocene Review*, the scope of which is outlined in this editorial.

Keywords

Anthropocene, Earth System, Great Acceleration, human environmental impacts, Industrial Revolution

Since its introduction by Crutzen and Stoermer (2000), the term ‘Anthropocene’ has generated lively interest across a wide range of institutions and an impressive diversity of individual scholars and writers. Dating the start of the Anthropocene to around AD 1800, as originally proposed, has generated some ongoing controversy, but there is general consensus around the view that the key to its definition is the onset of processes through which human activities began to move crucial aspects of Earth System function well outside the preceding envelope of variability. Throughout the Holocene, and increasingly since the transition to farming, the human species has increased its

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[1]University of Liverpool, UK
[2]University of California, Berkeley, USA
[3]University of Southampton, UK
[4]Univeristy of Vienna, Austria
[5]Georgetown University, USA
[6]Australian National University Climate Change Institute, Australia
[7]University of Leicester, UK

Corresponding author:
Frank Oldfield, School of Environmental Sciences, Roxby Building, University of Liverpool, Liverpool L69 7ZT, UK.
Email: oldfield.f@gmail.com

imprint upon Earth, but it is only after the start of the Industrial Revolution that this imprint has evolved into a major force impacting many global biogeophysical cycles to the point of becoming a strong, integral and, in some respects, dominating force in the Earth System. In recent years especially, an unprecedented degree of global economic, cultural and political interconnectedness has also developed – the increasingly globalized human social system is thus also a key feature of the Anthropocene. While it may be premature to talk about an integrated human society, the ongoing dynamics point in this direction. Science can help lead this evolving global society towards greater awareness of its impacts, and guide it towards responsible, wise use of the resource systems upon which it depends. The capacity of systemic self-organization on a global scale also enables human society, at least in principle, to use Earth System knowledge for self-governance. Clearly, it is now necessary to understand the increasingly globalized social system as well as the biogeophysical phenomena that led to the original definition.

Such observations foreshadow the breadth of concerns subsumed under the Anthropocene heading and highlight the many ways in which *The Anthropocene Review* will be a radical departure from any of its predecessors in terms of scope and orientation. Existing journals with recent geological periods in their title, such as 'Holocene' or 'Quaternary' do, by their designation, broadly define their subject matter. Their concerns are primarily retrospective, which is not to say that by dealing with the past their concerns have no bearing on present and future environmental issues. It is important to reconstruct and understand the past not merely as the pages in a history book, or even as essential records of the Earth System under changed conditions of external forcing and internal dynamics. The past also contributes to a continuum of insight into processes and interactions that flows through the present to the future.

It is evident therefore that the justification for the Anthropocene (and for *The Anthropocene Review*) does not rest on the issue of exact equivalence to past epochs in a formal sense, but on the dramatic physical and biological changes caused by human activities. Reviewing the familiar and lengthy litany of human impacts and their growing, global significance (see e.g. McNeill, 2000; Steffen et al., 2004) is one important way of acknowledging the distinctive nature of the Anthropocene. An additional and complementary way of framing our concern with the Anthropocene is to try to seek out those characteristics of emerging human–environment relations that lend it distinction in substantive, conceptual, methodological and philosophical terms.

Prior to the formulation of the Anthropocene, the iconic precursors of our present concerns with Earth System integrity and human sustainability were mainly focused on one aspect of human–environment interactions, for example land-ethic based conservation (Leopold, 1949), pesticides (Carson, 1962), population (Ehrlich, 1968), the unplanned overexploitation of shared resources (Hardin, 1968), and model projections of global limits (Meadows et al., 1972). Now, we are dealing with complex systemic impacts, requiring a more comprehensive conceptual framework, as well as newly emerging research priorities. Perhaps we can begin to explore these by establishing some relatively non-controversial propositions:

- Anthropogenic climate change, in combination with a wide range of additional human impacts on the Earth System, forces us to acknowledge that human activities are now an integral part of the range of processes driving environmental change.
- This has the effect of breaking down the dichotomy between humans and nature at the functional level which, in turn, brings into question the appropriateness of much previous thinking and writing, about human–nature relations, since the human–nature dualism, as conventionally framed, no longer provides an adequate basis for assessing the functional dimensions of human–environment interactions.

- Although there must, inevitably, be a major focus on all those aspects of the Earth System that are seen to contribute to human life-support and welfare broadly defined, our concerns must go well beyond these and also deal with features of the changing Earth System in their own right. It would be unwise, for both pragmatic and moral reasons, to use a too narrowly anthropocentric perspective, especially in view of the many ways in which human actions have often had unintended consequences, though it is important not to oversensationalize. The Earth System has withstood a number of major vicissitudes, the most extreme of which resulted in major shifts to a new planetary state and, in the case of the big five mass extinctions, it took at least hundreds of thousands of years to recover. Some of these past changes have greatly exceeded the sum total of our current anthropogenic impacts, but it is clear that human influences, especially over the last six decades, are already leading to huge adjustments to the biosphere, and that the geological signature of our activities will persist into the future.
- Identifying and understanding those aspects essential for human life and well-being and all the interactions upon which they, and the functioning of the Earth System depend, pose unprecedented challenges for human society, not least because of the complexity of environmental systems (sensu Scheffer, 2009) as well as the complexity, size and range of actions of the human population. These features of the Anthropocene make it virtually impossible to establish simple, linear links between causes and effects.
- Humans have changed the Earth in both positive and negative ways. The key challenge for the future is to ensure that the negative changes do not outweigh the positive ones. Optimizing human influences within an ever- (and inevitably) changing Earth System of huge complexity has many dimensions – scientific, social, economic and ethical – that interact with and should help to steer decision-making towards more sustainable and equitable choices. The destructive side of this human capacity has become manifest in two world wars and countless other conflicts, and it is encapsulated in the technical ability to wage a global nuclear war. A constructive side of this capacity could manifest itself in efforts at geo-engineering or Earth management, though both pose daunting challenges.

These considerations point to the great breadth of concerns implicit in our engagement with the Anthropocene, whether or not it acquires formal, geological recognition. They also highlight the need for a journal that is truly transdisciplinary in scope. This implies more than a wide spread of diverse themes. It calls for a commitment to *communicate among* disciplines and conceptual frameworks in a way that creates mutual understanding without compromising professional quality. Articles should be accessible to all, and every attempt made, through the use of simple language, to overcome the difficulty of translating between the languages used by the members of different scientific communities.

The overall aim of the new journal therefore must be to communicate clearly, across a wide range of disciplines and interests, the causes, history, nature and implications of a world in which human activities are integral to the functioning of the Earth System.

The question of what time frame to adopt for the Anthropocene still requires consideration, for it inevitably impinges on the content of the journal. The original concept, as conceived by Crutzen and Stoermer (2000) sees the start of the Anthropocene coinciding with the early stages of the Industrial Revolution. By contrast, Ruddiman, who has recently summarised his findings in a comprehensive review (Ruddiman, 2013) outlines the evidence for atmospheric greenhouse gas increases in response to the early impacts of Old World farming from Neolithic times onwards. He makes a persuasive case for the importance of these increases in warming mean global temperatures long before the onset of industrialisation. His analysis also serves as an essential reminder that many of the landscapes upon which global change is occurring have a long history of human modification. Ruddiman's review drives him towards a definition of the Anthropocene that differs strongly from that of Crutzen and Stoermer, which focuses on the growing scope and accelerating rate of change from early industrial times onwards. In this regard, human impacts in the wake of the Industrial Revolution go far beyond increased atmospheric CO_2 concentrations and their consequences. They include resource depletion and innumerable forms of environmental pollution, as well as the myriad other consequences, social, economic and political linked to the rapid growth of human populations and the spread of globalization.

Ruddiman, recognising the accelerating rates of change with industrialisation, suggests, towards the end of his review, an informally defined two-stage Anthropocene, pre-industrial and post-AD 1850. In fact, what may be observed is three broad stages, with a third stage post-dating what Steffen et al. (2007) call the Great Acceleration from around AD 1950 onwards. For the time being then, pending any formal definition of the Anthropocene, we might think in terms of these three stages, though we see a strong case for focusing above all on the later stages, from the start of fossil fuel use that empowered societies with an unprecedented amount of energy and capacity for action (Fischer-Kowalski and Haberl, 2007). There will, inevitably be further stages. For example, the greater part of projected global warming, marine flooding of coastal lands and biodiversity loss have not yet happened.

We are now living at a time around six decades on from the start of the Great Acceleration. During that time, not only has the pace of change accelerated, so has the connectedness of human–environment interactions and the range of impacts on ecosystems and ecosystem services. There is a growing awareness among both environmental and social scientists and the general public for the need to understand the likelihood of regional and global instabilities, including identifying those paths that could take us beyond safe operating spaces towards tipping points.

In response, we have seen the development of increasingly powerful research tools to explore present conditions and likely future trends, as well as a lively engagement with global change themes across a wide range of disciplines, spanning the whole spectrum from engineering to the humanities. This therefore must be the core time frame for the new journal, though it is important that, wherever possible, studies should be viewed in the context of the longer-term evolution of human–environment relationships. The drivers and legacy of human–environmental interactions during the pre-industrial and industrial periods cannot be ignored. Irrespective of the time frame within which contributions are placed, or indeed the lack or transgression of time frames, there are important criteria and priorities to be considered in framing the aims and scope of the new journal:

- global, or at least major continental/ocean basin significance in any environmental processes, human activities or human–environment interactions under consideration. We aim to emphasize 'macro-scale' perspectives on processes potentially affecting Earth and global systems, but recognise that case studies on a more limited regional scale may provide the key to wider understanding and applications;
- significant contributions to the understanding of present-day problems of human–environmental relations and their perception, assimilation and transformation into effective action;
- the application and development of complexity and resilience science concepts and tools for addressing the past and future behaviour of social-ecological systems;
- the promotion of appropriate methods to underpin decision-making in response to complex human–environment interactions or within social-ecological systems;
- relevance to our appraisal of future trends, threats and alternative responses;

- the development of conceptual frameworks for defining and communicating the challenges of the Anthropocene beyond the specialist scientific community;
- the portrayal and evaluation of key political responses to the major challenges posed by the changing Earth System;
- the articulation of cultural, behavioural, ethical and aesthetic responses to current and future global change in different societies;
- the evaluation of new technologies developed in response to the emerging problems posed by human activities and climate change;
- engagement with issues of governance, sustainability, human demography and human health in response to environmental change and human population growth.

Even if the above outline were intended to delimit the range of concerns for *The Anthropocene Review*, it would give enormous transdisciplinary scope. The intention here, however, is to be indicative, rather than prescriptive. The potential goes beyond what any group can spell out and holds enormous promise for what is a challenging and exciting new publishing venture.

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A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth

Marina Fischer-Kowalski, Fridolin Krausmann and Irene Pallua

Abstract

We search for a valid and quantifiable description of how and when humans acquired the ability to dominate major features of the Earth System. While common approaches seek to quantify the human impact upon the carbon cycle by identifying the area of land cleared by humans, our point of departure is different human modes of subsistence, and we base our analysis on their social metabolism, in particular their energy metabolism. As a starting point, we use Ehrlich's classical IPAT formula, and give it a specific interpretation: human impact on Earth = population size × affluence (interpreted as energy available per person) × technology – for each mode of subsistence. The overall impact (or rather human pressure) then equals the composite sum of these. We qualitatively describe the functional characteristics of hunter gatherers, agrarian and industrial modes of subsistence such as population dynamics, energy regime and the technologies by which they interact with their environment. In a 'toy' model, we translate these considerations into global numbers for the past millennia: we estimate the respective population sizes and affluence (energy), and finally also technology concerning its impact on the carbon cycle. We see a major historical dividing line around AD 1500: until then, human population growth and metabolic rates carry about equal weight in increasing human pressure on the environment approximately fivefold from the year AD 1 onwards. From then on, the overall pressure of humanity upon the Earth increases by one order of magnitude; energy intensity contributes to this rise by roughly tripling the impact of population growth. Technology, because it is based upon a shift from biomass to fossil fuels (and other 'modern' energy carriers), does not moderate this impact, but enhances it by a factor of 1.5.

Keywords

CO_2 emissions, energy regime, human impact, industrial transformation, IPAT, land use, social metabolism

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Institute of Social Ecology, Alpen-Adria-Universität, Austria

Corresponding author:
Marina Fischer-Kowalski, Institute of Social Ecology, Alpen-Adria-Universität, Schottenfeldgasse 29, A-1070 Wien, Austria.
Email: marina.fischer-kowalski@aau.at

Introduction

The 'Anthropocene' is defined by the observation that humanity has become a planetary force, on a par with the geological or climatic forces used to define phases of Earth history. There is ongoing debate regarding the date when the species *Homo sapiens sapiens* began to generate such severe impacts upon Earth that it appears justified to introduce a new geological epoch. Three periods of transformation have come under consideration.

1. The transition from humans as hunters and gatherers to humans as agriculturalists (the so-called Neolithic revolution) initially in the 'Fertile Crescent' some 12,000 years ago and springing up in most other parts the world during the following millennia (Kaplan et al., 2009; Ruddiman, 2003).
2. The industrial transformation, or rather the time when the industrial era gained strength on a global scale, dated by Crutzen and Stoermer (2000: 17) to the 'latter part of the 18th century'.
3. An additional discontinuity is characterized as the 'Great Acceleration' (Steffen et al., 2007), to denote the process of rapid global growth after World War II.

With regard to timing, the scientific traditions of geology differ from those in the social and historical sciences. While the first basically deal with planetary phenomena and distinguish Eras or Epochs by the global predominance of certain organisms or processes, historians (even the small group that is concerned with 'global' or 'universal' history such as Sieferle (2003a), Pomeranz (2000) or Simmons (2008)), usually operate on a much smaller grid, both temporarily and regionally. While almost all world regions experienced Neolithic revolutions, these occurred at times thousands of years apart. While, by now, all world regions have experienced an industrial transformation, these transformations started hundreds of years apart. We need a conceptual bridge between these traditions in order to identify the point when a certain mode of human operations began to dominate development at the global scale. Here, we also wish to question the notion that such a date should be determined by particular observable environmental impacts of the mode of human operation, as for example Ruddiman (2003, 2013) argues. Different environmental impacts of anthropogenic operations may occur with variable delays.[1]

In this paper we focus on the socioeconomic aspects of defining the Anthropocene and investigate the interaction of the major drivers behind the observed environmental impacts, in particular population, its resource use patterns (or social metabolism) and technology. We try to identify modes of human subsistence distinct enough to cause substantially different pressures upon the environment, and to identify the size of the populations that lived by these modes of subsistence through time. From this perspective we aim to contribute to a valid and quantifiable description of how and when humans acquire the ability to dominate major features of the Earth System.

We will take as our point of departure the classical formula of Ehrlich (1968) and Ehrlich and Ehrlich (1991):

$$I = P * A * T \tag{1}$$

where I is environmental impact (or rather: pressure upon the environment), P is human population numbers, A is the affluence this human population enjoys, and T represents the technologies by which it interacts with the environment and achieves the affluence it enjoys. In our analysis, we will give these variables a more specific interpretation.

First, we do not assume a homogenous human population, but a population differentiated into modes of subsistence, or, as we explain below, into *sociometabolic regimes*. Affluence we interpret as the metabolic rate, i.e. the average energy (and material) input into the respective socioeconomic system per individual per year. This metabolic rate must at least suffice to keep the individual alive and allow for its biological reproduction, that is it must cover the basic needs of the human organism, or else this segment of the population will die. But there can be much more affluence: average metabolic rates in certain regimes exceed the basic metabolism of humans by orders of magnitude (see Figure 3). Finally, *T* (technology) is supposed to be the coefficient by which one unit of affluence measured as material or energy use translates into a specific environmental pressure; the same amount of food, for example, may translate into widely differing areas of deforested land and greenhouse gas emissions (GHG emissions), depending on how it is produced.

We leave open what *I* (impact/pressure) may encompass – whatever we wish to measure, such as, for example, GHG emissions or biodiversity loss, are candidates for testing the validity of the results on the right-hand side of the equation.

Thus, the whole equation becomes more complex, minimally

$$\mathrm{I_t = P_{1t} * A_{1t} * T_{1t} + P_{2t} * A_{2t} * T_{2t} + \ \ldots,} \qquad (2)$$

where the index *t* is the point in time and the numerical index denotes the mode of subsistence (sociometabolic regime).

The full program of such an analysis, of which we can only show examples here, would allow parameterization of the environmental characteristics of sociometabolic regimes, and their coexistence and succession over time throughout human history.

In the next section we review human modes of subsistence, discuss their basic features in terms of population dynamics, affluence and the technologies they employ with reference to their environmental impact, and describe the process of transition between them. The following section then documents our efforts at quantifying these features of sociometabolic regimes in what we call a ‘toy model’ for human impact on Earth across the last two millennia. We then go on to discuss the model findings with regard to the size of human impact on Earth and the issue of dating the start of the Anthropocene, but also with regard to the future course of human history and its sustainability.

Sociometabolic regimes in human history

There is a long tradition in the social and historical sciences of distinguishing between qualitatively different modes of societal organization, modes of subsistence (in anthropology), modes of production (Marx, 2010; Smith, 1776) or stages of civilization (Spencer, 1862). The distinctions drawn, and the criteria upon which they are drawn, vary – but only rarely have they been related to society–environment relations or to the environmental consequences of human activity.

It was the special achievement of RP Sieferle (1997, 2001a) to regard the modes of societal organization not simply as socially or socio-economically distinct, but to systematize them so that they can be characterized as socioecological patterns, comprising social organization (in the widest sense of the word) and related modifications of the environment, through intended or unintended environmental impacts. Key to the distinctions Sieferle draws is the source of energy and the dominant energy conversion technology used by society. The attraction of this classification is that it increases our understanding of the differences in functional problems faced by societies when trying to establish and maintain themselves within their environment, the evolutionary advantages and drawbacks that occur and therefore, also the directionality of change.[2]

Sieferle distinguishes between the hunting and gathering mode, the agrarian mode (with some subdivisions) and the industrial mode. The energy system of hunters and gatherers is 'passive solar energy utilization'. Hunter gatherers live on the products of recent photosynthesis (plants and animals for their food, firewood for heat). That they use fire to cook (rather grill) their food widens the spectrum of edibles – but still, only a very small fraction of their environment qualifies as food. Its collection requires mobility, both on an everyday basis and seasonally, and allows only for very low population densities. The agrarian mode, in contrast, offspring of the Neolithic revolution that occurred, at different times, on all continents but Australia, is based upon 'active solar energy utilization'. This means that land is cleared of its natural vegetation and solar energy is as far as possible monopolized for human food plants. In effect, this leads to extensive deforestation of the Earth (and the enrichment of the atmosphere with the CO_2 that previously had been stored in trees and soils), to a sedentary way of life, and to a large human labour burden that even increases with progress in technologies designed to raise returns from the land (Boserup, 1965, 1981). The sedentary way of life (plus milk from livestock and ceramics to boil liquids) allows for a much higher fertility, and the large labour burden motivates the raising of children to share the labour. Thus higher population growth creates higher population densities and an expansion of the agrarian mode across the world. Control of territory, tools, livestock and stored reserves is essential, and frequent territorial conflicts bring forward specialised classes of people to defend and attack territories, social hierarchies to control them, and urban centres. In many parts of the world, these systems developed into major empires and civilizations that subsequently collapse (Diamond, 2005; Tainter, 1988).

In the 16th century a new energy regime emerged, a fossil-fuel-based energy system that supplied society with an amount of energy never accessible before. In the UK, the use of coal instead of increasingly scarce fuel wood allowed a process of urban growth; and manufacture, textile production for export became very profitable, and sheep gradually crowded out farmers growing food. The invention of the steam engine finally kicked off what is known as industrialization. This turn of history in Europe ('The European Special Course'; Sieferle, 2001a) could, as some argue, also have happened in the East (Pomeranz, 2000; Sieferle, 2003b), or maybe could not have happened at all. It caused large-scale ecological and social transformations and continues to spread from the industrial core countries (currently comprising about 20% of the world population) to the much larger rest of the world, at an accelerating speed (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2009). It remains an open question whether the final exhaustion of fossil fuels, a detrimental transformation of the Earth's climate system, or politically guided change will bring this energy regime to a close. In any event, this industrial regime will have been sustained for a much shorter period than the previous regimes.

As should be apparent from the description of sociometabolic regimes, not only their defining parameters but also their dynamics are very different.

The hunting and gathering mode

For the passive solar energy utilization strategy employed by hunter gatherers, two basic technologies need to be considered.

The first is universal for humankind and of great importance: the preparation of food with the help of fire. As Wrangham (2009) shows, cooking (or rather, grilling) food by fire allows not only the digestion of some feedstuff that would otherwise not be digestible or would be poisonous, it also saves on endosomatic energy in digestion, at the expense of exosomatic energy use (fuel wood). This efficiency increase is an evolutionary advantage over other omnivorous animals, as humans can sustain themselves on a smaller food intake (and correspondingly on a smaller territory) than competitors. There are also substantial side effects of this technology highly relevant for human cultural evolution. Food is not eaten by each individual where it is found, but collected through a division of labour and brought back to a shared fireplace. This reinforces social cohesion and stimulates communication and the evolution of languages. In terms of environmental effects, this technology saves on impacts as it allows the use of low quality energy sources (firewood) for high quality food sources (thus less meat and high quality vegetable foods are required).

The second class of relevant technologies is hunting gear. Sieferle (1997: 40f) argues convincingly that technological innovations that make hunting more successful (than by, say, spears and bows and arrows) would have had a tendency to be self-defeating: they would have speeded up the depletion of the preferred prey animals and forced the community into faster migration. If we follow this argument, then food collection technologies would have been more or less equivalent in terms of most environmental pressures, with one exception: the use of fire as a pressure upon biodiversity. Firing vegetation to drive large herbivores over cliffs, for example, would have killed more animals and destroyed more biomass than could be eaten and thus represent a very wasteful technology.[3] If species extinction and biodiversity loss are the environmental impacts we wish to consider, this technology gains special weight. It is known for some regions that apparently large-scale vegetation fires have been employed by hunter gatherers; for other regions, this is not documented. If we focus on GHGs as the impact, we do not need in every case to give special weight to this technology, as vegetation regrowth would often compensate for the additional emissions.

In effect, we should not expect technology development among foragers to be very dynamic – quite the contrary. Thus we should not expect affluence – i.e. the energy and materials used per person and year – to be dynamic either. Paleoarchaeological records indicate that hunter gatherers had been relatively well nourished, on the basis of a mixed and variable diet. But their food and the firewood they needed is about all one has to consider in terms of metabolic rates. Because of their migratory lifestyles, foragers could not accumulate more personal belongings than they were able to easily carry with them and they did not build any durable infrastructures.

What about their population dynamics? Here again, we should expect only very low growth, of the order of less than 0.05% annually[4] in the long run. There are a number of arguments why this should be so. For example, the food intake of foragers provided very little fat (as wild animals typically are low on body fat, and most plant food, except for nuts, is also low in fat), and a chronic fat deficiency is known to reduce ovulation in women (Sieferle, 1990: 45). Foragers lacked containers that would allow boiling liquids over fire (such as ceramics), and thus babies fully depended on their mothers for lactation – again a factor contributing to lower fertility (and to reducing the survival chances of closely spaced siblings). On the other hand, children were important to secure the survival of the group, but there was little incentive to have the group growing; to have many children was a burden rather than an asset.

How should the transition to an agrarian or agro-pastoralist mode be envisaged? We may expect this transition to be a very slow process starting in favourable areas (such as river basins with secure water supply and rich soils, possibly well protected by mountains or deserts); in these areas, population density increased and permanent settlements were built. Foragers may have adopted elements of simple types of cultivation to support their food supply in these regions. Those that remained foragers who used to inhabit the same territory were gradually driven towards the less productive peripheries; in conflicts, they may have succeeded in raids but had little chance in the long run to win against the much more populous and maybe also increasingly fortified settlers.

Thus, in favourable environments, the agrarian mode had an inherent evolutionary advantage over foraging; social change moved slowly, but only in one direction,[5] and foraging was gradually extinguished by the advance of pastoralism and agriculture.[6] The respective population may have been partly assimilated to the new mode and partly driven into decline.[7]

The agrarian mode

As explained above, the 'active solar energy use' (Sieferle, 2003a) of the agrarian mode consists of manipulating terrestrial ecosystems so that they provide a higher return of those kinds of biomass humans wish to use in their social metabolism. Humans begin to control key parameters of ecosystems such as vegetation cover, elements of the water and nutrient cycles, and, by this, create colonized areas in which they concentrate solar energy for the photosynthesis of plants they desire.

The technologies to be considered are manifold and we refer to them here only at the most general and abstract level. First, agrarian populations share with foragers the technology of food preparation with the help of fire, but by creating fireproof containers they also become able to cook soups and broths. This widens the spectrum of plants used for human consumption, of food essential for smaller children and maybe also the elderly. Second, they convert forested land into land suitable for cultivation and thereby have a substantial impact on the carbon cycle. If the release of accumulated carbon stocks in vegetation and soil is considered as a component of I (environmental pressure/impact), this technology enhances the impact beyond the amount to be derived from metabolic rates alone.

Third, they keep domesticated animals as sources of labour and food and as a means of making extensive use of vast land areas. Keeping livestock has a massive impact on metabolic rates as the nutrition of these animals boosts socioeconomic biomass use. Further, the disease vectors of these animals, enhanced by increased density, impact on the health of humans as well as on wild species. Fourth, they deliberately intervene in the evolution of plants and animals by selectively favouring species variants more appropriate for human use, and by seeking to eradicate food competitors. This enhances the impact on biodiversity loss beyond the pressures resulting from metabolic rates and land conversion; some gain in biodiversity may also arise. Fifth, they create solid, built structures, first only houses and paths but increasingly also roads, ships, bridges, dams, urban settlements and protective walls around them and the like. All these not only require substantial amounts of materials (wood, stones, sand) and energy (thus raising metabolic rates), but they also destroy habitats and open ways for fast transportation and trade across large distances.

Sixth, they mine for minerals and metals. This constitutes a novel (if still small) compartment within the metabolic profile, and opens a huge spectrum of opportunities for human activities, among them the development of more effective weapons and of coins that function as an economic representation of value. If there is a focus on the toxicological impacts of social metabolism, metallurgy needs to be considered as an enhancer of impact. And finally, agrarian populations slowly but continuously advance their technologies to intensify their use of land, becoming able to nourish more people on ever-smaller areas, often at the expense of more human labour which substitutes for ecosystem services (Boserup, 1981). If considering the amount of land used agriculturally as an environmental impact, this technological change is beneficial, by alleviating impacts as it reduces land conversion and some of the consequences of a given metabolic rate and a growing population.

How should we regard the affluence variable within agrarian societies? Findings from historical reconstructions of biomass use (e.g. Cussó et al., 2006; Krausmann, 2004), from anthropological field studies (e.g. Coughenour et al., 1985) and from material flow studies of agrarian economies (e.g. Krausmann et al., 2008c) allow us to estimate the range of metabolic rates for the agrarian mode (see Figure 3). This range is quite wide in its extremes depending, to a large degree, on the ratio of livestock to humans. On average, metabolic rates in agrarian regimes are 3–4 times higher (both in terms of energy and in terms of materials) than those of hunter gatherers. Nevertheless, agrarian societies are energetically strongly constrained. The only major source of their affluence is land, and working the land requires population for labour. Small elites in agrarian societies may acquire additional riches by conquering and controlling larger territories (or engaging in non-agrarian trades). For the vast majority of the population, the expansion of territory may mean additional security from raids and foreign invasions, but it may also mean just the opposite, loss by continuous wars and civil strife. Elites may also increase their affluence by increasing the tax burdens on their subjects and tributaries, but also this strategy meets its limits at the subsistence boundary of those who do the agricultural work. Thus, we claim in effect that affluence (that is, average metabolic rates) in agrarian systems may rise initially when land and biomass are abundant but does not increase continuously and in the long run.

How is it possible that a technologically more dynamic mode of subsistence does not produce growing affluence for its members? The key answer to this question is population growth. As Boserup (1965, 1981) has convincingly shown, there is a trade-off of increasing area efficiency in agricultural systems: higher labour input and lower labour productivity.

In the agrarian sociometabolic regime, there is both an opportunity and a motive for high fertility. The opportunity derives from the sedentary mode of living that allows mothers to take care of a large number of children simultaneously and to feed small children also from sources other than breast milk, thus allowing for short child spacing. The motivation derives from an insatiable need for labour in agriculture, for both simple tasks that even small children easily can do (such as weeding, or looking after goats), and for heavy, physically demanding tasks that older people cannot do any more, and that require more mature children to take over.[8] In the cultural and religious systems of practically all agrarian societies, many children within marriage are usually considered a blessing, and methods for controlling their number (contraception techniques and abortion) are usually banned. At the same time, there are strong controls to prevent sexual relations and child birth outside of marriage. Another entry point for the cultural regulation of fertility is through prescriptive conventions concerning prerequisites for marriage. These may constitute economic limitations, (dowry requirements, requirements for the man to be able to support a family[9]) leading to the creation of substantial celibate population segments, and/or strictures linked to age (Grigg, 1980). So religious authorities and agrarian communities worldwide are clearly not interested in allowing for unsupported and landless children, but they do support high fertility within the confines of marriage and land tenure. An additional motivation for fertility may be security: a rural community, comprising an ethnic or religious subgroup, is stronger against outside attacks if it is larger, and has many young men to defend itself.

Thus the expansion of agricultural land and the intensified use of land both generate what ecological economics calls a 'rebound effect', feeding population growth and annihilating gains in affluence for the individual.

With regard to the components of our IPAT formula we therefore assume for the agrarian sociometabolic regime that there is, after an initial increase in metabolic rates from hunter gatherer levels (with the spread of livestock keeping), no substantial further growth and eventually even a slow decline of affluence over time. While metabolic rates remain largely constant, substantial population growth strains the boundary conditions of the agricultural mode (Malthusian hypothesis). With technologies, we assume there to be slow learning processes subject, on the one hand, to a rebound effect on population and, on the other hand, to the need to be differentiated according to the type of impact variable chosen.

How should the transition from the agrarian to the fossil-fuel-based sociometabolic regime be envisaged? In contrast to the Neolithic revolution that originates in many locations across millennia, the transition to fossil fuels originates in one region, Western Europe, in particular the UK (and also to some degree, the Netherlands) and spreads from there by processes of trade, technology transfer, imitation and economic domination across the world within centuries. The introduction of fossil fuels during the 16th century, peat in the Netherlands and then coal in the UK, first provided a highly valuable opportunity for urban growth. Urban growth, and with it the growth of manufacture, trade and other non-agricultural occupations, had been severely constrained, particularly in those two countries, by a lack of fuel wood. The removal of this constraint set in motion, or allowed for, scores of novel economic processes.[10] For the agrarian population in these countries, this offered mainly an opportunity to deliver their produce to larger urban markets and to migrate to the cities and seek employment.

The fossil-fuel-based industrial mode

If we date the beginnings of the industrial mode back to the beginnings of fossil fuel use for everyday subsistence, then we are back in the early 16th century – at least for the Netherlands and the UK.[11] By AD 1500, these two countries accounted for less than 2% of world population. This is where and when the fossil fuel energy subsidy to humanity started that would gradually enhance the human range of activity beyond anything ever possible before. Initially, peat and coal were used solely as a fuel for hearths in the households of manufacturing workers in growing urban centres, whose increasing requirements could no longer be supplied by fuel wood. The use of coal in the UK gained momentum with the redesign of houses so that coal could be used without suffocating the inhabitants (brick chimneys, iron stoves, see Allen, 2012); coal could be transported at low cost via waterways. Before even the invention of the steam engine by Newcomen in 1715, coal supplied already 20% of the UK's primary energy.[12] The use of steam engines finally enabled the conversion of heat into mechanical power; this not only introduced a positive feedback in coal mining (with the steam engine coal supplied mechanical power to pump out the water from coal mines and thus harvest ever more coal in ever deeper pits), it also revolutionized the transport system by railways (Grübler, 1998). The mechanical performance of coal-powered machines created conditions for large numbers of jobs in final manufacturing, and accelerated urban growth (see also Figure 1).

At the very core of the industrial mode there is an increase in affluence in the sociometabolic sense in which we use this term: affluence in energy. Before the technologies are developed that allow use of the additional energy source efficiently and for all kinds of purposes, there is a 250 year period of learning. By 1800, the primary energy available to the UK had increased fivefold, even by 50% per capita, despite substantial population growth. This signifies a doubling of metabolic rate over the previous agrarian level. In the earlier phase, there is mainly a build-up of production capacity and infrastructure with high environmental impact. Subsequently, owing to the intermediate phase of accelerated population growth, there follows a phase of only limited growth in average affluence per capita. This is followed by a later phase dominated by oil rather than coal (globally after World War II) leading to a strong growth in affluence. Across the whole sociometabolic regime up to a certain saturation in mature industrial countries, there is around a quadrupling of affluence over previous agrarian levels (Krausmann and Fischer-Kowalski, 2013; Krausmann et al., 2008a). This long-term change has been demonstrated by Wiedenhofer et al. (2013) for a number of now mature industrial countries, showing also that indeed there seems to have been a kind of saturation in metabolic rates in those economies from the 1970s onward (see also Gales

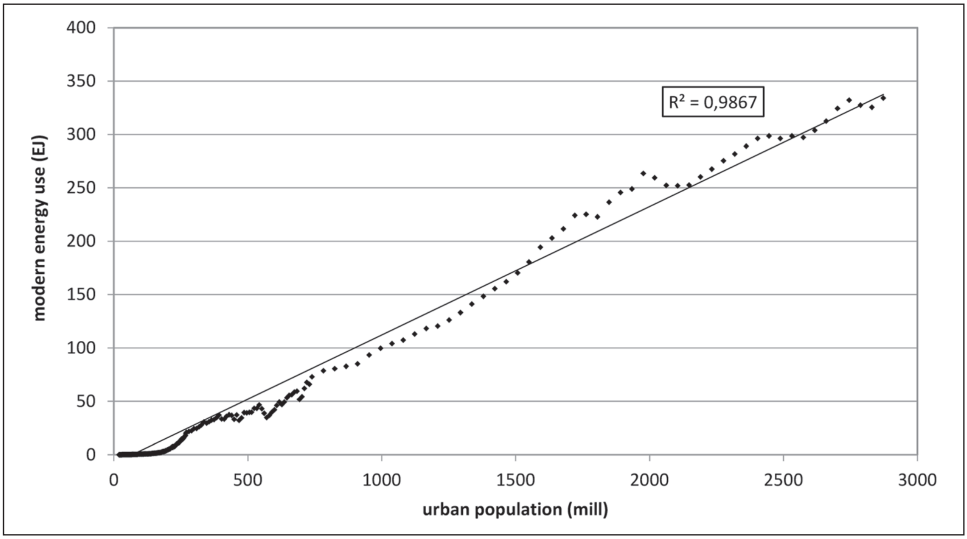

Figure 1. Global urban population numbers and global modern energy use (AD 1500–2000).
Sources: own calculation; urban population from Klein Goldewijk et al. (2010) (settlements with 2500 inhabitants or more); modern (primary) energy use includes fossil energy carriers such as peat, coal, petroleum and natural gas, hydropower and nuclear. Time series based on data compiled in Krausmann et al. (2009), Pallua (2013), Podobnik (2006). See also Figure S3, available online.

et al., 2007; Warr et al., 2010). While (slow) technological innovation in the agrarian regime feeds into population growth, in the industrial regime (fast) technological innovation feeds into affluence.

As far as population dynamics is concerned, a most dramatic transformation takes place that is commonly, but we think insufficiently, described by the term '(contemporary) demographic transition'. If we consider the full process of transformation up to the situation that dominates contemporary mature industrial countries, we see a demographic system of very low mortality rates, but even lower fertility, and a substantial prolongation of generation spacing (Lutz et al., 2004). In terms of biological reproduction, this is a system of negative population growth.

Functionally speaking, fertility decline comes about for good reasons. Under industrial conditions, from the perspective of parents the use-value of children is low: while they cost time and money and complicate the organization of daily life, of which the largest part is spent at a workplace away from home, they may provide comfort and emotional satisfaction – but these benefits can easily be reaped by one or two children. At the same time, parents can expect to be able to manage their (prolonged but healthier) old age on their own, and neither wish to nor can confidently rely on support from their children. This intergenerational setting is supported by the welfare state; if the welfare state should happen to break down, this would possibly again strengthen family ties, but it would simultaneously make children even more expensive for parents and shorten the life expectancy of the elderly: few families would be able to shoulder the high health expenditures that incur in late stages of a prolonged life. From the perspective of young people, there is no longer any barrier to enjoying a full sexual life without either marriage or pregnancy: both a technical and a moral decoupling of sex and childbearing has taken place. The educational career of young people, increasingly also of women,[13] takes up many years of reproductive age, and the start of a satisfactory job career, particularly for educated women, takes time, as does the search for an appropriate partner. In effect, many women begin their active reproduction towards the very end of their biological capacity, if at all.

Why, then, can it be that under conditions of a world dominated by fossil fuels and industrial development, we have had in the past decades, and still have on the global level, substantial population growth? The answer we give, derived from our theory of sociometabolic regimes, is the following: population numbers in the industrial sociometabolic regime do not increase by biological reproduction but by economic 'development', that is, a shift from the agrarian to the industrial regime that encompasses a larger and larger part of the global population – in urban industrial centres in developing countries, in large urban populations in emerging economies, and through immigration to fully industrialized countries. The cultural and demographic changes that go with the industrial regime may occur with some delay, while its benefits, such as medical assistance and long-distance food transport, reduce mortality also in the (co-existing) agrarian populations. Thus, in the past six decades, globally there has been both rapid population growth (culturally driven by the agrarian regime plus industrial technical assistance) and growth in affluence (driven by the fossil fuel regime). Both processes together make for a 'great acceleration' of impacts.

A toy model for populations and their affluence by mode of subsistence

As explained above, our point of departure is the IPAT model. Whatever environmental impact (I) we consider, we suppose it to be a function of population numbers (P), affluence (A) and a technology parameter (T) that tells us how this affluence is acquired. The main explanatory power lies in population numbers and affluence. For each sociometabolic regime, we can derive 'affluence' as a typical sociometabolic rate, technically speaking, as material or energy use per capita and year, from material and energy flow accounts and estimates provided in the literature (see Haberl et al., 2011; see Figure 3).[14] We believe that this parameter is a reasonably good indicator for a range of impacts. If there is a specific intervening variable between metabolic rate and a certain impact, this has to be captured by the T parameter in the equation. Of course, there is a range of variation and of uncertainty in metabolic rates within regimes. In those cases in which we see affluence within a metabolic regime as dynamic, we have to specify this dynamic. This we try to do in the following paragraphs; but the first task we have to resolve is providing estimates for the size of the changing human population through time, for each mode of subsistence.

Estimating population numbers by modes of subsistence

While there are increasingly reliable estimates for world population through time (Klein Goldewijk et al., 2010; Kremer, 1993; Livi-Bacci, 2006; McEvedy and Jones, 1978; Maddison, 2001, 2008; Thomlinson, 1975), estimating the share of each mode of subsistence remains to be resolved. Our effort at a solution was inspired by Heinz von Förster's 'doomsday equation' (Cohen, 1995: 90). This equation models world population as the sum of two exponential functions: an originally large population with very low growth rates, plus a new, initially minute population with very high growth rates.[15] For a long period of history, this portrays well the simultaneous existence of a hunter gatherer and an agrarian population. On top of this, we need to represent the population of the industrial regime, which since the 16th century is growing despite an endogenous negative growth rate. Its rise in population numbers, we claim, is mainly fed by 'conversions' from the agrarian regime, be it by migration (to cities or industrial states) or by the development of national economies from agrarian to industrial.

How can we generate an estimate of hunter gatherer populations? We have little choice but to build on the population growth dynamics known from literature. In Table S1 (available online), we assemble a few such estimates. Apparently, growth rates are very low, but these populations existed over very long time periods.

- Based upon the information in Table S1, we assume an average 'endogenous' annual growth rate from 10,000 BC onward of 0.036%[16] annually. We assume that this growth rate turns negative when hunter gatherers are confronted with an agrarian majority, which happens in the last centuries BC.
- Finally, we assume that by AD 1500 the populations in North America and Oceania are still hunter gatherers, while there are only a few hundred thousand left in the rest of the world.[17]
- In the 16th to 19th centuries, we assume hunter gatherer populations to become largely extinct.

In a next step, we need to generate an estimate for the agrarian population. There are two pathways to arrive at such an estimate. One is to calculate the difference between our estimate of the hunter gatherer population and the total global population (demographic estimate) up to the onset of industrialization. This can be cross-checked by a second, independent estimate which rests on sociometabolic assumptions (metabolic estimate). This estimate rests of the following arguments: in agrarian populations, urban centres emerge (in contrast to hunter gatherers, where no urban agglomerations develop). From a sociometabolic perspective, urban populations are distinct from rural populations by not producing food,[18] and therefore they metabolically depend on a rural-agrarian population to provide them with staples. According to what we know about pre-industrial agriculture, urban centres typically need a large hinterland and a substantial number of peasants working the land from which to extract the surplus food and fodder to sustain a city (Fischer-Kowalski et al., 2013). Thus we can use the existing estimates of the development of the global urban population and assumptions on how large a rural population is required to feed one city dweller to generate an estimate of the total agrarian population.[19] Table S2 (available online) summarizes our assumptions and estimates.

As we can gather from Table S2, there is not a bad fit between the two estimates of agrarian population: the sociometabolic estimates stay nicely within the range of population we need to combine with the hunter gatherer population to generate a full world population. In effect, we may assume that the agrarian population overtook the hunter gatherers in numbers in the late centuries BC and dominated them from thereon at the global level, but some world regions (such as North America and Oceania) were still only occupied by hunter gatherers (see Figure 2).

In the succeeding period to AD 1500, we see quite substantial population dynamics on the part of the agrarian population. Assuming a gradual absolute decline of hunter gatherers from the first century AD onwards, growth rates of the agrarian population must have been rising in order to achieve the observed overall world population growth.[20] During this period, there is also a slightly disproportional increase in urban populations. If we refer this urban population to the agrarian population, we find the share of urban population increasing slightly, from about 2% to 3.5% of the agrarian population (see Table S2). This is quite plausible in the face of gradual technological improvement in agriculture.

The year AD 1500 is a dividing line, as at that point fossil fuels enter the stage. Recent research (Gales et al., 2007; Gerding, 1995) provides quantitative data on the use of peat in the Netherlands; the use of peat as energy source started slowly in the late Middle Ages, but by 1550 peat already amounted to 10% of primary energy supply and helped the Netherlands in its 'Golden Age' to an

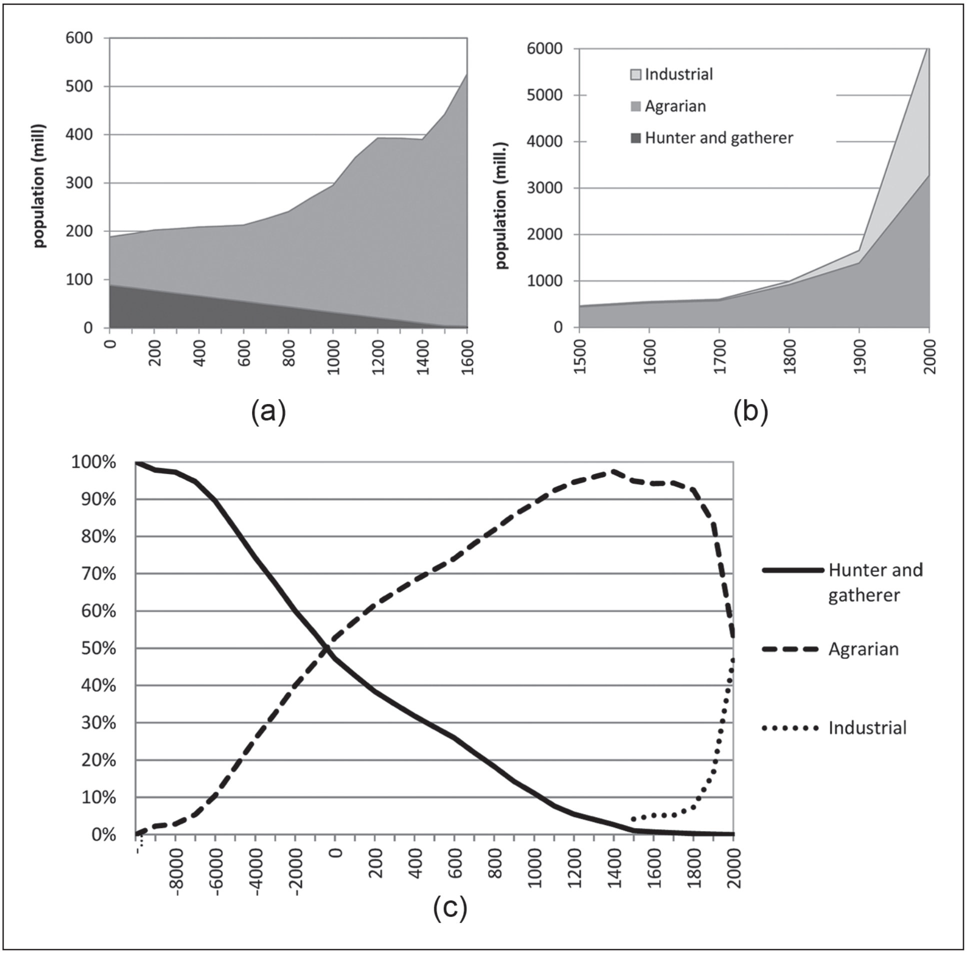

Figure 2. Global population dynamics 10,000 BC–AD 2000 by modes of subsistence. (a) Hunter gatherers and agrarian population (AD 0–1500). (b) Rise of the industrial population (AD 1500–2000). (c) Global shares and transitions, 10,000 BC–AD 2000.
Note: Time axis is not to scale for different periods: 10,000 BC to AD 0: 1000 year intervals; AD 0–1900: 100 year intervals; AD 1950–2010: 10 year intervals. See Table S3 (available online) for data and sources.

energy level per inhabitant above any other European country – and also to the highest urbanization level in Europe (Centre for Global Economic History, 2013; De Zeeuw, 1978; Livi-Bacci, 2003). Next in line is the case of coal in the UK. According to recent estimates, by 1550 coal amounted to 3% of its primary energy supply. While the Netherlands gradually ran out of peat in the next century, the UK could steadily increase its use of coal, export coal to other European countries and move along a learning track towards industrial technologies while substantially increasing its urban population.

Based upon these forerunners, it makes sense to date the onset of the human use of fossil fuels rather precisely at the beginning of the modern era; from a sociometabolic perspective we would argue that the control of a new energy source with an hitherto unknown power (Smil, 2003) that allows expanding social energy use much beyond previous levels is highly relevant

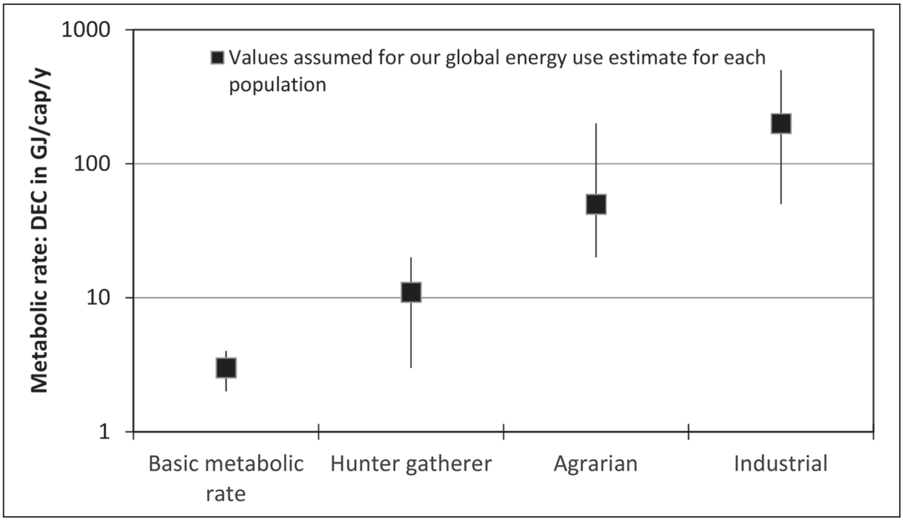

Figure 3. Metabolic rates (primary energy use) of different modes of subsistence. See text for underlying assumptions.

– even if the technologies to make efficient and diverse use of this energy evolve and spread only gradually. The functional inter-linkage with urban growth is apparent from the beginning: without a source providing heat for a rapidly increasing number of urban households and trades no proto-industrialization would have taken place. But even more so: on the global level, there is a near-perfect fit between urban population numbers and the amounts of fossil fuels used globally, across the next 500 years (see Figure 1).

It is interesting to see that across the urbanization literature, a link between urbanization and energy is not seen or is sometimes even categorically denied (e.g. Dyson, 2011); Bairoch (1990), Davis (1955) and Livi-Bacci (2003) provide notable exceptions. It is well beyond the scope of this paper to join that debate, but for the purpose of our toy model, we find it legitimate to use the global urban population as an approximation for the size of the population living by the standards of the industrial sociometabolic regime. They rarely hunt and gather anymore; and they do not sustain themselves by working the land; they sustain themselves by earning money for non-food-producing activities and satisfy their needs via markets. In very simple terms, this describes the industrial mode. Of course there has, for a long time, been urban populations living on agricultural surplus as their energy base; but the share of these populations remained, as we have shown above, very small. By including these into the 'industrial population' estimate we overestimate this population by a few percent. The other possibility would have been to define the size of the industrial population by some, for example, UN-based classification of countries. Apart from the fact that such classifications would not reach far enough back in history, we then would ignore the gradual nature of countries' transition to the industrial mode. So we decided to base our estimate of population living by the industrial mode on the population living in settlements with more than 2500 inhabitants ('urban settlements'). The size of this population extends much beyond the inhabitants of current OECD countries,[21] but we think with good reason this is linked to fossil fuel use: these urban populations outside the OECD could not live as they do unless an energy-rich system driven by fossil fuels provided them with the commodities they require. Even if people sustain themselves at a very low level (e.g. as a beggar in one of the megacities of the developing world), they share more characteristics with the other inhabitants of the city than with a traditional rural farmer or day labourer under an agrarian regime.

But how could this population rise as fast as it did, and what role did fossil fuels play in this? In a first, admittedly superficial, answer, we can say the following: fossil-fuel based-technologies have been instrumental in:

- reducing mortality through hygienic and medical interventions (fighting infectious diseases, antibiotics …);
- providing reliable and fast long-distance transport (for example of food);
- raising agricultural output per area (about fivefold);
- providing fast global information exchange (and thus accelerating learning).

Still, as demographers rightly say, people only come from people. Can our hypothesis hold that all or at least most of the population increase in both the agrarian world population, and in the industrial population, has been fed by agrarian population growth? Mathematically, an average annual population growth rate of 0.46% on the part of the agrarian population since 1400 would have sufficed to populate both regimes. Such a growth rate looks adequate (see Grigg, 1980).

This cross-check is our last step towards reconstructing global population numbers by sociometabolic regimes from AD 1 to the year 2000. Figure 2 presents our results in three different time frames in order to keep smaller changes visible.

According to our population estimates, the world had been populated once by a maximum of about 90 million hunter gatherers around 500 BC, then the numbers began to decline; in the last century BC, hunter gatherers had been overtaken by agrarian populations that rose to about 450 million by AD 1500 and kept rising until today (AD 2000) to 3 billion people. The rise of the industrial population started around AD 1500 and continued to a population of also 3 billion by AD 2000, just matching the agrarian world population (see Table S3).

Estimating affluence by modes of subsistence

In a next step, we have to attribute to these populations a certain affluence, following our introductory arguments. As we are heading for environmental pressures/impacts, and nature is insensitive to money, we operationalize affluence in biophysical terms: we use indicators derived from material and energy flow accounting (MEFA) to quantify the socioeconomic use of energy and to estimate metabolic rates in energy terms.[22] Energy use in MEFA is defined in a more comprehensive way than in conventional energy statistics (Haberl, 2001). The indicator DEC (domestic energy consumption) not only includes 'technical' primary energy such as fuel wood, coal, oil, gas or hydro and nuclear power (as is included in the more common indicator TPES, total primary energy supply), but also all types of biomass used as food and feed for domesticated animals or as raw material. It is thus a more appropriate measure to also characterize energy use in foraging and agrarian societies (see section 'Sociometabolic regimes in human history'). The sum total of the DEC of all population groups corresponds to global energy extraction. DEC per capita and year is defined as average energetic 'metabolic rate' (of a certain society or regime).

Reliable data on metabolic rates only exist for the last two or three centuries (Haberl et al., 2011; Krausmann and Fischer-Kowalski, 2013) and global energy use is usually not differentiated by modes of subsistence. Some authors have provided rough estimates of metabolic rates for material and energy by metabolic regimes (see Haberl et al., 2011; Krausmann, 2011; Krausmann et al., 2008b). While the estimates for per capita DEC in hunter gatherer and agrarian societies do carry considerable

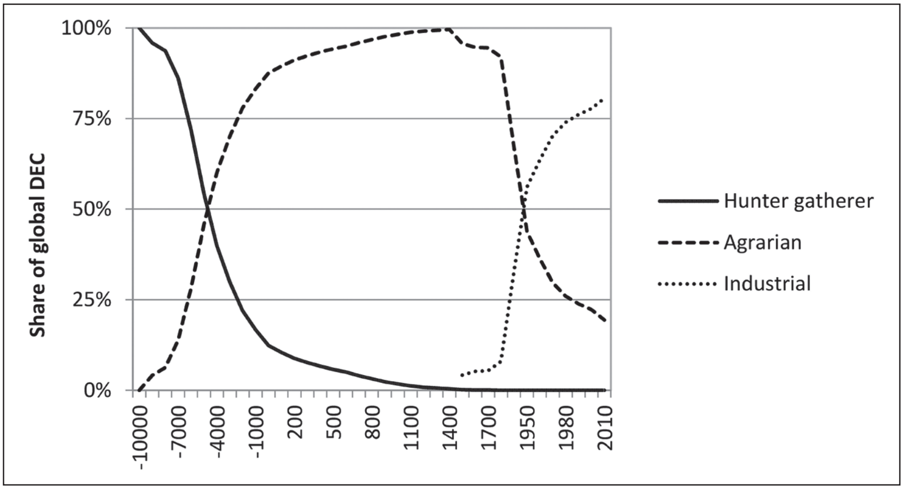

Figure 4. The share of different modes of subsistence in global affluence (indicated as DEC).
Notes: Global DEC comprises biomass (including all food for humans, feed for livestock and all biomass used as fuel or raw material) and modern energy carriers (primary energy) such as fossil fuels, nuclear heat and hydropower (see Table S3 for data and sources). Time axis is not to scale for different periods: 10,000 BC to AD 0: 1000 year intervals; AD 0–1900: 100 year intervals; AD 1950–2010: 10 year intervals.

uncertainty (see Figure 3), we assume that the general differences in metabolic rates between modes of subsistence are robust enough to be used in our toy model to estimate the global use of biomass, their exclusive energy source, across a time span of 10,000 years (see Figures 4 and 5). For the industrial regime and modern energy carriers (fossil fuels, hydro- and nuclear power) we can base our estimate on data available from long-term global energy flow accounts (Cleveland, 2011; Krausmann et al., 2009; Podobnik, 2006).

In the following paragraphs, we briefly explain the rationale and the assumptions on which we base our estimates for the metabolic rates by mode of subsistence.

Hunter gatherers. The literature suggests that the metabolism of hunter gatherers is larger by a factor of 2 to 4 than the basic (endosomatic) metabolic rate of human beings (Figure 3) (Boyden, 1992; Sieferle, 2001b; Simmons, 2008). Energy use of hunter gatherers is, by and large, restricted to two components: the amount of food they extract from their environment, and fuel wood. The amount of food (including waste and losses) may range between 200 and 300 kg/capita per yr, with an energy content of 3–4 GJ/capita per yr. The use of fuel wood can probably vary largely depending on climate and availability of wood. As a rough proxy, we assume wood consumption to be around 500 kg/capita per yr, or 7 GJ/capita per yr. This adds up to a total metabolic rate of 11 GJ.

Agrarian societies. Next to more sophisticated processing of food, the use of crop residues, rising demand for wood for constructing shelter and tools, and above all animal husbandry drive biomass use in agricultural societies:[23] agriculturalists keep animals to provide them with labour, fertilizer, food and raw materials, thus increasing their socioeconomic level of biomass use considerably (Krausmann, 2004). This is even more so in pastoralist societies, which keep animals to make use of often vast land areas with comparatively little input of labour. Pastoralists keep several large

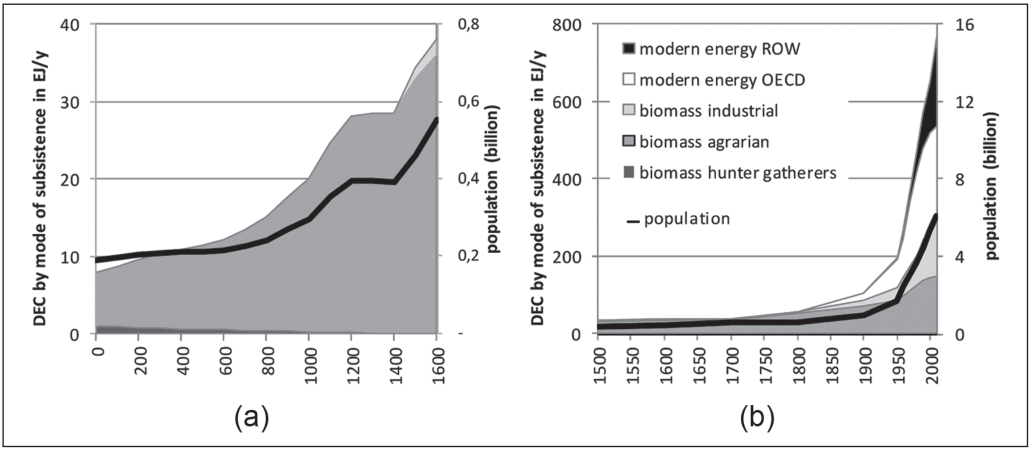

Figure 5. Global human pressure on Earth expressed as population × affluence during the last two millennia. (a) Global human environmental pressure (DEC) for AD 1–1600. (b) Global human environmental pressure (DEC) for AD 1500–2010.

Note: For modern energy use of the global industrial population, we distinguish between modern energy use in OECD countries and in developing emerging countries (rest of the world, ROW).

animals per capita and these animals graze substantial amounts of biomass (e.g. Coughenour et al., 1985). Their biomass consumption may easily be an order of magnitude more than the biomass demanded by the corresponding human population. Overall, the range of biomass use in agrarian societies probably ranges from a level which is not much different to that of hunter gatherers for simple shifting cultivation, to several 100 GJ/capita per yr in pastoralist communities (Krausmann, 2011). Mixed farming systems range most likely somewhere between 20 and 80 GJ/capita per yr – as global accounts of biomass harvest in the last century indicate (Krausmann et al., 2013). For our toy model, we have tried two assumptions:

(1) Lacking any reliable information on long-term trends in metabolic rates of biomass use, we may assume constant average metabolic rates for agricultural societies of 45 GJ/capita per yr according to general information of energy use across metabolic regimes (Haberl et al., 2011; Krausmann et al., 2008b, and see Figure 3).

(2) In a more sophisticated version, we assume that early agrarian societies used 50% more biomass than the hunter gatherer average. We further assume that as long as land and biomass were abundant, this rate increased slowly to 75 GJ/capita per yr, in particular as livestock numbers grew at a faster pace than population and civilizations became more complex. With rising population pressure the relative significance of livestock began to decline (population was growing faster than livestock numbers) – a process which has been observed in Europe in the Middle Ages (Abel, 1978; Montanari, 1994) and has been described as horticulturalization for China (Helbling, 2003). In the absence of any reasonable global information on these trends, we use the European trends and assume that metabolic rates of agrarian societies stabilized around AD 1000 and began a slow decline after AD 1500 to the global average of 45–50 GJ/capita per yr that we observe for the last century (Krausmann et al., 2013). While approach (2) results in a steeper increase in global biomass use between AD 0 and AD 1000 and a level of 17 EJ/yr compared with 12

EJ/yr in approach (1), this difference is not significant for the long-term trends of energy use that we are interested in. Therefore, we only refer to results from method (2) in Figures 4 and 5 and the text; a comparison of the results of both approaches is provided in Figure S5 (available online).

Industrial societies. Energy use in the industrial mode of subsistence (AD 1500–2010) comprises biomass (food, feed, fuel wood and raw material) and what we call ‘modern’ energy carriers (peat, coal and other fossil fuels, hydro- and nuclear power). We assume that average metabolic rates of biomass use in the industrial population segment are the same as in agrarian societies (45–50 GJ/capita per yr). This lies well within the observed range of patterns and long-term trends of biomass use in industrial countries (Krausmann et al., 2008b). For modern energy carriers we can use data from estimates of global energy and material use (Krausmann et al., 2009; Podobnik, 2006; Schaffartzik et al., unpublished data, 2013). Based on population estimates and regional data, we arrive at average metabolic rates for modern energy carriers which increased in the industrial core countries from 0.3 GJ/capita per yr in AD 1500 to 85 GJ/capita per yr in AD 1900 and further to 280 GJ/capita per yr in 1980; since then they slightly declined. The rates of modern energy carriers for the industrial population in developing economies rose from 4 GJ/capita per yr in 1900 to 99 GJ/capita per yr in 2010.

As visualized in Figure 3, human affluence as expressed as the use of primary energy per person has been increasing by roughly one order of magnitude from one sociometabolic regime to the next. The average differences in affluence between regimes obscure the differences within: we see a more or less log-linear increase.

The long-term change in the shares of modes of subsistence and their different levels of affluence now allow us to locate temporally the transitions in global dominance between regimes in terms of their shares in human energy use, or global affluence (see Figure 4). We see the hunter gatherer mode dominating global energy use until about 5000 BC, followed by the agrarian mode dominating until about the end of World War I, and then the industrial mode achieving a share of three-quarters of global human energy use, and still on the rise.

As each consecutive mode of subsistence is by one factor more energy intensive than the previous one, the global dominance between them in terms of share in global affluence shifts at an earlier point in time than their share in population (compare Figures 2(c) and 4).

Discussion: The human impact on Earth through time

Based on our estimates of population and affluence we can, in a first step, explore the overall size of human impact – or rather pressure – on Earth as far as it is derived from these two factors; the third factor, technology, is implicitly set as 1, which is a rather conservative assumption as impact per unit of socioeconomic energy use has increased from the hunter gatherer to agrarian and to industrial regimes, as we shall show below. For the time period AD 1 to 1600 (Figure 5a) the increase in pressure/impact results from the agrarian population dynamics plus higher metabolic rates compared with hunter gatherers. In effect, we see an almost five fold (4.8) increase of human impact between AD 1 and 1500 if we consider both population growth and differential affluence (energy use). In contrast, population growth alone would only account for a 2.4 fold increase in impact. Thus, increasing affluence doubles the pressure/impact of population during this time period.

In the period from AD 1500 onwards, the rate of increase in pressure/impact is much steeper. From AD 1500 to 1800 it more than doubles, which is substantially faster than the 23% growth across the three centuries before. From then on a veritable take-off can be observed. From 1700 onwards, human impact doubles every century, from 1900 on it doubles in 50 years, and from 1950 on it triples in 50 years, with no sign of saturation yet. But Figure 5(b) also shows that in recent decades the contribution of the old industrial core (OECD countries) to the overall growth in modern energy use has become less significant and that the dynamic is increasingly driven by growing industrial population and by rising metabolic rates in emerging and developing countries (ROW countries). All components – population, and affluence in terms of biomass energy and modern energy carriers – play together to generate the rocketing rise of global energy use shown in Figure 5(b).

So far we have kept the technology coefficient constant over time. But the question arises as to whether technology rather enhances or mitigates the effect of growth in population and affluence on pressures/impacts. As we have explained above, while population numbers and affluence may be considered as being responsible for a wide range of possible pressures/impacts, technology needs to be examined with reference to specific pressures/impacts. In a second step, following the tradition of the Holocene/Anthropocene discussion (e.g. Boyle et al., 2011; Ruddiman and Ellis, 2009), we focus on carbon emissions as one major global environmental pressure. We can only develop a very crude scenario for the development of the technology coefficient and overall carbon emissions during the last two millennia. In order to do this we need to make assumptions on the technology coefficient for the different modes of subsistence and energy types, respectively. In the absence of any data we assume that hunter gatherers do not cause net emissions of carbon; we assume that all C emitted through their biomass use and the vegetation fires they induce is assimilated again by vegetation regrowth. Hence, their technology coefficient for carbon emissions in our equation is set at zero. In contrast, agriculturalists cause large-scale lasting deforestation, and substantial amounts of carbon are emitted from reductions in carbon stocks in vegetation and soils (Boyle et al., 2011; Houghton 2008; Kaplan et al., 2011). With growing population, land use intensifies and the output per unit of land that has already been cleared is increased. This improves the intensity of carbon release through biomass utilization: the amount of net carbon emissions per unit of biomass harvested will slowly decline. Finally, in the industrial metabolic regime a new source for carbon emissions is added: carbon from burning fossil fuels. Fossil fuel combustion releases more carbon per unit energy than biomass (see Figure 6). That is, with the transition to the industrial regime, the aggregate technology factor increases. In later stages, this is counteracted to some degree by two factors: the adoption of less carbon-intensive energy carriers and forms (oil, gas, hydro, nuclear) and the (fossil fuel driven) industrialization of agriculture which boosts biomass harvest while aggregate deforestation slows down.[24]

For the time period from 1800 to 2010 we can draw on estimates of both carbon emissions from land use change and from fossil fuel combustion and we can use these data to derive values for the technology coefficient. Figure 6 shows that the average amount of carbon emitted per unit of energy used (biomass and modern energy) increased from 1800 to 1950 by roughly 65%, and then the intensity of carbon use begins to improve (by 16% until 2000, see Figure 6).[25]

Based on the assumptions outlined above and the empirical evidence we have for the last two centuries we can provide a rough estimate for carbon emissions during the last centuries. In this scenario the aggregate technology factor for C emissions per unit of energy use shows a slow increase during most of the last two millennia. From 1800 onwards, growth in the intensity of carbon use began to accelerate until 1960, when it began a slow decline which lasted until 2000. In spite of all uncertainties involved in this calculation, it is evident that technological change in the long run did not moderate, but further enhanced, the effect of population growth and increasing

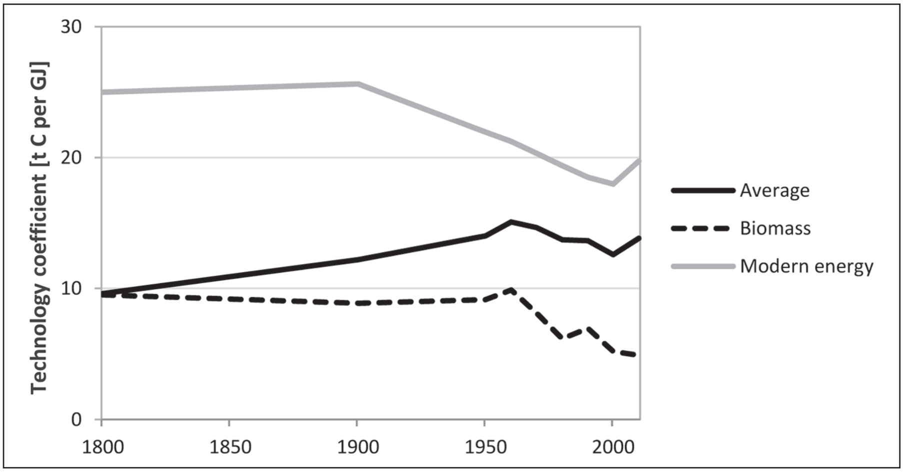

Figure 6. Development of technology coefficients for carbon emissions in t carbon per unit energy use (DEC).
Note: This empirical reconstruction of technology coefficients is based on information on energy use (DEC) and carbon emissions from land change and fossil energy combustion. The technology coefficient for biomass is here defined as C emissions from land use and land cover change per unit of biomass extraction; that of modern energy is defined as C emissions from fossil fuel combustion per unit of modern energy use (this also includes fossil fuels used to intensify land use). The black line shows the aggregate technology coefficient (total C emissions per total energy use).
Sources: own calculations based on DEC data and emissions data from Houghton (2008) and Boden et al. (2013).

affluence by a factor of 1.5 (see Figure 7); only in the last decades has it had a slight counteracting effect.[26] Overall, our calculations result in a rise of global human carbon emissions by two orders of magnitude during the past two millennia, accelerated by technological change in the generation of human affluence through a shift towards using fossil fuels. This is certainly unprecedented in human history.

Conclusions

Constructing the toy model and playing with it has yielded a number of interesting insights. We show that it is reasonably possible to estimate the size of pre-industrial agrarian populations from the size of urban populations. We find that there seems to be a log-linear function of increasing average energetic metabolic rate from human basic metabolism across hunter gatherers and the agrarian mode to the industrial regime; and that from AD 1500 onwards, there is a very close relation between the urban population and fossil fuel use. We see a major historical dividing line around AD 1500: up to then, human population growth and metabolic rates carry about equal weight in increasing human pressure on the environment approximately fivefold over the year AD 1. From then on, fossil fuel use gradually raises the socially disposable energy to unprecedented levels and the overall pressure of humanity upon Earth increases by one order of magnitude; rising metabolic rates contribute to this increase by roughly tripling the impact of population growth. Technology, because it is based upon a shift from biomass to fossil fuels (and other ‘modern’ energy carriers), does not moderate this impact, but enhances it by a factor of 1.5.

The analysis based on sociometabolic theoretical assumptions, in contrast to much other research, includes the observation that metabolic rates in the fossil fuel/industrial mode have run

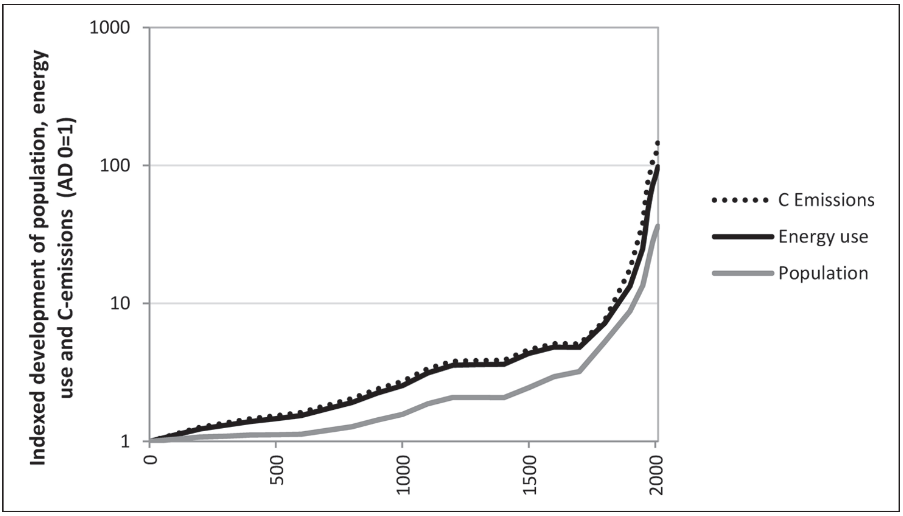

Figure 7. Change in human pressure/impact in terms of global carbon emissions during the past two millennia, resulting from population numbers, affluence (energy use) and technological emission intensity.

into saturation and the industrial population, at least by endogenous biological growth, is running into decline. While environmental impacts therefore might be expected to decline eventually (even without assuming any external constraints), this reversal in trend may occur too late to prevent climate change seriously damaging human civilization.

Overall, our findings clearly point to a dividing line in the scale and dynamics of human impact upon Earth with the onset of fossil fuel use, which coincides with what the cultural historians regard as modernity. The virtue of this solution would lie in the temporal coincidence between using a new geological resource (fossil fuels) with a discontinuity observed in cultural history. While there was a period of latency in which only rising urbanism and so-called proto-industry in some countries benefited from the increasing energy availability, the breakthrough of major technologies was being gradually established that would then reshape the world.

But is incorporating the complexities of modes of subsistence and sociometabolic rates in the calculation of human pressure on Earth actually warranted? Don't they just more or less replicate what is known from the dynamics of human population numbers? Here we arrive at the limitations of Ehrlich's IPAT model. It cannot be assumed that the three components – population, affluence and technology – are independent from one another. On the contrary: they are functionally deeply interlinked, but in ways that differ between sociometabolic regimes. In the hunter gatherer regime, population numbers basically are constrained by available food energy, and the availability of food from ecosystems can hardly be controlled by humans. In the agrarian regime, the relation between food and population becomes more complex: While food energy still constrains population numbers, population growth allows investing more labour and drives technological progress increasing the overall amount of food energy available from agro-ecosystems. Thus we have not only a 'Malthusian' (Malthus, 1803), but also a 'Boserupian' (Boserup, 1965, 1981) relation; this generates a rebound effect on fertility. In the industrial regime, the link between land and energy availability is largely disrupted, as well as the link between available energy and population dynamics. But still, the industrial regime, while reducing its own fertility below reproduction rates, subsidizes population growth in the remaining agrarian population segments by reducing mortality. Furthermore, the new energy source also allows drastically increased food availability independent of labour. Thus we do not only have an interdependence between the factors driving human impact within each regime, but also an interdependence between regimes.

We argue that it is exactly these qualitative changes in functional interrelations among socioeconomic characteristics, interlinked with functional changes in humanity's relation to the Earth System, that make it impossible to use homogenous indicators for human impact across all of human history. This is particularly apparent when we think of future prospects. Earth's carrying capacity will not allow for the projected human population to sustain itself by the energy standards of the current industrial regime, not least because fossil fuels are a finite resource. Thus a transition to another regime is inevitable, and it may re-link human population and land use in novel ways.

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Notes

1. Just to illustrate our point: we would not be tempted to name an age in which severe climate change and sea level rise eradicated all major human civilizations as 'Anthropocene' – irrespective of the fact that these changes in the natural environment had been triggered by human activities a few centuries before.
2. It is also interesting to see how older and often Eurocentric distinctions based upon property rights, the division and organization of labour or forms of stratification neatly fall in place when applying Sieferle's distinctions.
3. Concerning the extinction of megafauna see, for example, for North America, Gill et al. (2009); for Australia and the role of fire regimes (where human arrival rather than climate impacts seems to have caused extinction of animal and plant species) see Rule et al. (2012).
4. In a recent study of genetic data Gignoux et al. (2011) calculated annual growth rates of Pre-Neolithic foraging populations in Europe, Western Africa and Southeast Asia: In Europe, where the period from 23,000–1000 BC was analysed, the annual growth rate was 0.021%, in Western Africa 0.007% (48,000–10,000 BC) and in Southeast Asia 0.011% (48,000–10,000 BC). The low growth rate depends heavily on the long birth intervals in foraging societies (for an explanation, see for example Ellison (2008)). Birth intervals in forager populations were twice as long as in (pre-industrial) agrarian populations (Ammermann and Cavalli-Sforza, 1984).
5. Flannery (1998) explains the lack of a Neolithic revolution in Australia by ENSO and the periodic occurrence of very long droughts that would have made any effort at agricultural cultivation futile and forced people back into the hunting and gathering mode of subsistence. This could be an example where the evolutionary advantage of the agrarian mode could not play out.
6. Sieferle (1990: 55) sees a functional explanation of the Neolithic revolution viewing it as a process of self-organizing dynamics in which one emergent pattern is evolutionarily superior and creates a pathway of no return.
7. A narrative of this for sub-Saharan Africa across the millennia, based upon synthesized knowledge from various sources, may be found in JA Michener (1980).
8. See the case studies put together in Clark and Haswell (1967); see also a new volume containing a number of case studies replicating Ester Boserup's work (Fischer-Kowalski et al., 2014).
9. Oesterdiekhoff (2001) seeks to explain the relatively moderate fertility among the agrarian populations in western and northern Europe as compared to Asia, as a result of the 'collateral' (in contrast to

patrilineal) family type that originated from (urban) Rome and requires the young man to have an independent economic existence before marriage, while the typical agrarian patrilineal pattern allows him to bring his wife into his father's family. Thus marriage in Europe occurred at a later age and is responsive to economic downturn situations. In effect, population growth was slower and less volatile than for example in most of Asia.

10. Only European countries that had thrived on overseas trade (such as Portugal, Italy, Spain, Greece and the Netherlands) in that period already have a substantial proportion of urban population, that is 15–20%, as defined for example in the Clio-Infra DB 2013 (settlements with more than 3000 inhabitants) (Centre for Global Economic History, 2013). See also Grigg (1980). For the rest of Europe, urban proportions lay between 2% and 10%.
11. Ayres (1956) and Pomeranz (2000) give anecdotal evidence for earlier use of coal in China. Quantitatively, this seems not to have been very widespread and according to Pomeranz possibly have been terminated by the Mongol invasion in the 14th century (Pomeranz, 2000: 63).
12. For the Netherlands, we find a decline of peat use from 1650 onwards, related to government reactions to peat mining threatening agricultural land; but also in the Netherlands, peat supplied 18% of primary energy in 1650 (Gerding, 1995).
13. Lutz and Samir (2011) argue female education to be the most powerful key to reducing fertility, even in the Global South. We would argue that a rise in female education does not happen unless there is a transition towards the industrial regime ongoing. So these processes are intertwined.
14. For a more detailed description of the conceptual foundations of material and energy flow accounting and the underlying accounting principles and system boundaries see Fischer-Kowalski et al. (2011); Haberl (2001).
15. This function is termed 'doomsday', because it leads to an infinite population within a finite time. The parameters used for the year AD 1 are 250 million people for the slow-growth, and 1 person for the high-growth compartment. Respective annual growth rates are 0.01% and 1.125% (Cohen, 1995: 90). This leads to 5.2 billion people in the year 2000.
16. We keep the annual growth rate of 0.036% constant for the period 10,000–0 BC. The size of this population was calculated applying a basic exponential model $P_t = P_0 (1 + r)^t$. P_0 is the population size at time 0, t is the duration of the process (years) and r is the annual growth rate. This is a very rough-and-dirty estimate as such a growth rate may vary very strongly between favourable and unfavourable environmental conditions (for example between North America and Oceania, see Table S1).
17. The only source we could find estimates a share of 1% hunter gatherers among the global population in 1500 (Rakelmann, 2004), which would be 4.61 million people, out of which about 2.6 million would have lived in North America and Oceania (Klein Goldewijk et al., 2010).
18. This distinction may not always be as sharp: people in urban centres keep chicken and rabbits, an occasional goat and horse, grow vegetables and fruits … But the staple food cannot, for lack of area, be grown within urban centres. In some regions (of Italy, for example) though, there exist traditional settlement patterns where the peasants do not live among their fields, but in compact villages that may grow to small towns of the size we define as 'urban'.
19. We have deliberately chosen a very low cutting point for what we treat as 'urban': settlements of 2500 inhabitants or more (if we go by the data from Klein Goldewijk et al., 2010) or 3000 and more according to the Clio-Infra data base.
20. Of course our toy model cannot adequately represent negative population growth impacts such as the Bubonic Plague and the Mongolian raids in the 14th century, nor the stagnation caused by the collapses of the Roman Empire in the West and the Han Dynasty in the East (see McEvedy and Jones, 1978).
21. This assumption neglects the fact that in the second half of the 20th century agriculture also became industrialized in the industrial core and the shrinking rural population of fully industrialized economies rapidly adopted industrial metabolic rates. From a systemic perspective, the non-urban populations in OECD countries (roughly 0.4 billion since 1950) should therefore also count as 'industrial population'.

22. It would also be reasonably justified to express ‘affluence’ in material terms, as quantity of materials used in a society. We decided in favour of energy use for reasons of better data availability, on the one hand, and because energy and material use are very highly correlated, anyway.
23. We neglect wind and water power in our estimate of energy use in agrarian societies. While these energy technologies can be significant at a regional and local scale, their quantitative contribution to global primary energy use before industrialization has been very small (e.g. Gales et al., 2007; Smil, 2008).
24. As shown in Figure 6, net carbon emissions from land cover change (deforestation) per unit of harvested biomass decline in the second half of the 20th century. This improvement in the intensity of carbon use is partly offset by high fossil fuel inputs of industrial agriculture. Overall, the increase in biomass harvest was considerably larger than direct and indirect fossil fuel use in agriculture (see Krausmann et al., 2013). While carbon intensity of biomass as shown in Figure 6 only includes net C emissions from land cover change, direct and indirect fossil fuel use in agriculture is included in the average carbon intensity of energy use (black line in Figure 6).
25. The turn upward after the year 2000 is due to the renewed globally increasing use of coal.
26. This has been shown empirically for Asia and the Pacific for the last two decades (see Schandl and West, 2012; United Nations Environment Program (UNEP), 2011) by a decomposition analysis according to the Ehrlich formula for the period 1980–2005.

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The technofossil record of humans

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Jan Zalasiewicz,[1] Mark Williams,[1] Colin N Waters,[2] Anthony D Barnosky[3,4,5] and Peter Haff[6]

Abstract
As humans have colonised and modified the Earth's surface, they have developed progressively more sophisticated tools and technologies. These underpin a new kind of stratigraphy, that we term technostratigraphy, marked by the geologically accelerated evolution and diversification of technofossils – the preservable material remains of the technosphere (Haff, 2013), driven by human purpose and transmitted cultural memory, and with the dynamics of an emergent system. The technosphere, present in some form for most of the Quaternary, shows several thresholds. Its expansion and transcontinental synchronisation in the mid 20th century has produced a global technostratigraphy that combines very high time-resolution, great geometrical complexity and wide (including transplanetary) extent. Technostratigraphy can help characterise the deposits of a potential Anthropocene Epoch and its emergence marks a step change in planetary mode.

Keywords
Anthropocene, human artefacts, stratigraphy, technology

Introduction

From the beginnings of geology, fossils have been recognised as central to the science, not only because they are a record of life (the most important feature of our planet) but because biological evolution has provided a means of dating and correlating strata, and hence underpinning the Geological Time Scale. Thus, the Phanerozoic Eon (roughly, the last half-billion years of Earth history) was characterised by complex metazoans with hard skeletal parts. It has a finely resolved timescale largely founded on fossil zones, reflecting the evolution of these organisms. In this way, Phanerozoic time can be split into intervals that may be less than 1 million years in duration, for

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[1] University of Leicester, UK
[2] British Geological Survey, UK
[3] University of California, USA
[4] University of California Museum of Paleontology, USA
[5] University of California Museum of Vertebrate Zoology, USA
[6] Duke University, USA

Corresponding author:
Jan Zalasiewicz, Department of Geology, University of Leicester, University Road, Leicester LE1 7RH, UK.
Email: jaz1@le.ac.uk

example exploiting the evolution of graptolites (the remains of extinct colonial plankton) in strata of the Ordovician and Silurian periods, of ammonites in the Jurassic, and of mammals and marine microfossils in the Tertiary. The Precambrian (that is, pre-Phanerozoic time), some 4 billion years in duration, retains a cruder timescale still largely based on arbitrary numerical time divisions (Gradstein et al., 2012).

In more recent geological times, of the later Tertiary and Quaternary periods, other means of correlation have been used, such as magnetostratigraphy and cyclostratigraphy, that exploit changes in the Earth's magnetic field and in its spin and orbit respectively (Cande and Kent, 1992; Pälike et al., 2006; Wade et al., 2011). These have provided the highest time-resolution, locally to millennial scale, and in the best cases of ^{14}C dating, to the decadal (or in some cases even of annual/seasonal) scale. By comparison, late Tertiary/Quaternary biostratigraphic divisions based upon appearances and extinctions of various species provide relatively coarser subdivision than these recently developed means of dating. In this interval, biostratigraphy, especially on land, mostly reflects local patterns of species immigration and emigration driven largely by climate change, that were in turn driven by the astronomical variations. (There have, though, been some notable extinctions, particularly of large mammal species over the past ~50 millennia, likely at least in part through impacts by early hunters: Koch and Barnosky, 2006; Martin and Klein, 1984.)

However, for time intervals since the evolution of humans during the Quaternary, new ways to use fossils as geological time markers have arisen. These are largely the physical objects devised and made by species of humans beginning at least 2.5 Myr ago (Ambrose, 2001; Kimbel et al., 1996). Changes in these artefacts have been driven by cultural, not biological, evolution. Using tools is not quite singular to humans, limited examples being provided by other species such as apes and crows (Van Lawick-Goodall, 1970) but humans have taken tool production to levels of sophistication that are without precedent in the history of life. The study of human-produced artefacts has been largely the province of archaeologists and, for more recent years, historians (using that term in its widespread meaning of referring to human rather than natural history: Chakrabarty, 2009). Because human colonisation of Earth has for most of history been local, patchy and of low density, artefacts are sporadically distributed (though locally common) and reflect local cultural development. Nevertheless, the artefacts can be used to date sedimentary deposits and so help constrain the timing of events in natural history. For example, the Palaeolithic, Mesolithic and Neolithic, each referring to successively younger stages of development, are defined and recognised by the presence of certain tool kits (though these are not synchronously developed around the world).

With the explosive growth in human numbers since around the end of the 18th century, associated with and reflecting the increased exploitation of energy, mainly steam in the 19th century and largely hydrocarbons in the 20th century, there has been an orders-of-magnitude increase in the production of human artefacts, as outlined by such measures as the PAT (population × affluence × technology) scale (e.g. Steffen et al., 2011), especially since the 'Great Acceleration' (Steffen et al., 2007) of the mid 20th century. This has been accompanied by acceleration in the rate of technological evolution (and hence in the rate of appearance of different types of artefacts) and by globalization, which has spread these artefacts around the Earth, making them consistently transregional rather than diachronous or local time markers.

All of these objects may be considered in general as ichnofossils (trace fossils), as suggested by Ford et al. (forthcoming), Barnosky (2013), Zalasiewicz et al. (forthcoming a) and others. As such, they have the capacity to characterise and date the enclosing sedimentary deposits, complementing the data provided by more conventional organic remains (Barnosky, 2013; Wilkinson et al., forthcoming). However, these particular human-made phenomena have several quite distinctive characteristics, which serve to separate them from trace fossils as normally understood. Hence, we distinguish them here as *technofossils*, a biological innovation that may be exploited to provide ultra-high resolution geological dating and correlation in *technostratigraphy*, after the concept of the technosphere proposed by Haff (2013; see also Haff, 2010, 2012).

In this paper, we outline the distinctive nature of the biostratigraphic information provided by technofossils, discuss its novel aspects, and explore how this may be of use to help characterise the deposits of a potential Anthropocene Epoch (Crutzen, 2002; Waters et al., forthcoming; Williams et al., 2011; Zalasiewicz et al., 2008), much as previous biological innovations provide the material and conceptual basis for characterising the geological eras, periods and ages that have been assembled as the Geological Time Scale (Williams et al., 2013). We note, too, the wider significance of this phenomenon to Earth history.

Human artefacts as technofossils: Composition and form

Composition

The origin and diversification of metazoans has produced relatively few new mineral types over and above inorganic mineral species (Hazen et al., 2008). Non-human fossils, both body and trace, tend to be made of a limited number of materials that are specific to the species: thus molluscan body fossils are of mostly of calcium carbonate (either aragonite or calcite) while vertebrate ones are typically of apatite or its diagenetic derivatives. Non-human trace fossils tend to be yet more limited, being either impressions in sediment (molds), sediment-filled holes (casts), or in rare cases are made of selected local clasts as in the case of some solitary wasp nests (Ratcliffe and Fagerstrom, 1980). Some diversity of composition can be found in the case of trace fossils secreted with specific compositions (spider-web silk and honey-comb wax), excreted (rock hyrax latrines: Chase et al., 2012) or gathered (packrat middens). In all of these cases, however, the diversity of composition consists almost exclusively of organic materials.

Humans, by contrast, produce artefacts from materials that are either very rare in nature (uncombined iron, aluminium and titanium) or unknown naturally (uncombined vanadium, molybdenum). There is a wide variety of novel minerals such as boron nitride, tungsten carbide and ‘mineraloids’ such as artificial glasses and plastics (Zalasiewicz et al., forthcoming b). The number of these novel materials continues to grow.

Where sufficiently common, widely distributed and preservable, these component materials themselves may be used in themselves as fossil indicators of time (Ford et al., forthcoming; Zalasiewicz et al., forthcoming b). Modern plastics such as polyethylene and polypropylene are essentially a post-World War II phenomenon; their current global production is some 270 million tonnes a year (Rochman et al., 2013), sufficient to cover the USA in a layer of standard kitchen cling-film (plastic wrap). The total production of aluminium metal, also virtually all since 1950, is at least 500 million tonnes (Zalasiewicz et al., forthcoming b). The distribution of these materials is patchy, with densest concentrations in landfill sites and recycling and combustion plants. However, there is sufficient escape, essentially as litter, for these to be common elements of both marine (marine rubbish gyres and fragments in sediments) and terrestrial sedimentary environments, and thus to be time markers in recent, current and near-future deposits.

Novel and natural minerals commonly combine into anthropogenic lithologies. These include concrete (annual production 3.4 billion tonnes and rising: Amato, 2013), bricks, mortar/cement, breeze-block material, road metal (‘tar macadam’), ceramics and so on. As with the minerals, these have evolved in type and amount in tandem with human cultural development. Particularly since the mid 20th century, and the growth of urban areas in developing countries, they have become more globally widespread (Ford et al., forthcoming).

Form

Minerals (considered sensu lato, including organogenic materials such as paper and textiles) and rocks, both natural and artificial, are combined in a diversity of patterns to produce the diverse and changing range of technofossils, that range in scale from the near-continental (urban conglomerations) to small (e.g. bottles, pens) to microscopic (e.g. fly ash particles and other 'nano-artefacts': Nowack and Bucheli, 2007). Some are fixed to the ground surface (buildings and roads), others are not fixed (cups, books) while yet others are built for long-distance travel (cars, aeroplanes) that may even extend beyond this planet (spacecraft). All that are preservable (see below) in the short term (decades/centuries) can help characterise Anthropocene deposits for present-day Earth scientists, while all that are preservable over geological timescales will contribute to the 'far-future' signal of the Anthropocene.

The morphological range of technofossils is almost infinitely greater than the range of trace types produced by any other species. Most trace fossil-formers produce a single type of trace, though some may produce a small number of different types (e.g. trilobite species that produce at different times both *Cruziana* walking traces and *Rusophycus* resting traces). The number of different types of potentially preservable human artefacts, by contrast, numbers in the millions, as a result of cultural evolution, and is growing daily.

Rate of evolution of technofossils

Early in hominid history, technofossil evolution roughly reflected the pace of human evolution. Since the appearance of *Homo sapiens*, the two have been largely decoupled. Through the time of *Homo sapiens* on Earth, some 200,000 years, the general trend has been for the rate of evolution of technofossils to increase.

Thus, in the Late Pleistocene to early Holocene, discernable changes in technologies were accomplished in millennia – e.g. from Stone Age, to Bronze Age to Iron Age. Within most human communities, the technology produced during (and therefore the material life of) one generation was very much like that of another. This was particularly pronounced in small hunter-gatherer communities (where technologies stayed much the same, even towards the present day.

With the development of large, settled, agrarian communities, technofossil development speeded up – though even here, some large agrarian communities, such as those of the ancient Egyptians, remained relatively conservative in this respect. Subsequently, over most of the last 2–3 millennia, technofossil evolution was more rapid, although patchily distributed globally.

The quantity and variety of technofossils grew most quickly in the ancient Chinese and Mediterranean worlds. The most durable sorts consisted of metal tools and weapons, and monumental architecture, often of carved stone. The capacity to cast bronze originated some time about 2500 BC and reached an apex by 1500 BC. A surge in technofossil production followed with the emergence of iron technology, because iron was more abundant if harder to work. By 1000 BC iron tools and weapons were widespread in lands from China to the Mediterranean, and were coming into use in parts of Africa. By contrast, in the Americas, technofossils consisted mainly of carved stone, and metal-working remained negligible until AD 1500.

The quantity and variety of technofossils continued to grow, at an irregular pace. A high point came during the Song Dynasty in China (10th–11th centuries), when a large-scale iron-working complex arose, using coal for fuel. During the Song Dynasty, the Chinese littered the landscape with arrowheads, pots, hinges, nails, anchors and dozens of other types of iron artefacts.

The Song surge in technofossil production slackened in the 13th century. By the 16th century, Europeans (and to an extent Africans) spread iron-working to the Americas, extending the geographic range of technofossils. By 1800, new production technologies and cheaper energy in the form of fossil fuels, ratcheted up the rate of technofossil generation. This process, familiar under the title ‘industrialization’ began in Britain but emerged in different forms within three generations in diverse lands on all continents. By 1900, the quantity and variety of objects that would soon become technofossils was orders of magnitude larger than in 1800.

From the Industrial Revolution, the items made and used by humans – and the resulting technofossils – began to markedly change from one generation to the next. From the mid 20th century onwards, the changes were globally synchronised and sufficiently rapid for social commentators to write of ‘future-shock’ experienced not only between, but within human generations (Toffler, 1970). For example, the generation that lived from the early to late 1900s saw transportation change from horses to automobiles to airplanes to rockets, and communication change from hand-delivered letters, to telegraph, to land-line telephones, to email and mobile phones. All of these changes are clearly reflected in the technofossil record.

The accelerating pace of technofossil evolution correlated strongly with increases in population, not only globally, but also within specific cultures. It is in direct contrast to the pattern classically seen in biological evolution, where the most rapid evolution typically occurs in small isolated populations, with larger populations remaining more stable (e.g. Mayr, 1942).

Current evolution of the technosphere, of which the technofossils are the preserved remnant, is hence now orders of magnitude faster than biological evolution. The rate of technospheric evolution corresponds in part with increased human numbers and energy expenditure, together with enhanced cultural evolution through institutional means, such as expanded university and training systems. But, there are clearly further factors at work. One factor is the exponentially increasing technical possibilities founded on earlier advances, and the multiplying potential cross-links between them, acting in positive (and accelerating) feedback systems.

Distribution and preservation

With acceleration of technofossil evolution has come increase in geographical distribution. Technofossil evolution correlates in part with human population, with increased energy and material use, and with increased globalization; the resulting stratigraphic signal within recent strata, hence, is growing increasingly distinct. Artefacts of the past millennia mostly reflected local to regional cultures, with a few exceptions. Arrowheads became widely distributed on every continent except Australia and Antarctica over the past 4000 years, while coins became widely distributed in Eurasia and northern Africa from 500 BC. However, post-World War II times have seen the spread of, to take just a few out of many examples, paper-clips, aluminium cans, ball-point pens and plastic bags over every continent, and spilling over into the marine realm. The human trace fossils reflect geographic setting, as do the fossils in ancient strata. They are more typical of terrestrial settings, especially in and around urban regions, but they have spread widely into rural and ‘wilderness’ regions, too. Their spread into the marine environment is now significant, both from being washed in from land and being transported into deep water via shipping traffic (Ramirez-Llodra et al., 2011), as well as via the ebb surge currents following major storms and tsunami.

The abundance of technofossils reflects great current differences between the technosphere and biosphere as regards recycling of its component matter. Many biological systems (e.g.

tropical forests) recycle virtually all of their component matter, the decay-related entropy increase being balanced by solar energy input to recreate and maintain complex organic systems. Even where component matter accumulates into organic-rich sediments, typical percentages of production sequestered are less than 1%, and so in many strata fossils are rare. In the contemporary technosphere, by contrast, recycling rates are much lower (e.g. ~50% for aluminium, <20% for plastics, <10% for concrete). Detritus from the technosphere is hence abundantly disseminated.

At the surface, technofossils will degrade physically and chemically over time, particularly as the deposits that they lie on or that enclose them undergo erosion. The long-term preservation of technofossils therefore requires burial. In detail, it reflects the conditions of that burial – many are buried actively today, for instance in landfills – and of the subterranean environment, as they undergo various degrees of alteration. Information regarding the preservability of various ‘tissues/artefacts’ may be partly derived from knowledge of how fossils are preserved, and partly from study of the condition of archaeological remains, though an increasing number of modern materials and artefacts have few direct analogues either in palaeontology or in archaeology. Much, though, is poorly digestible for scavenging metazoa and microbes (e.g. plastics, metals – even wood is commonly seasoned or varnished to resist decay). Technofossils, particularly from their expansion in production of the last few decades, are unlikely to be rare.

Once buried underground, rates of chemical and physical alteration of technofossils will be controlled, as with natural sediments, by moisture content, temperature, oxygen content and pH. Seemingly robust materials such as bricks or concrete may degrade in the presence of water, temperature fluctuations and sulphate- or chloride-rich groundwaters, iron-based metals can corrode in the presence of oxygen and chloride ions, and plastics degrade in the presence of light, oxygen, heat or corrosive fluids (Ford et al., forthcoming). However, leachates sourced from these altered deposits, notably rich in calcium carbonate sourced from degraded cement, concrete or plaster, may produce cements that can ultimately bind and solidify deposits.

The last century, too, has seen the extension of humans to great depths in the crust, as mining activities commonly reach hundreds of metres into the ground, and drilling operations penetrate to several thousands of metres. This deep crustal penetration by the metazoan biosphere is without precedent in Earth history. Simultaneously, human-made structures have invaded the skies and even outer space, to reach other planets and moons of this star system. In the translation of this contemporary phenomenon to stratigraphy, the deep crustal traces have extremely high preservation potential (until the rocks affected are carried to the surface and eroded, or until they are affected by mountain-building processes so that borehole traces, for example, are obliterated by high-grade metamorphism). The constructions that travel through the atmosphere, by contrast, are only rarely preservable, for instance as aeroplanes that crash into the sea. In the case of extraterrestrial satellites and landing-craft, some are now distributed among other planets and moons, while there is much currently human-made space debris in orbit. The technofossils left on our Moon, at least, having also very high preservation potential. This phenomenon marks a new transition in the history of not just the Earth, but of the Solar System (indeed, the the Voyager spacecraft recently left this realm to enter interstellar space: http://www.jpl.nasa.gov/news/news.php?release=2013-277).

Technofossil nomenclature

Trace fossils, like body fossils, may be classified using standard Linnean binomial nomenclature, as ichnospecies. However, using this approach with technofossils (i.e. by reference to the trace-maker, as *Homo sapiens* ichnosp.) is clearly of little help in distinguishing between the many types of individual traces.

Some broad categories may be equated with those applied to ichnofossils following the widely used classification of Seilacher (1964); thus, as traces that are locomotory, resting, dwelling, feeding and so on. Many if not most human artefacts could likely be classified thus. Thus, implements ranging from stone tools to steel knives and electric food mixers could be identified as for killing and processing food, and be feeding traces (pascerichnia). Buildings from the most primitive huts to skyscrapers could be housing traces, i.e. domichnia. Roads and airport runways (and cars and aeroplanes) could be locomotion traces, or repichnia.

The range and diversity of technofossils means that one could indulge in fine taxonomic 'splitting' and hierarchical categorization of the artefacts in terms of morphology and function. For instance, a toothbrush may be regarded as one type of artefact, within a wider category of brushes and brooms. Collectively, these are all cleaning traces. In detail, thousands of different types of toothbrushes have been produced. The range of diversity rivals biological diversity – but ichnological characterisation of this sort may complement standard archaeological, historical and everyday vernacular categorization to provide useful insights. For instance, while some categories of traces may have clear ichnological (and therefore wider biological) counterparts, others may be more or less uniquely human – for instance, the technofossils that we build for recreation (tennis rackets, concert halls), and where novel categories may be needed.

Technostratigraphic classification

Just as the classification of the technofossils themselves merits careful consideration to encompass the enormous, and growing, diversity of these phenomena, so does their formal exploitation in biostratigraphic classification.

In palaeontology, the range and diversity of fossilizeable organisms is simplified to produce a limited number of temporal divisions, often based on the most common, widespread and distinctive of the fossils. Thus, in the Silurian, biostratigraphic zonation is largely based upon graptolites, conodonts, chitinozoans, acritarchs and brachiopods (Melchin et al., 2012), with the most important divisions being those where new grades of organisation are attained (such as the origin of monograptid graptolites). Other types of fossil (even common ones such as corals, trilobites and nautiloids) do not have widely employed zonations, although their recognition in strata may be used to constrain geological age.

Similarly, the recognition of technostratigraphic zones may depend upon common technofossils, and newly achieved grades of organisation. We suggest that the incoming of certain materials (e.g. mass-produced plastics and aluminium) and the objects made from them (cans, bags) may provide useful marker levels. Given the rate of technological progress, technostratigraphic divisions may encompass as little as a decade. The middle of the 20th century has seen a change from local techostratigraphies to, essentially, a global one, enhancing the potential of this time level (Waters et al., forthcoming; Wolfe et al., 2013) as an appropriate and perhaps formal Anthropocene beginning. Within this, evolutionary appearances and extinctions (particularly the latter) clearly do not have the finality of their biological equivalents (consider long-playing vinyl records, now making something of a comeback following their virtual disappearance two decades ago). Nevertheless, the scale and rate of technostratigraphic change has produced abundant, preservable and effectively exploitable evidence of the passage of time, particularly when first-appearance datums are considered.

The future of technofossil evolution

Human traces clearly differ in several major respects from traditional ichnofossils, that are characterised by narrow morphological ranges predetermined by genetic control. The extraordinary diversity of human artefacts (linked to the activities of just one species), rate of morphological evolution, and the acceleration in the rate of this change are without precedent in the Earth's geological record. Hence our suggestion that these represent a new category of fossil: technofossils, the preserved remains of the technosphere of Haff (2012) and the basis for technostratigraphy, for ultra-high resolution dating and correlating of strata, concerned with a putative Anthropocene time interval. They clearly reflect specific qualities that so far are unique to their initiating force, *Homo sapiens*.

The technosphere comprises the interconnecting technological systems that underpin modern human civilization (Haff, 2012), and is a phenomenon that has now reached a scale sufficient to perturb the natural physical, chemical and biological cycles of the Earth (Röckstrom et al., 2009) and provoke the suggestion of an Anthropocene Epoch (Crutzen, 2002).

The continued development of the technosphere and of the technostratigraphic imprint on Earth, currently depends on the continued success of *Homo sapiens* on Earth. However, the technosphere, although clearly currently mediated through human agency, has a dynamic of its own, and cannot be said to be under any central human control. Further, as a complex system representing contemporary global economic networks, it is prone to unpredictable systemic failure (cf. Helbing, 2013) (an early example of this may be the disappearance of the Song Chinese coal–iron complex, and its attendant technofossils, after 1200 CE). The resultant technostratigraphy, hence, may follow the catastrophist trajectory envisaged for Earth history by the 19th century savant Baron Cuvier, rather than the gradualist progression later proposed by Charles Lyell. With the development of artificial intelligence and self-repair systems, some degree of extra-human autonomy may be appearing, and the emergence of self-replicating 'von Neumann' machines cannot be ruled out. In any event, continued technospheric evolution is set to produce new and distinct, short-lived technofossil assemblages that will succeed the present ones, to result in greater and geologically more long-lasting technostratigraphic change.

Given its central role in ongoing global change, not least in the perturbation of mass and energy flows, the emerging technosphere, if sustained, may represent the most fundamental revolution on Earth since the origin of the biosphere. The technofossil assemblages shed from it chart a step change in planetary mode.

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Population health in the Anthropocene: Gains, losses and emerging trends

Anthony J McMichael

Abstract

The health of human populations, measured by life expectancy, is at an historical high. Will this continue – or are we reaching Peak Health? The gains have been unequally shared, but the gap between low-income and high-income countries is narrowing. Meanwhile, there is clear evidence that levels of wealth per se do not predetermine population health, and that today's depleting and disrupting of Earth's biophysical, life-supporting, systems will sooner or later translate into a substantial decline in population health. It is likely, for example, that current trends in the late-stage Anthropocene, including continued population growth, will cause a crisis in food production, affordability and hence substantial health losses. There is a widespread misplaced assumption, reinforced by today's pervasive neoliberalism, that the determinants of health reside largely in *individual* behaviours, genes and access to healthcare. But at *population level* and over the longer term the determinants of health and survival lie with nature's life-supporting systems. Ultimately, without trade and aid, the profile of a population's health reflects the underlying ecological, human–environment coupled, relationship. The adverse health impacts of climate change illustrate well the present and likely future health consequences of humankind's overloading of nature's capacities. Human-generated greenhouse gases are increasing the atmosphere's capture of heat-energy; that heat accumulates, particularly in the oceans; and Earth is warming. A major moral (and geopolitically enlightened) task is for international assistance with social and economic development in poorer countries. That may seem to clash with the now-urgent need to curtail global non-renewable energy use and constrain ongoing exploitation of forests, aquifers, soils and coastal ecosystems, and nitrogenous fertiliser use. Yet integrating these two agendas, potentially mutually reinforcing, is technically possible. This would assist transition to a world of environmentally sustainable living, in which the universal norm is to remain healthy and survive into comfortable older age.

Keywords

Anthropocene, climate change, environmental change, history, human health, urbanisation

The Australian National University, Australia

Corresponding author:
Anthony J McMichael, The Australian National University, Building 62, Mills Road, Acton, Canberra, ACT 0200, Australia.
Email: tony.mcmichael@anu.edu.au

Introduction

This opening paragraph is necessary, regrettably, to help counter the false and misleading model of ‘health’ that prevails in developed-world culture. Understanding the threats to human health and survival from the systemic environmental stresses and disruptions that characterise the later-stage Anthropocene requires recognition that the mainsprings of health and disease reside in the wider environmental milieu. In that sense the collective health of a human population resembles that of a farmer’s herd; it is an expression of the underlying ecological relationships.

If warmer and wetter conditions foster mosquito proliferation and, within them, the accelerated growth of the juvenile malarial pathogens, the regional risks of malaria may increase, as might the geographic range and seasonal duration of its transmission. If increasingly adverse climatic conditions impair food yields in a local subsistence-based population then a food shortage is likely, resulting in a high prevalence of undernutrition, impaired child development and increased susceptibility to infection because of weakened immune systems. Community stability, development and morale will be eroded. These are all ‘herd’ effects; they differ fundamentally in scale and mode from the health consequences of a personal decision to start or stop smoking. Such population-level effects will be the hallmark of the adverse impacts of the Anthropocene on humans.

This population perspective is not new; but it has been obscured during the 20th century by the rise of the biomedical model in individual healthcare, by increasing access to the ‘wonders of modern medicine’, and now the hope of applying genetic bar-coding and hence personalised medical care. Those (mostly) welcome clinical advances should not preclude a primary focus on the larger-scale and more fundamental influences that affect the health of whole communities and populations. Various such systemic environmental risks to population health are now emerging in that quarter as a result of the increasing human-caused disruption of the Earth system. These pose unfamiliar, great and growing risks to the health of human populations.

In the mid 19th century, the great German cell biologist and pathologist Rudolf Virchow provided an early example of the sort of thinking that is, now, largely outside the prevailing neoliberalism-reinforced mental model. Virchow was a polymath, politician and passionate advocate for public health. In 1848, the year of revolutions in Continental Europe, Virchow was asked by the Prussian government to investigate an epidemic of louse-transmitted typhus in impoverished Upper Silesia. His *Report on the Typhus Epidemic in Upper Silesia* concluded that the outbreak could not be solved by dispensing drugs or by minor changes in food, housing or clothing laws (Virchow, 1848).[1] Only radical action to reduce exploitation and promote the advancement of an entire population would solve the problem, and this would require ‘full and unlimited democracy’ and ‘education, freedom and prosperity’. The government was mightily displeased by this report (just as today’s right-wing governments disparage health-protecting Nannyism, retorting ‘Whatever happened to personal responsibility?’).

There is a clear analogy here to one of the central problems we face as the mixed fruits of our intensified economic activities during the Anthropocene become apparent. Some fruits are sweet, some are bitter, some could be damaging and lethal. Only by reducing humankind’s system-disrupting exploitation of the environment and living within nature’s limits can the long-term health and longevity of human populations be made secure (McMichael and Butler, 2011). And only by having insight into the long and tortuous paths travelled by *Homo sapiens*, through diverse terrains, climates, diets and microbial milieus, can we really appreciate the fundamental influences of these components of life on Earth on the wellbeing, health and survival of humans. That long-running story continues today as we come to terms with living in, and hopefully redirecting, the Anthropocene.

The prehistorical and historical background

If mighty oak trees can grow from an acorn, perhaps a planet-changing dominant mammal can emerge from humble knuckle-walking hominin[2] origins. Indeed one such creature has now done so. After 2.5 million years of climatic and environmental changes, eliciting trial-and-error evolutionary branching, *Homo sapiens* is the sole surviving species of the *Homo* genus, a branch of the hominin lineage which previously split from the proto-chimpanzee line 6 million years ago. That split was enforced by natural climate change in regional eastern Africa following the tectonic rupture that created the Rift Valley. The ancestral chimpanzee species living west of the rift maintained its arboreal life in rain-fed forests. But those stranded east of the rift, on lower land and now under the rain shadow of the newly sculpted western escarpment, faced a drier future with far fewer trees on a savannah landscape. Knuckle-walking no longer sufficed.

As the natural environment changes, species gradually become environmental misfits and are remodelled or discarded by evolution. Humans, via the unique feature of *cultural* evolution, have unintentionally amplified their misfit with the environment – and yet, by overexploiting and mismanaging environmental resources, they have maintained the supply of life's necessities (and more). However, on current trends, our species' escalating environmental dominance and disruption may hasten that fateful journey towards decline. If this were well understood, then, rationally, we humans should be motivated to throw off the shackles of instinctual resistance to change and take radical restorative action.

The environment–climate–human relationship comprises three phases: first, from the Early Pleistocene around 2.5 million years ago to its transition into the early Holocene 11,000 years ago; second, from the early Holocene into the 20th century; and third, extending from the recent past into the coming centuries. During each phase the changing profile, and the contextual ecological significance, of human health and survival have highlighted different facets of human interaction with climate and environment (McMichael, 2012). Climatic influences, in particular, are embedded in our bones and brains and have determined the health, longevity and fate of diverse human populations over the ages.

Step by step to the future

Phase 1. The 2.5 million year Pleistocene period of increasingly cold and variable climates led to regular cyclical glaciations over the past 1 million years. Throughout this climatically stressful time, the key evolutionary determinant of survival of hominin species was a level of biological health that enabled reproductive success. As food sources changed in the Early Pleistocene and as climatic fluctuations placed a higher premium on intellectual flexibility ('neocortical plasticity') the *Australopithecus* lineage yielded supremacy to the nascent *Homo* lineage. Two million years of branching succession within the *Homo* genus led to the emergence of archaic *Homo sapiens* and then, 200,000 years ago, the anatomically modern *Homo sapiens* – us. A larger brain, an all-purpose dentition, versatile hand movements, fleetness of foot and a capacity for basic within-group communication were all at a premium.

Life-spans were compressed by comparison with modern times. For those spared serious injury, predation or incidental infection from contact with animals, seasonal foods were plentiful and body growth was robust, females began reproducing in their early teens, and full adulthood was attained by late teens. Dental health was precarious, and often carious; broken bones were difficult to fix; and intestinal infections and infestations by helminths, hydatid cysts and liver flukes were common. Extreme weather events presumably also culled the numbers. Average life expectancy, estimated from skeletal remains, was around 30 years.

Then from around 17,000 years ago postglacial warming occurred. For *Homo sapiens*, now spread far beyond the confines of Sub-Saharan Africa, these differing climatic-environmental conditions in newly inhabited regions fostered further genetic fine-tuning, both anatomical and metabolic. Hence the extant differences in stature between Ethiopians and Inuit, in skin colour between low and high latitudes, and in metabolising enzymes such as alcohol dehydrogenase and arylamine acetylation between east and west Eurasia (McMichael, 2001).

Phase 2. During the ensuing 11,000-year Holocene, environment-driven genetic change was increasingly overshadowed by faster-moving human-directed cultural evolution. The advent of farming opened a Pandora's Box of potential cultural, social and material changes and their future consequences. This included the widely corroborated evidence of nutritional deficiencies, skeletal deformities, weakened bones and stunted growth as the food and nutrient diversity of those farmed diets contracted. Hence the early agrarians were shorter in stature than were hunter-gatherers of the same general period.

This new primary reliance on crops also brought greater dependence on constancy of climate. Serious droughts could be killers, and religious rituals evolved to appease and petition the raingods. Meanwhile, in the short term, farming and harvest surpluses opened up many new vistas of civilisation, trading, wealth, power, social stratification – and population growth. But the longer-term environmental consequences and their eventual human impacts were, of course, unforeseeable. Seeds of future human hardships and crises were also being sewn.

Throughout the Holocene, human health and survival have served as crude markers of the consequences of cultural change: settled living, food production, urbanisation, physical security, social structures and workforce stratification. The consequences, though unevenly shared, were mostly positive in the short term at least. Those health-based markers also testify to the recurring power of food shortages, famines, undernutrition and starvation, often caused or amplified by adverse climatic conditions, to cause huge numbers of deaths, disrupt communities, and destabilise governments and dynasties. As the Holocene progressed, the growing legacy of written and archaeological records provided clearer indices of human health and survival in relation to climatic and environmental stressors on populations (McMichael, 2012).

Then, over the past two centuries the Anthropocene, the Age of Humans, arrived (Crutzen and Stoermer, 2000). *Homo sapiens* had become an increasingly dominant force on the world stage. During early *laisser-faire* 19th-century industrial capitalism, human health, life and survival – best documented in front-running Britain – suffered widely. Death rates were high, especially among the urban poor, as described by Friedrich Engels (1845). In industrial cities such as Manchester and Liverpool in England the death rate from smallpox, measles, scarlet fever and whooping cough was four times higher than in the adjoining countryside. Cities were overcrowded, lacking sanitation, befouled by black factory smoke, and rife with infections and recurrent major epidemics; they acted as population sumps, recharged by youthful aspirants or desperate unemployed from the countryside. Less visibly, the lower atmosphere was beginning to accumulate excess carbon dioxide from coal-burning industries associated with William Blake's 'dark satanic mills'.

The apparent good news was that, in Europe at least, famines had receded over the last two centuries as food yields increased (helped by newly introduced crops from the Americas) along with improved storage, transport and market connectivity. In Eurasia in the 20th century the cause of famines was more often political-ideological than environmental – as in 1930s Ukraine (Stalin's genocidal 'famine') and in China around 1960 (misguided policies under Chairman Mao). Further afield, and especially in Sub-Saharan Africa and South Asia, famines relating to climate adversity, water supplies and social discrimination persisted (Sen, 1981). The great famines of the 1880s and

1890s, extending from eastern and southern Asia to Mexico and Brazil, were largely driven by extreme El Niño events and great droughts, exacerbated in India by rigid colonial export policies (Davis, 2001) similar to the callous policy that amplified the 1840s Irish Potato Famine. During the 1960s–1980s the Green Revolution greatly enhanced food yields by intensified application of fertilisers and irrigation to crops of selectively bred higher-yielding cultivars. This averted much food insecurity and childhood stunting and death in South Asia during that period, but also reinforced the continuing growth of population. In the past several decades, however, the post-1950 gains in food yields have flattened off in most of the world (Brown, 2011) including the USA, Europe, China, South Asia, Australia, while population growth has continued, albeit at a decreasing rate. Hence, over the past decade the *absolute* number of significantly underfed people has remained fairly constant at around 1 billion.

Detailed pluses and minuses aside, by late 20th century an extraordinary juncture had been reached. Human populations were no longer merely exposed to natural climate change; increasingly they were contributing to it. Indeed, human activity is now the overwhelming dominant cause of global climate change (Intergovernmental Panel on Climate Change (IPCC), 2013). The onrush of energy-subsidised growth in the 20th century led to an unprecedented four-fold increase in human numbers, a similar increase in overall economic activity and escalating disruption of biophysical environmental systems. This phenomenon, packed into the past half century, became 'The Great Acceleration'. Proposed as the second stage of the Anthropocene (Steffen et al., 2007), that multidimensional intensification has had far-reaching consequences for patterns of human health and life expectancy in nearly all regions of the world, both gains and losses (McMichael, 2001).

Phase 3. In today's unfamiliar context, as planetary functions falter, human health and survival assumes a special significance. Population health trends and indices now provide feedback about what aspects of our continually changing biophysical and socio-demographic environment, locally and globally, are good or bad for population health and longevity.

The initial population health outcome reflects the immediate biological and survival consequences, many of them beneficial. During the 20th century, production of more food calories resulted in better pregnancy outcomes, enhanced childhood survival and stronger adult bodies. But, crucially, in the longer term the feedback often reveals the downside – the health costs of a way of life that chronically deviates from the early environmental conditions (especially dietary sources and physical activity patterns) that shaped human evolution and equipped it to thrive and reproduce within a particular range of natural environmental conditions (Boyden, 1987). Hence, when even more calories become part of the daily milieu, particularly those from concentrated fats and sugars in modern processed foods, the weight, metabolism and healthy functioning of human bodies becomes disordered in whole populations (though manifested in some individuals before others). Again, a herd effect.

The experience of the past two industrialising and urbanising centuries has shown that literacy, emancipation of women, food security, safe drinking water, good housing, modern preventive medicine and public health are all essential for health. In contrast, industrial food processing, commercially inculcated consumerism, industrial and agrochemical pollution of local environments (air, water, soil), loss of sense of community, mass-marketed tobacco products, road trauma and many industrial workplace exposures are all bad for health. But those are the *familiar* components of the recent narrative of progress and regress in population health. They are only part of the unfolding Anthropocene story.

Looming ever-larger and casting a much longer shadow, the deterioration in the conditions of Earth's natural biophysical *systems*, along with the large-scale changes in social-economic conditions and persistent material disparities between rich and poor, play a much more fundamental and longer-term role in setting the bounds on population health and survival. To set this in recent context, the following review of current country-specific life expectancy provides a useful index of human life and survival in today's world. But it cannot tell us where this current general uptrend will end up later in this century.

Human life expectancy

> The phenomenon [increasing population life expectancy] is inclusive, in the sense that all populations, whether they are rich or poor, techno-quick or dawdling in the digital slow lane, democratically ruled or under the thumb of despots, all are eventually tugged along. And it is directional: for 150 years the tide has been running in, pushing life expectancy further and further up the shore. Knowledgeable people frequently say 'it will go no higher', and stick flags in the sand to mark the turning point. They hardly turn their backs and the flags are under water. (Woodward and Blakely, forthcoming)

Since the late 19th century a widely shared and unprecedented increase in human life expectancy, evident first in Western industrialising countries, has occurred. From the early 20th century the average life expectancy at birth, globally, has increased from around 35 years to 69 years; for many countries, including China and Cuba, it now exceeds 75 years. In most high-income countries life expectancy has also been increasing among those aged over 80 years, with the exception of recent pauses in Denmark, the Netherlands and the USA (Rau et al., 2008). That temporary plateauing is likely to have reflected the wave of deaths from the tobacco-smoking epidemic passing, in generation-bound fashion, through those populations.

Females generally have higher life expectancies than males, except for the several southern African countries *below* the gender-equality line in Figure 1. Clearly, the gains have not been equally shared, but that gap is now closing as countries with the lowest life expectancies are generally achieving the fastest gains.

This remarkable demographic transition follows on from the epidemiological transition and its associated gains in hygiene, sanitation, maternal education, vaccination and antibiotic treatment. The resultant lower rate of infant and childhood deaths has led to lessened pressure to have more 'reserve' children, assisted by gradual (though inadequate) gains in understanding of and access to contraception. As infectious diseases receded in the wake of improving family and civic hygiene and the emergent Germ Theory in the 1880s, the diseases that killed many people a century ago, including tuberculosis, measles and poliomyelitis, have been brought under increasing control – or, in the case of oft-fatal smallpox, eradicated.

The Global Burden of Disease Study (Horton, 2012) reported that most deaths in developed countries, and increasingly in urbanising populations in lower-income countries, are now caused by chronic non-communicable diseases such as heart disease, stroke, cancer and chronic lung diseases (Murray et al., 2012).[3] Rates of diabetes have recently surged in China in association with increasing wealth and consumerism, urban living and sedentary forms of work, recreation and travel. Other developing countries are likely to follow suit.

Yet, at this time of great changes in the scale and geographic distribution of environmental risks to health, GBD2010 included only a few conventional candidate environmental hazards – and nothing in relation to the large-scale systemic environmental changes that now press increasingly on human health. In part this reflects the lack of 'respectable' textbook epidemiological research on that topic, much of which cannot be reduced to simplified and acceptably precise estimates. The inadequately estimated 'total' burden of disease attributed by GBD2010

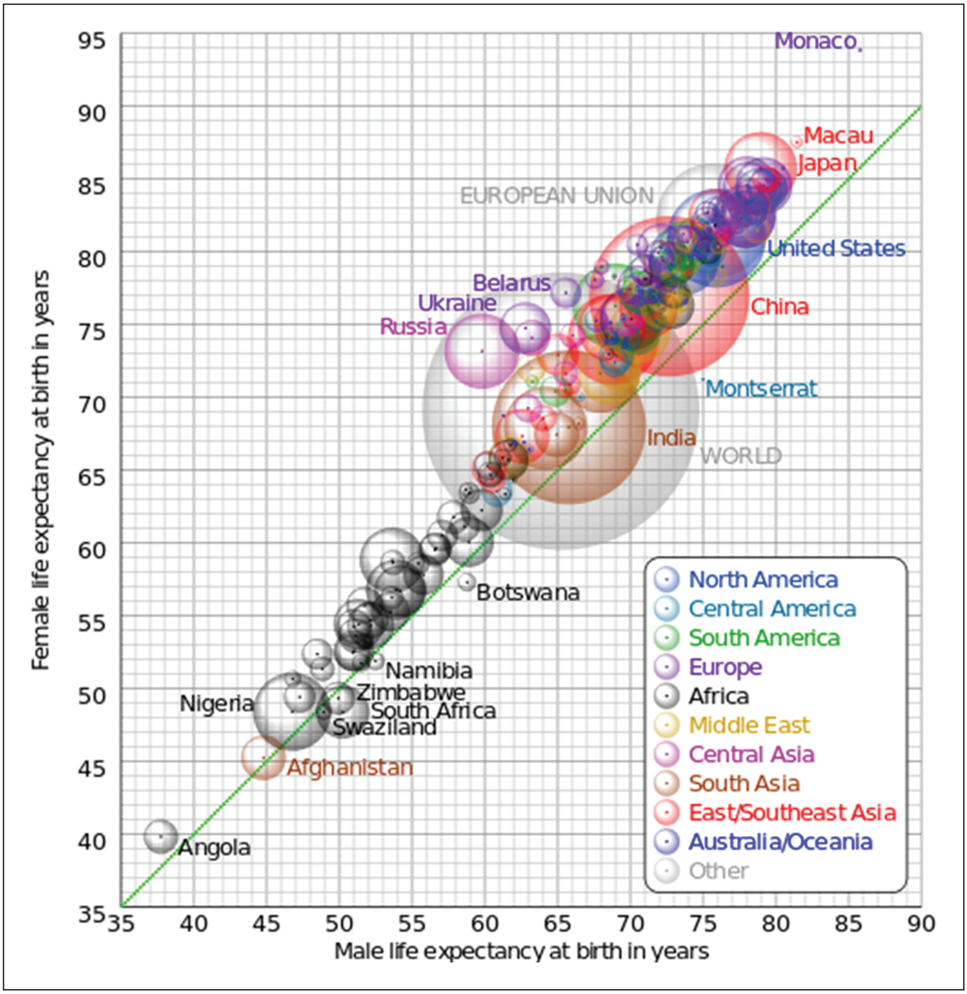

Figure 1. Comparison of male and female life expectancy at birth for countries and territories.

Notes: The straight diagonal line corresponds to equal female and male life expectancy. Selected country-specific bubbles are labelled, and their apparent 3D volumes are proportional to their population size.

Source: This graph is from Wikimedia Commons, available at: http://en.wikipedia.org/wiki/File:Comparison_gender_life_expectancy_CIA_factbook.svg. It incorporates data from the CIA World Factbook, available at: https://www.cia.gov/library/publications/the-world-factbook/fields/2102.html and https://www.cia.gov/library/publications/the-world-factbook/fields/2119.html.

to long-familiar local environmental factors was less than one-tenth of the overall total (Lim et al., 2012).

In all of this there lies the tantalising so-called 'environmentalist's paradox' (Lomborg, 2001). The issue is: 'How come human life expectancy has continued to increase despite the endless examples of local and regional environmental pollution, destruction and depletion resulting from intensified industrial practices?'. The question, though interesting, is actually miscast. Certainly, local environmental pollution by chemicals in air, water and food, and in the workplace, has everywhere slowed the upward thrust in population health indicators to some extent. So too has the continued toll from infectious diseases, especially in poorer countries, during much of the past century. Without those hazards, health gains would have been greater. The 'paradox', as generally understood, does not allow for emerging and likely (though necessarily uncertain) future adverse health consequences, including those that will impinge on populations as Anthropocenic pressures weaken the planet's life-support system.

So, there is no real paradox (McMichael and Butler, 2011; Raudsepp-Hearne et al., 2010). Instead, the environment–health relationship must be understood within the larger socio-ecologically based frame, extending into the future, and entailing *disruption* and *depletion* of crucial components of Earth's operating system. Those components include the climate, the stratosphere, the temperature, the pH and circulatory pattern of the oceans, the global cycling of elements (nitrogen and phosphorus) and loss of biodiversity (Rockström et al., 2009). The health impacts impinge on whole communities or populations, often via circuitous and diffuse routes, and often entailing time-delays.

Finally, we face an ethical dilemma. Concern for distributive justice raises the question as to how much effort any one society might invest in further increasing its population's average longevity (Childress et al., 2002) especially if this depends on high carbon-intensive energy inputs and damaging environmental imposts. Distributive justice requires 'proportionality' of actions, a balancing of benefits and dis-benefits. This includes acting so that health inequalities are lessened, not perpetuated. And in a globally interconnected world, increasingly aware that our present ways of living pose serious systemic environmental risks to future generations, consideration of distributive justice also transcends national borders and generations.

Urbanisation

The urban environment is becoming a centre-piece for research, concern and the prospects for attaining an environmentally and socially sustainable way of living if human health and longevity are to be sustained into the future, and shared evenly between and within countries. In ecological terms, urban environments have recently become the dominant human habitat, and by mid-century two-thirds of the world's population will live in cities (Seto et al., 2012).

The historic milestone was reached in 2007 when just one-half of the global population was classified as living in cities – though mostly cities and towns with populations of less than 2–3 million, not mega-cities. The motives for moving are protean. Many people are 'pulled' by job opportunities, welfare possibilities and new opportunities; many are 'pushed' by farm failures, hunger and land ownership strife. Around two-thirds of the vast recent influx of impoverished people into Dhaka, Bangladesh's mega-city capital, have relocated because of the growing impacts of climate change on the extremity of weather disasters (including cyclones in the notorious Bay of Bengal), increased saltiness of coastal groundwater and impaired agricultural yields (Tacoli, 2009).

This urbanising transformation of human ecology began slowly around six millennia ago. Throughout most of the ensuing time, human health has borne an *urban penalty*, especially from the Four Horsemen of the Apocalypse: famine, pestilence, war and conquest. Over several millennia, large and densely crowded populations, often living in unhygienic conditions, have long been vulnerable to age-old infectious diseases. Even more basic is urban population dependence on the countryside for sustenance, meaning that they have always been vulnerable to food crises and starvation.

> As I walk through the slums of Africa, I find it hard to witness children suffering under what can only be described as an urban penalty. (Anna Tibaijuka, Executive Director, UN-Habitat)[4]

Cities have long represented concentrations of assets, property, wealth and political control, always attractive prizes for avaricious enemies – and thus at risk of inflicted misery, suffering and death. More recently, in the industrial era, urban populations in developed countries faced new health hazards from toxic effluent chemicals in air, water and soil. Those hazards are now spreading worldwide. They are the Anthropocene's underbelly of localised risks to human health resulting from the huge increases in energy generation, industrial (and agricultural) chemicals, artificial food preservation and packaging and so on.

But, as those traditional urban health risks recede in modern cities, new threats are arising from anthropogenic system-disrupting global environmental changes. These include the risks arising at the urban interfaces with climate change, water shortage, rising seas and loss of community. Climate change, for example, brings heightened heat exposures, amplified by the urban heat island effect wherein these huge, often treeless, agglomerations of masonry, steel and asphalt absorb much more heat than does the surrounding countryside, and also retain much of it overnight. This heat-trapping deprives inner-city residents, especially those in uninsulated housing, of physiological relief at night. It also exacerbates the often serious health risks in overheated workplaces – a considerable hazard to physiological functioning, behaviour and judgement, physical safety, longer-term health and work productivity (Kjellstrom et al., 2009).

The concept of urban sustainability extends beyond assessing whether local conditions are conducive to achieving and maintaining a high and shared level of health. It must factor in the life-supporting flows of food and other materials, and outgoing wastes, along with measures of alienation of arable land, clearing of forests and losses of biodiversity (Baynes, 2012; Seitzinger et al., 2012; Wiedman et al., 2013). This relates to the concept of the 'ecological footprint'. When first proposed by Canadian ecologist William Rees and others more than 20 years ago, humans were viewed as 'patch disturbers', like gorillas and elephants (Rees, 2011).[5] But it is no longer just a matter of local patches; many of our actions, aggregated worldwide, now disrupt whole global and regional biophysical and ecological systems (Rockström et al., 2009).

In public discourse and the policy arena, the highest-profile of these disruptions is human-induced climate change. It is now virtually certain that atmospheric heat-capture by human-generated greenhouse gases (especially carbon dioxide) is increasing, that removal of carbon dioxide by the land and sea 'sinks' is declining, and that Earth is consequently warming. This topic of climate change provides illustrative insight into the diversity, complexity and uncertainty of many of the risks to human health from the human-induced changes to the structure and working of the Earth system that define the Anthropocene.

Health impacts of climate change: Overview

The climate, as a source of threats to health, is not a toxin, a microbe or a miasma. It is a dynamic and changeable system with many local and regional manifestations, most of which can influence rates and patterns of health outcomes. It is often referred to as a health 'risk multiplier'. Of course, it can also act as a 'risk divider' if, for example, temperatures become too hot for mosquito survival, or a local increase in rainfall improves crop yields and nutrient supplies (McMichael, 2013). Figure 2 shows the three main types of paths by which changes in climatic conditions affect the health and survival of human populations in many and diverse ways (Butler and Harley, 2010; McMichael and Lindgren, 2011). Most of these, though not all, will be adverse (IPCC, 2007). Even so we seem to be more aware of the fundamental threat to polar bear food supplies in the melting Arctic than from what some fear is the 'Coming Famine' (Cribb, 2010).

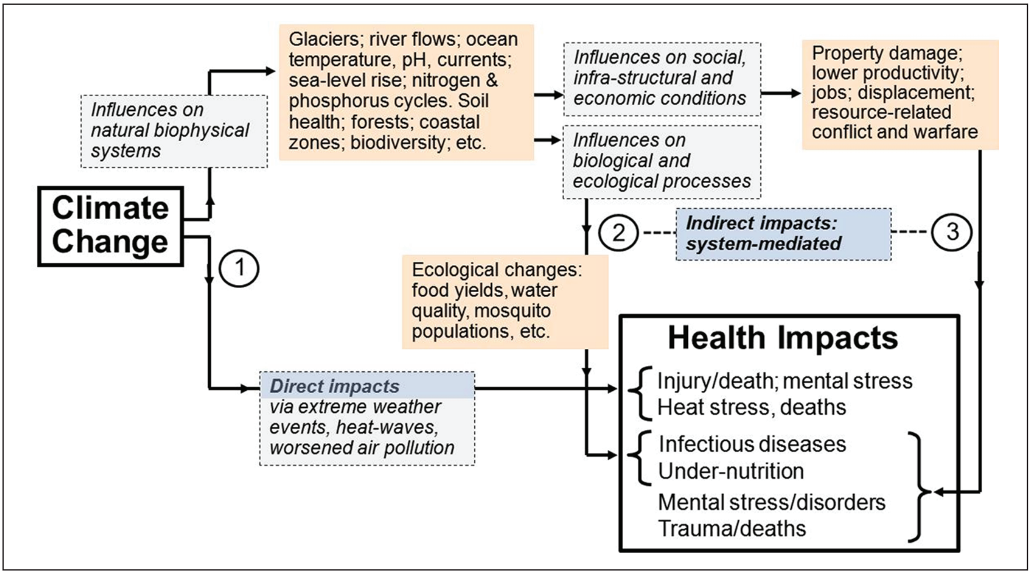

Figure 2. The three pathways by which a change in climatic conditions can affect human health. Some are direct and immediate; many are (and will become more prominent in future) mediated, less immediately, via biophysical, ecological, social and geopolitical disruptions.

Some causal paths are essentially direct. These are the ones that most people are aware of: heat-wave deaths; impacts of floods, storms and fires; and exacerbation of urban air pollution. But they are only the readily visible tip of what (to use an inappropriate metaphor) is likely to become a very large iceberg.

The most serious risk to health and survival posed by climate change comes from its disruption or weakening of much of the biosphere's fundamental life-support system. Many of these secondary health impacts will result from indirect and often complex systems-based processes affecting the following: regional food yields, water flows, natural constraints on infectious disease agents, the inhabitability of low-lying coastal regions, and the physical protection conferred by reefs, mangroves and forests.

Many of the economic and social consequences of these environmental disruptions, in turn, will engender job loss, impoverishment, out-migration, often leading to tensions between countries and communities, conflict and, probably, open warfare (Jarvis et al., 2011). All these will cause illness, misery, depression and premature death, examples of tertiary health impacts.

Note, finally, that we are no longer only discussing a likely future. Evidence of climate change influences on health outcomes around the world, in the present, is strengthening. They include the following:

- Recent uptrend in adverse health impacts from cyclones, storms, wild-fires, flooding.
- Increasing annual deaths attributable to heat-waves in a range of countries.
- Shifts in range and seasonality of some climate-sensitive infectious diseases (and, where relevant, their vectors): Lyme disease, malaria, schistosomiasis (China), cholera.
- Contribution to declines in food yields in some regions: risk of malnutrition-related child development.

- Adverse mental health consequences in various rural communities affected by drying and extreme weather events.

Concluding comments

Patterns of health, disease and survival in human populations have always been intimately connected to external environmental conditions – the climate, food species, water supplies, infectious agents, physical hazards and others. During the Pleistocene the biological evolution of the emerging *Homo* genus was much influenced by these exposures to changeable climatic and environmental conditions. During the Holocene, dietary deficits, activity patterns, food crises, emerging infectious diseases from domesticates animal sources especially and property-seeking conflict and warfare all took their toll on human health – often influenced by the natural ups, downs and fluctuations in regional climates. Over time, urbanisation and then industrialisation became increasingly more dominant as the frame and source of the determinants of health, disease and longevity.

We know that story fairly well, but it has not prepared us for the new and different task of transforming how we live and relate to our planetary habitat: transforming our core values, social goals and interactions with the Earth system. Nor has it imparted the profound realisation that the long-term good health of communities and populations – the ‘herd’ at large – does not originate with disciplined individual consumer behaviour, genetic factors, good doctors, medications and high-tech hospital equipment. The health of the population and its average life expectancy provide the best sentinel measure of how society is tracking in terms of sustaining the essence of the natural environmental and social conditions in which humans evolved.

A primary moral task in this environmentally precarious later stage of the Anthropocene is to ensure that future generations inherit a liveable world (Gardiner, 2011). The major concurrent moral and geopolitical obligation is to achieve rapid social and economic development in the world’s poorer countries. That second obligation may seem to clash with the world’s now-urgent need to curtail non-renewable energy use and constrain depletion of forests, aquifers, soils and coastal ecosystems and nitrogenous fertiliser use. Yet, with enlightened choice of small-footprint technologies, these two agendas can be mutually reinforcing. This would help drive the transition toward an environmentally sustainable way of living, in a future world in which people everywhere would have a high probability of long-term good health and comfortable longevity (Friel et al., 2008).

Making the transformative, not piecemeal, changes that are prerequisite to environmental sustainability and human equity presents a huge challenge. Radical changes in social priorities, human connectedness with the natural world, attitudes to material growth and acquisition, and to an economic system antithetical to limits-based constraints and a Topsy-like system of national and international governance are all needed. If and when the threat to actual *human* futures from the trends spawned by the Anthropocene are fully understood – especially the great threat to human health and survival from eroded life-supporting systems – then majority forces within our ranks will surely be more likely to respond, redress the excesses of the Anthropocene and help set a new course to the future.

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Notes

1. Virchow, as parliamentarian, was a leading political antagonist of Chancellor Bismarck. His opposition to Germany's excessive military budget provoked Bismarck to challenge him to a duel in 1865. Contemporary sources record that Virchow who, as the challenged party was entitled to choose the weapons, selected two pork sausages – one normal and the other loaded with *Trichinella* larvae which, when ingested, invade the muscle tissue, causing fever, myalgia, malaise and oedema. The Chancellor wisely declined.
2. The *hominin* lineage extends back to the split with the chimpanzee line, around 6 million years ago. Once the *Homo* genus evolved within that lineage, around 2.3 million years ago, that new (and ultimately usurping) branch was referred to as the *hominids.*
3. The paper reports: 'In 1990, 47% of DALYs worldwide were from communicable, maternal, neonatal, and nutritional disorders, 43% from non-communicable diseases, and 10% from injuries. By 2010, this had shifted to 35%, 54%, and 11%, respectively'.
4. Quoted in Worldwatch Institute (2007: xix).
5. Rees defines patch disturbance as: 'The measurable habitat and ecosystem modification caused by large animals, including humans, as they forage for food or other resources. Patch disturbance is most pronounced near the den, temporary camp, or other "central place" within the overall home range of the individual or group'.

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Perspectives and controversies

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The Anthropocene: A governance perspective

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Frank Biermann

Abstract

The classification of a new epoch in planetary history as the 'Anthropocene' is fundamentally changing the way we understand our political systems. Given the inherently political nature of human societies, the Anthropocene also has to be understood as a global political phenomenon. The paper elaborates on how the Anthropocene is changing societal interdependence relationships, and sketches foundations of an emerging new paradigm in the social sciences, 'Earth System' governance. The notion of Earth System governance is developed as both an analytical and a normative research problem that is of fundamental relevance for the disciplines of political science and governance studies.

Keywords

Earth System governance, international relations, political science

The classification of a new epoch in planetary history as the 'Anthropocene' is fundamentally changing how we understand our political systems. The transition from the Holocene to an Anthropocene signifies a new role for humankind: from a species that had to adapt to changes in their natural environment to one that has become a driving force in the planetary system (Steffen et al., 2011; Zalasiewicz et al., 2011). Yet the human species, as the defining element of this notion of an Anthropocene, remains a highly abstract concept. It masks the multitude and variety of human agency, the differences in human resources and the diversity of human desires. It masks, in particular, the *political nature* of human society. Following Aristotle, humans are a *zoon politikon*, a 'political animal' that distinguishes itself from other species by its capacity to collectively organize its affairs through joint institutions. This political characteristic of humans is fundamental also for the notion of the Anthropocene. *The Anthropocene is political*; it has to be understood as a global political phenomenon (see, in more detail, Biermann, forthcoming).

VU University, The Netherlands;
Lund University, Sweden

Corresponding author:
Frank Biermann, Environmental Policy Analysis, VU University, De Boelelaan 1087, Amsterdam 1081 HV, The Netherlands.
Email: frank.biermann@vu.nl

To start with, the Anthropocene creates, changes or reinforces multiple interdependence relations within and among human societies. For one thing, it creates new forms and degrees of interdependence among the more than 190 formally sovereign countries and their national jurisdictions. Some of these new interdependencies emerge from functions of the Earth System that transform local pollution into changes of the global system that affect other places that have (much) less contributed to the problem, with examples being climate change, stratospheric ozone depletion, the global distribution of persistent organic pollutants and the global spread of species with potential harm for local ecosystems. Countries are also becoming more interdependent when local environmental degradation leads to transregional or global social, economic and political crises, for instance through decreases in food production that raise global food demand and prices. In short, the Anthropocene creates a new dependence of states, even the most powerful ones, on the community of all other nations. This is a defining characteristic as well as a key challenge that requires an *effective institutional framework for global cooperation*.

Second, the Anthropocene increases the functional interdependence of human societies. For example, political response strategies in one economic sector are likely to have repercussions for many others. Functional interdependence also relates to the mutual substitutability of response options, which poses special problems of international allocation. In climate governance, for example, for every global policy target there are an unlimited number of possible combinations of local responses across nations and time frames with equal degrees of effectiveness. In short, increased functional interdependence in the Anthropocene requires new degrees of effective policy coordination and integration, from local to global levels.

Third, the Anthropocene creates new *intergenerational dependencies* that pose novel political challenges. Causation and effect of transformations of the Earth System are usually separated by (often several) generations. Sea-level rise, for example, is expected within a time-range of 100 years and more. Such planning horizons exceed the tenure and often the lifetime of present political leaders. Among other things, this poses the questions of *international credibility* and trust that future governments will reciprocate and comply with international rules, and the problem of *democratic legitimacy* of policies in the intergenerational context. What rights and responsibilities do present generations – and their representatives in parliament – owe to their unborn successors? And to what extent can present generations be held accountable for activities of their ancestors, for instance regarding the burning of fossil fuels in Europe before the greenhouse effect became more widely known in the 1990s?

Fourth, the Anthropocene comes with persistent uncertainty about the causes of Earth System transformation, its impacts, the links between various causes and response options, and the broader effects of policies. Most transformations, such as global climate change, are non-linear and might accelerate, or slow down, at any time. Surprises in system behaviour can be expected, but are by definition unforeseeable. This creates a new political context, as exemplified by Ulrich Beck's notion of a global 'risk society'.

Finally, the Anthropocene is an epoch that sees the human species with extreme variations in wealth, health, living standards, education and most other indicators that define wellbeing. According to the World Bank, the richest 20% of humanity account for 76.6% of the world's total private consumption. The poorest 20%, on their part, account for just 1.5% of global wealth. Almost half of humanity – roughly, 3 billion people – lives on less than US$2.5 per day (Chen and Ravallion, 2008). 850 million people lack sufficient food. The poorest 25% of humanity still has no access to electricity (United Nations Development Programme (UNDP), 2007). About one-third of all children in developing countries are underweight, and every day, 20,000 children die of poverty (United Nations Children's Fund (UNICEF), 2004). Today, 1 billion people lack sufficient access to water, and 2.6 billion have no basic sanitation (UNDP, 2006). Politics in the Anthropocene has to operate in this global situation of large inequalities in resources and entitlements.

All these developments call for a new perspective also in political science. One such new perspective is a newly emerging paradigm in the social sciences, *'Earth System' governance* (Biermann, 2007; Biermann et al., 2009). The Earth System governance paradigm is a response and a reaction in the social sciences to the notion of an Anthropocene (and related concepts such as Earth System analysis). It accepts the core tenet of the Anthropocene, that is, the understanding of the Earth as an integrated, interdependent system transformed by the interplay of human and non-human agency. The focus of Earth System governance is not 'governing the Earth', or the management of the entire process of planetary evolution. Instead, Earth System governance is about the *human impact on planetary systems*. It is about the societal steering of human activities with regard to the long-term stability of geobiophysical systems.

The notion of Earth System governance now underpins a 10-year global research initiative under the auspices of the International Human Dimensions Programme on Global Environmental Change. This initiative – the Earth System Governance Project – was launched in 2009 and has evolved into a broad, vibrant and global community of researchers who share an interest in the analysis of Earth System governance and in the exploration of how to reform the ways in which human societies (fail to) steer their co-evolution with nature at the planetary scale. More than 2500 colleagues are subscribed to the Earth System Governance newsletter, and about 250 researchers belong to the group of lead faculty and research fellows closely affiliated with the Project. The term 'Earth System governance' already generates about 450,000 Google hits daily.

Research on Earth System governance needs to address both analytical and normative questions. The *analytical theory of Earth System governance* studies the emerging phenomenon of Earth System governance as it is expressed in hundreds of international regimes, international bureaucracies, national agencies, local and transnational activist groups, expert networks, etc. The analytical perspective is, in short, about how the current governance system functions.

The *normative theory of Earth System governance* is the critique of the existing systems of governance in light of the exigencies of Earth System transformation in the Anthropocene. The normative theory understands Earth System governance as a political reform programme that will benefit from both evidence-based policy research and more fundamental social science critiques of underlying systemic driving forces. Such critiques are surely needed, given that – to name one example – after 20 years of global negotiations and national policies, carbon dioxide emissions in 2010 still grew by 5.9% to a new record high (Peters et al., 2012). In the academic community, pleas for drastic change in global governance are becoming a frequent feature of scientific gatherings. For example, the 2011 Nobel Laureate Symposium on Global Sustainability called in its *Stockholm Memorandum* for 'strengthening Earth System Governance' as one of eight priorities for coherent global action (Third Nobel Laureate Symposium on Global Sustainability, 2011). One year later, the 2012 *State of the Planet* Declaration, supported by various global change programs and international agencies, called for '[f]undamental reorientation and restructuring of national and international institutions'. It is fundamental, the Declaration continues, 'to overcome barriers to progress and to move to effective Earth-system governance. Governments must take action to support institutions and mechanisms that will improve coherence, as well as bring about integrated policy and action across the social, economic and environmental pillars' (Co-chairs of the Planet under Pressure Conference, 2012: C1).

A press release preceding this Declaration, supported by the International Council for Science and others, even requests governments to fundamentally 'overhaul' the entire UN system (Planet

Under Pressure Conference, 2012). In the preparation to the 2012 UN Conference on Sustainable Development, members of the Earth System Governance research alliance had advanced a number of proposals for such an overhaul of the UN system, for example to create a new World Environment Organization and a UN Sustainable Development Council; to better monitor and support private governance mechanisms; to strengthen the involvement of civil society in international institutions; and to more often rely on qualified majority-voting as opposed to the more common system of consensus-based decision-making (Biermann et al., 2012).

Yet Earth System governance is not only about strengthening global institutions, which are merely part of the entire effort. Notably, also technological change and incremental policies at local and national levels will remain a driving force of progress in Earth System governance. For instance, just cutting down the emissions of black carbon and methane – which is a precursor of tropospheric ozone – could be a win-win solution by reducing global mean warming by around 0.5°C by the middle of the 21st century (Shindell et al., 2012). Incremental change by national and regional policies is possible, too. For example, a mix of technological change and climate change policy has allowed the European Union member countries to cut greenhouse gas emissions by 18% from 1990 while growing their economies at the same time by 48% (European Commission, 2013).

Transformations in social behaviour are crucial as well, moving from a focus on mere cooperation and efficiency to broader notions of 'sufficiency' (Princen, 2003). Large-scale changes of lifestyles are likely to be non-linear and might depend on 'social tipping points' (Lenton et al., 2008: 1792). There is ample historic precedence of drastic changes in perceptions of good and appropriate lifestyles, often motivated by religion, national renaissance (for example, Gandhism) or philosophy. Environment-related changes in public perceptions of good and appropriate living include the public ban on smoking as inappropriate behaviour for movie actors, politicians and other perceived role models; the change in perception of whale-meat consumption that is hardly affected by a recovery in some species stocks; and the rising social movement of vegetarianism. Another example is the increasing acceptance of bicycles as default vehicle of transportation in cities. In October 2013, 70 top managers of Dutch companies publicly left their chauffeur-driven cars behind in support of a week-long national 'Low Car Diet' campaign, thus accepting a partial redefinition of the appropriate lifestyle in the most affluent segments of society (Takken, 2013). The branding of bicycle transportation as the 'new normality' is also rapidly taking off in parts of North America. New York City, for instance, has, in recent years, increased its network of bicycle lanes by 700 km and counts today 73,000 members in its bicycle sharing programme, with 35,000 rides per day (Kuin, 2013).

However, it would mean throwing out the baby with the bathwater if intergovernmental institutions were discarded. The UN system and international negotiations do not stand in an antagonistic relationship with local action and non-state movements. The one needs the other. In a world of over 190 independent nation states, there is no way around strong and effective international cooperation. Effective international cooperation must be a basis for Earth System governance in the Anthropocene. A concerted effort is needed to bring these institutions in line with the exigencies of the changed political context of Earth System transformation.

In sum, in the course of the 21st century the Anthropocene is likely to change the way we understand political systems both analytically and normatively, from the village level up to the United Nations. This makes the Anthropocene one of the most demanding, and most interesting, research topics also for the field of political science, which has to develop novel, more effective and more equitable governance systems to cope with the challenges of Earth System transformation.

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The geology of mankind? A critique of the Anthropocene narrative

Andreas Malm and Alf Hornborg

Abstract
The Anthropocene narrative portrays humanity as a species ascending to power over the rest of the Earth System. In the crucial field of climate change, this entails the attribution of fossil fuel combustion to properties acquired during human evolution, notably the ability to manipulate fire. But the fossil economy was not created nor is it upheld by humankind in general. This intervention questions the use of the species category in the Anthropocene narrative and argues that it is analytically flawed, as well as inimical to action. Intra-species inequalities are part and parcel of the current ecological crisis and cannot be ignored in attempts to understand it.

Keywords
Anthropocene, inequality, society

Since Nobel laureate Paul Crutzen (2002) proposed ‘the Anthropocene’ as a new geological epoch in his short piece ‘The geology of mankind’ in *Nature* in 2002, the concept has enjoyed a truly meteoric career. The currently unfolding discourse on the Anthropocene represents a convergence of Earth System natural science and post-Cartesian[1] social science as represented, for instance, by Bruno Latour. Both fields suggest that the Enlightenment distinction between Nature and Society is obsolete. Now that humanity is recognised as a geological force, the story goes, we must reconceptualize not only the relations between natural and social sciences but also history, modernity and the very idea of the human.[2] Indeed, the increasingly inextricable interfusion of nature and human society is incontrovertible, as evidenced not only by climate change but also by other kinds of anthropogenic transformations of ecosystems.

The question we wish to address in this brief intervention is whether this should really prompt us to abandon the fundamental concerns of social science, which importantly include the theorization of culture and power. We shall suggest that the physical mixing of nature and society does not

Lund University, Sweden

Corresponding author:
Andreas Malm, Human Ecology Division, Lund University, Geocentrum 1, Lund 22362, Sweden.
Email: Andreas.Malm@lucid.lu.se

warrant the abandonment of their *analytical* distinction. Rather, precisely this increasing recognition of the potency of social relations of power to transform the very conditions of human existence should justify a more profound engagement with social and cultural theory. We find it deeply paradoxical and disturbing that the growing acknowledgement of the impact of societal forces on the biosphere should be couched in terms of a narrative so completely dominated by natural science. Moreover, in line with the abandonment of Cartesian dualism in our approach to the material conditions of human existence, we have no less reason to reconsider human economies and technologies as similarly hybrid phenomena interlacing biophysical resources, cultural perceptions and global power structures.

According to the standard Anthropocene narrative, the Industrial Revolution marks the onset of large-scale human modification of the Earth System, primarily in the form of climate change, the most salient and perilous transgression of Holocene parameters. More precisely, in his 2002 piece, Crutzen suggested that James Watt's invention of the steam-engine inaugurated the new epoch, and the chronology stuck: in the burgeoning literature on the Anthropocene, the steam-engine is often referred to as the one artefact that unlocked the potentials of fossil energy and thereby catapulted the human species to full-spectrum dominance (e.g. Alberts, 2011: 6; Beerling, 2007: 8; Berners-Lee and Clark, 2013: 8–10; Irwin, 2010: 1; Lynas, 2011: 21; Robin and Steffen, 2007: 1699; Sayre, 2012: 58; Steffen et al., 2011: 844–845).

Theorists of the epoch have little to say about the actual causes of the rise of steam, but they do propound a general framework for understanding the transition to fossil fuels in the Industrial Revolution, which, for reasons of logical necessity, is deduced from human nature. If the dynamics were of a more contingent character, the narrative of an entire species – the *anthropos* as such – ascending to biospheric supremacy would be difficult to uphold: 'the geology of mankind' must have its roots in the properties of that being. Anything less would make it a geology of some smaller entity, perhaps some subset of *Homo sapiens*. Even when the Anthropocene is dated to the time of Watt – and not to the rise of agricultural civilisations, as in the 'early Anthropocene' hypothesis (e.g. Ruddiman, 2003; Smith and Zeder, 2013) – the fuse is often traced back into the mists of time, lit in the early evolution of the human species.

A key component of the Anthropocene narrative is thus the manipulation of fire: the path to the fossil economy was laid down when our hominid ancestors once upon a time learned to control fire. Here was 'the essential evolutionary trigger for the Anthropocene', in the words of Rapuach and Canadell: fossil fuel combustion is result of the fact that 'long before the industrial era, a particular primate species learned how to tap the energy reserves stored in detrital carbon' (Raupach and Canadell, 2010: 210–211). Or, in the words of Will Steffan, Paul J Crutzen and John R McNeill: 'The mastery of fire by our ancestors provided humankind with a powerful monopolistic tool unavailable to other species, *that put us firmly on the long path towards the Anthropocene*' (Steffen et al., 2007: 614, emphasis added; cf. Clark, 2012; Crosby, 2006; Steffen et al., 2011: 846). In this narrative, the fossil economy is the creation precisely of humankind, or 'the fire-ape, *Homo pyrophilis*', as in Mark Lynas' popularisation of Anthropocene thinking, aptly titled *The God Species* (Lynas, 2011).

A scrutiny of the transition to fossil fuels in 19th-century Britain (Malm, 2013a), however, reveals the extent to which the historical origins of anthropogenic climate change were predicated on highly inequitable global processes from the start (cf. Frank, 1998; Pomeranz, 2000). The rationale for investing in steam technology at this time was geared to the opportunities provided by the constellation of a largely depopulated New World, Afro-American slavery, the exploitation of British labour in factories and mines, and the global demand for inexpensive cotton cloth. Steam-engines were not adopted by some natural-born deputies of the human species: by the nature of the social order of things, they could only be installed by the owners of the means of production. A tiny minority even in Britain, this class of people comprised an infinitesimal fraction of the population of *Homo sapiens* in the early 19th century. Indeed, a clique of white British men literally pointed steam-power as a weapon – on sea and land, boats and rails – against the best part of humankind, from the Niger delta to the Yangzi delta, the Levant to Latin America (cf. Headrick, 1981, 2010). Capitalists in a small corner of the Western world invested in steam, laying the foundation stone for the fossil economy: at no moment did the species vote for it either with feet or ballots, or march in mechanical unison, or exercise any sort of shared authority over its own destiny and that of the Earth System.[3]

The ability to manipulate fire was, of course, a necessary condition for the commencement of fossil fuel burning in Britain. So were tool-use, language, co-operative labour and a whole range of other human faculties – but they were *trivial* necessary conditions, lacking correlation with the outcome of interest. The error here is well-covered in historiographical textbooks. To invoke ultra-remote causes of this kind 'is like explaining the success of the Japanese fighter pilots in terms of the fact that prehumans evolved binocular vision and opposable thumbs. We expect the causes we cite to connect rather more directly to consequences', or else we disregard them, as pointed out by John Lewis Gaddis (Gaddis, 2002: 96; cf. Bloch, 1992: 158–159). Attempts to attribute climate change to the nature of the human species appear doomed to this sort of vacuity. Put differently, transhistorical – particularly species-wide – drivers cannot be invoked to explain a qualitatively novel order in history, such as mechanized, steam-power production of commodities for export to the world-market.

How about later stages of the fossil economy? The succession of energy technologies following steam – electricity, the internal combustion engine, the petroleum complex: cars, tankers, aviation – have all been introduced through investment decisions, sometimes with crucial input from certain governments but rarely through democratic deliberation. The privilege of instigating new rounds appears to have stayed with the class ruling commodity production. Reflecting an intra-species concentration on another level, as of 2008, the advanced capitalist countries or the 'North' composed 18.8% of the world population, but were responsible for 72.7 of the CO_2 emitted since 1850, subnational inequalities uncounted. In the early 21st century, the poorest 45% of the human population accounted for 7% of emissions, while the richest 7% produced 50%; a single average US citizen – national class divisions again disregarded – emitted as much as upwards of 500 citizens of Ethiopia, Chad, Afghanistan, Mali, Cambodia or Burundi (Roberts and Parks, 2007). Are these basic facts reconcilable with a view of *humankind* as the new geological agent?

We would argue that, to the contrary, uneven distribution is a condition for *the very existence* of modern, fossil-fuel technology (Hornborg, 2001, 2011). The affluence of high-tech modernity cannot possibly be universalized – become an asset of the species – because it is predicated on a global division of labour that is geared precisely to abysmal price and wage differences between populations. The density of distribution of technologies that are ultimately dependent on fossil fuels by and large coincides with that of purchasing power. These technologies are an index of capital accumulation, privileged resource consumption, and the displacement of both work and environmental loads. After more than 200 years, we still tend to imagine 'technological progress' as nothing but the magic wand of ingenuity which, with no necessary political or moral implications elsewhere, will solve our local problems of sustainability. But globalized technological systems essentially represent an unequal exchange of embodied labour and land in the world-system. The world-view of modern economics, the emergence of which accompanied the Industrial Revolution in the hub of the British Empire, systematically obscures the asymmetric exchange of biophysical resources on which industrialization rests. This disjunction between exchange values and physics is as much a condition for modern technology as engineering. The uneven accumulation of technomass visible on satellite photos of night-time lights proceeds by means of a simple algorithm: the more fossil fuels and other resources capital has dissipated today, the more it will afford to dissipate tomorrow. Perceptions of ‘technology’, no less than perceptions of ‘Nature’, are cultural constructions conditioned by global power structures: the promises of fossil-fuelled technology to humankind were illusory all along. Our narratives of this destructive force should not replicate those illusions.

The best counter-shot for the Anthropocene narrative seems to be population growth: if it can be shown that fossil fuel combustion is largely fanned by the multiplication of human numbers, the species can indeed be held causally responsible. Thus the leading Anthropocene theorists like to foreground this as one or even *the* major perturbation of the biosphere (e.g. Crutzen, 2002, 2006: 14; Steffen et al., 2007: 618; Zalasiewicz et al., 2008: 4, 2010: 2228–2229). Granted, there is a correlation between human population and CO_2 emissions, but the latter increased by a factor of 654.8 between 1820 and 2010 (Boden et al., 2013), while the former ‘only’ did so by a factor of 6.6 (Maddison, 2006: 241; United Nations, 2011), indicating that another, far more powerful engine must have driven the fires. For recent decades, the correlation has been revealed as outright negative. David Satterthwaite juxtaposed rates of population growth to rates of emissions growth in the quarter-century between 1980 and 2005, and found that numbers tended to rise fastest where emissions grew slowest, and vice versa (Satterthwaite, 2009). The rise of population and the rise of emissions were disconnected from each other, the one mostly happening in places where the other did not – and if a correlation is negative, causation is out of the question.

A significant chunk of humanity is not party to the fossil economy at all: hundreds of millions rely on charcoal, firewood or organic waste such as dung for all domestic purposes. Satterthwaite concluded that one-sixth of the human population ‘best not be included in allocations of responsibility for GHG emissions’ (Satterthwaite, 2009: 547–550). Their contribution is close to zero. Moreover, 2 billion people, or nearly one-third of humanity, have no access to electricity, and so, in the words of Vaclav Smil, ‘the difference in modern energy consumption between a subsistence pastoralist in the Sahel and an average Canadian may easily be larger than 1,000-fold’ (Smil, 2008: 259). Depending on the circumstances in which a specimen of *Homo sapiens* is born, then, her imprint on the atmosphere may vary by a factor of more than 1000 (Satterthwaite, 2009: 564). Given these enormous variations – in space and in time: the present and the past – humanity seems far too slender an abstraction to carry the burden of causality.

Now, proponents of the Anthropocene might object that from the standpoint of all other living things, and indeed from the biosphere as a whole, what really matters is that climatic disruption originates from *within* the human species, even if not *all* of it is to blame, and so a species-based term for the new geological epoch is warranted. A Tuareg pastoralist or a Toronto paymaster, the burner of fossil fuels is, after all, *human*. This seems to be a compelling argument, providing the Anthropocene concept with a rather solid rationale. It is indicative of the term’s origins in the natural sciences, geologists, meteorologists, biologists and others having detected an overwhelming human influence on ecosystems, now ranged alongside natural selection, solar radiation and volcanic activity. The ‘Anthropocene’ registers this moment of epiphany: the power to shape planetary climate has passed from nature into the realm of humans.

As soon as this is recognised, however, the main paradox of the narrative, if not of the concept as such, becomes visible: climate change is *denaturalised* in one moment – relocated from the sphere of natural causes to that of human activities – only to be *renaturalised* in the next, when derived from an innate human trait, such as the ability to control fire. Not nature, but human nature – this is the Anthropocene displacement. It backs away from the vertiginous depth of perhaps the most ground-breaking scientific discovery of our time, which tells us that human beings have caused global warming over the course of their *history*. This kind of history does not appear in the biography of any other species: beavers and bonobos continue to construct their own micro-environments as they always have, generation upon familiar generation, while a certain human community may burn wood for ten millennia straight and then coal the next century. Realising that climate change is 'anthropogenic' is really to appreciate that it is *sociogenic*.[4] It has arisen as a result of temporally fluid social relations as they materialise through the rest of nature, and once this ontological insight – implicit in the science of climate change – is truly taken onboard, one can no longer treat humankind as merely a species-being determined by its biological evolution. Nor can one write off divisions between human beings as immaterial to the broader picture, for such divisions have been an integral part of fossil fuel combustion in the first place (Hornborg, 2001, 2011).

Following climate science out of nature, we should dare to probe the depths of social history: not relapse into the false certitude of another natural inevitability. The Anthropocene narrative could here be seen as an illogical and ultimately self-defeating foray of the natural science community – responsible for the original discovery of climate change – into the domain of human affairs. Geologists, meteorologists and their colleagues are not necessarily well-equipped to study the sort of things that take place between humans (and perforce between them and the rest of nature), the composition of a rock or the pattern of a jet stream being rather different from such phenomena as world-views, property and power. Now that the latter layers of earthly existence mould the former, some epistemological confusion is perhaps to be expected. Against this background, 'the Anthropocene' resembles an attempt to conceptually traverse the gap between the natural and the social – already thoroughly fused in reality – through the construction of a bridge from one side only, leading the traffic, as it were, in a direction opposite to the actual process: in climate change, social relations determine natural conditions; in Anthropocene thinking, natural scientists extend their world-views to society.

Needless to say, this re-naturalisation of climate change is as much (if not more) a product of behaviour in the social sciences and humanities, namely the late awakening to a warming world. The baton has failed to pass between 'the two cultures', and now that the latter is slowly catching up, 'the Anthropocene' is already an entrenched concept and mode of thinking. Regrettably, many a social scientist and humanist has swallowed it lock, stock and barrel, oblivious to its anti-social tendencies, attracted by the idea of the *anthropos* as centre and master of the universe (be it productive or destructive), which speaks to certain humanist sensibilities (e.g. Alberts, 2011; Palsson et al., 2013; Szerszynski, 2012).

Perhaps the most important interventions from critical theory into the Anthropocene debate has been made by Dipesh Chakrabarty, who, in his essay 'The climate of history: Four theses', reflects on some of the pitfalls of species-thinking, but ends up endorsing it as a necessary project (Chakrabarty, 2009). Humanity really is constituted as a universal species agent that 'flashes up in the moment of the danger that is climate change', most starkly in the extreme weather events emblematic of the new epoch: 'Unlike in the crises of capitalism, there are no lifeboats here for the rich and the privileged (witness the drought in Australia or recent fires in the wealthy neighborhoods of California)' (Chakrabarty, 2009: 221). But this is a flawed argument. It blatantly overlooks the realities of differentiated vulnerability on all scales of human society: witness Katrina in black and white neighborhoods of New Orleans, or Sandy in Haiti and Manhattan, or sea level rise in Bangladesh and the Netherlands, or practically any other impact, direct or indirect, of climate change. For the foreseeable future – indeed, as long as there are human societies on Earth – there *will* be lifeboats for the rich and privileged. If climate change represents a form of apocalypse, it is not universal, but uneven and combined: the species is as much an abstraction at the end of the line as at the source (cf. Malm, 2013b; Malm and Esmailian, 2012).

As for the drivers of climate change, naturalisation has an easily recognisable form. 'Certain social relations appears as the *natural properties of things*', to speak with Karl Marx: production is 'encased in eternal natural laws independent of history, at which opportunity *bourgeois* relations are then quietly smuggled in as the inviolable natural laws on which society in the abstract is founded' – or the human species in abstract (Marx, 1990: 1005, 1993: 87, emphases in original). The effect is to block off any prospect for change. If global warming is the outcome of the knowledge of how to light a fire, or some other property of the human species acquired in some distant stage of its evolution, how can we even imagine a dismantling of the fossil economy? Or: 'the Anthropocene' might be a useful concept and narrative for polar bears and amphibians and birds who want to know what species is wreaking such havoc on their habitats, but alas, they lack the capacity to scrutinise and stand up to human actions. Within the human kingdom, on the other hand, species-thinking on climate change is conducive to mystification and political paralysis. It cannot serve as a basis for challenging the vested interests of business-as-usual.

There is, however, a noteworthy difference between the bourgeois political economists Marx attacked and the Anthropocene narrative. Scholars naturalising climate change are rarely if ever working on behalf of the vested interests of business-as-usual. Most would likely wish to see them gone. Insofar as it occludes the historical origins of global warming and sinks the fossil economy into unalterable conditions, 'the Anthropocene' is an ideology more by default than by design, more the product of the dominance of natural science in the field of climate change and, perhaps, the general blunting of critical edges and narrowing of political horizons in the post-1989 world than of any malicious apologetics. It is not necessarily any less harmful for that. It is one of several theoretical frameworks which happen to be not only analytically defective, but also inimical to action.

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Notes

1. By 'post-Cartesian', we mean approaches that abandon Cartesian distinctions such as between Society and Nature or between subject and object.
2. Programme for the conference 'Thinking the Anthropocene', Paris, 13–15 November 2013.
3. Nor is the Anthropocene narrative itself today conducive to democracy, but rather the opposite; cf. Leach (2013).
4. The neologism 'sociogenic' is, of course, means to indicate that the driving forces derive from a specific social structure, rather than a species-wide trait. Similarly, Richard Norgaard (2013) has recently suggested that we think in terms of the 'Econocene', in view of 'the 50-fold increase and the globalization of economic activity during the 20th century'. Two other candidates worth consideration – both proposed to better integrate social and natural aspects – are the 'Technocene' and the 'Capitalocene'.

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Anthropogenic climate change and the nature of Earth System science

Frank Oldfield[1] and Will Steffen[2,3]

Abstract

One of the criticisms made by those sceptical of the majority scientific consensus on climate change and its likely future consequences is that the Earth System science upon which it is based is fundamentally flawed. This contention is challenged here by an outline of the nature of the science needed to make future projections possible. The classic Popperian approach to science, in which potentially refutable hypotheses are defined and tested is not well suited to the challenges posed by an Earth System that is characterised by high degrees of complexity, non-linearity and a lack of definable cause–consequence relationships. A science based on model–data comparisons and interactions is the only effective approach both to increasing our understanding of the Earth System and developing a well substantiated basis for future projections.

Keywords

Anthropocene, climate change sceptics, Earth System science

Introduction

Anthropogenic climate change – human activities that alter the energy balance at the Earth's surface and destabilise the climate system – is a core framing issue for the Anthropocene, irrespective of the date favoured for its onset. The first instalment of the Fifth IPCC Assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013) – the Summary for Policy Makers for the Working Group 1 (Physical Science Basis) – has just emerged after much deliberation among hundreds of scientists.

The most recent IPCC report has increased the level of confidence, already high, in the scientific community's basic understanding of the causes and effects of anthropogenic climate change. First, warming of the climate system is unequivocal. Second, we are even more certain that human activities, mainly the emission of greenhouse gases, are the primary cause for the warming observed

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[1] University of Liverpool, UK
[2] The Climate Council of Australia, Australia
[3] The Australian National University, Australia

Corresponding author:
Frank Oldfield, School of Environmental Sciences,
University of Liverpool, Roxby Building, Liverpool L69
3BX, UK.
Email: oldfield.f@gmail.com

since the mid 20th century. Third, climate change creates serious risks for human wellbeing, often through the exacerbation of extreme weather events. Finally, rapid and deep reductions in greenhouse gas emissions are required to stabilise the climate system this century.

Predictably, the IPCC report has generated renewed, sceptical responses. Indeed, a disinformation campaign had already sprung up prior to the release of the report, based on leaked copies of early drafts of the report. Most of the sceptic attacks can be immediately dismissed for a number of reasons that are not science-based. Some sceptics are funded by special interest groups, often fossil fuel lobby groups that have much to lose if fossil fuel use is significantly reduced. They often use cherry-picked data and flawed logic to cast doubt on the science involved – the so-called 'merchants of doubt' approach that was thoroughly exposed by the work of Oreskes and Conway (2010) and by Mann (2012). Other attacks are clearly based on underlying political motivations, such as equating climate change science to a push for a world government, or other such ultra-rightwing fear campaigns. Yet others are driven by conspiracy theory – that there is a conspiracy throughout the global scientific community to rig the science so that funding is increased by governments intent on promoting ways of reducing carbon emissions. A few of the sceptics, such as Richard Lindzen, express concern about the veracity of mainstream climate change science, and employ more scientifically based approaches to question the science. This type of critique includes both challenges to specific research programmes, climate models and the inferences based on them (e.g. Lindzen and Choi, 2009; 2011, Lindzen et al., 2001) and also blanket assertions that Earth System science itself is fundamentally flawed (Lindzen, 2013).

In keeping with the aim of a highly transdisciplinary journal such as this one, the present paper addresses the sceptics' concern about the scientific method, and examines the ways in which science itself is evolving to deal with something as challenging and complex as the Earth System.

The nature of Earth System science

The common assertion is that successive IPCC reports and the wide range of research upon which they are based consist of flawed, incomplete or fuzzy science, sometimes derisively referred to as 'junk science' (http://junksciencearchive.com/). The starting point for this science-based attack on the IPCC, and on mainstream climate science more generally, is that the only valid type of science is that which rests on the testing of falsifiable hypotheses. Sceptics of this persuasion claim that, in the case of climate change, this requires a null hypothesis to the effect that '*currently observed changes in global climate indices and the physical environment, as well as current changes in animal and plant characteristics, are the result of natural variability*' (Nongovernmental International Panel on Climate Change (NIPCC), 2013). Their claim is that the evidence so far fails to force rejection of this null hypothesis. Notwithstanding that this claim is incorrect (Blois and Hadly, 2009; Diffenbaugh and Field, 2013; Moritz and Agudo, 2013), the underlying scientific philosophy underpinning the claim is essentially the approach to science outlined by Karl Popper, who, in his formulation, requires crucial tests that refute or fail to refute (but never prove) any given hypothesis. This Popperian model of science (Popper, 1963) is the frame of reference within which the sceptics make the more philosophically based component of their critique. All the other supposedly scientific criticisms are underpinned by the claim that this is the only valid type of science and the rest can be regarded as flawed or invalid.

Other sceptics attack the concept of 'consensus' in science, with obvious reference to the commonly made statement that there is a majority consensus among climate scientists regarding the reality of anthropogenic climate change and its likely consequences. The history of environmental science over the last century tells us, however, that no matter how strong the majority consensus is, there is no guarantee that a particular interpretation is correct, especially if new evidence becomes available. Up until the 1960s, the visual evidence for Wegener's hypothesis of 'continental drift' (Wegener, 1929/1966) was largely discounted as coincidental. Only when the mechanism of plate tectonics was promulgated did the idea become accepted by geologists (Blackett et al., 1965). For even longer, the proposal by Milankovitch (1941) that orbital variations triggered major changes in Earth's climate, such as the swings between glacial and interglacial conditions, was a minority view. It took the deciphering of the record of climate change in marine deposits (Hays et al., 1976) to confirm that orbital forcing provided the beat to which global climate responded on multi-millennial timescales.

The common theme in these past examples of scientific consensus first rejecting and then embracing new understanding of complex phenomena is uncovering underlying mechanisms. In this, the present state of consensus on anthropogenic climate science (understanding the underlying mechanism leading to widespread consensus) in fact represents the same kind of transition as occurred earlier from initial scepticism about the idea that continents moved or that orbital variations caused ice ages, to widespread consensus among scientists as mechanistic underpinnings of the empirical observations came to light.

Fundamental are the conflicting perspectives arising from different concepts of science. What kind of science is possible and appropriate when research questions are necessarily concerned with changes through time in systems of immense complexity, with many feedbacks and non-linear interactions, and no simple cause and effect relationships? This, in fact, is the fundamental nature of Earth System science and the scientific method involved is much more complex than simply formulating hypotheses and designing experiments to test them (see, e.g., Barnosky and Kraatz, 2007).

Looking back to the future

All the *evidence* we have regarding environmental change comes from the past, whether of the previous few seconds as changes are logged continuously, or of the more remote past revealed through the study of environmental archives. The latter are especially important as they provide evidence that has accumulated over decadal to millennial timescales, evidence that is vital for understanding those processes that have shaped the present and promise to drive changes in the future on timescales of critical importance to human populations. The research field as a whole has rarely proved amenable to the Popperian approach, though there are a few striking exceptions that live up to the seminal exhortation by the biologist Ed Deevey, to 'coax history to conduct experiments' (Deevey, 1969). These are exemplified by the work carried out to identify the causes of freshwater acidification (Battarbee et al., 1985). By choosing a variety of field-based case studies with or without key characteristics, each of which was a putative cause of acidification, it proved possible to isolate past variables such as land-use change or catchment afforestation and thereby home in on the only remaining hypothesis not rejected by the evidence, namely the dissemination of industrially generated SO_2.

This type of study is exceptional and more often, inferences about past environmental changes are interpreted in the context of multiple working hypotheses, each of which stands equally until further evidence accumulates to narrow the range of potential explanations. Indeed, this approach has proven effective in the historical sciences since TC Chamberlain's publication of his seminal paper 'The Method of Multiple Working Hypotheses' (Chamberlain, 1890). The alternative explanations often need to be presented without choosing among them (Dearing et al., 2006). Despite these limitations, interpretations improve as more data accumulate, better techniques become available and more sophisticated paradigms take hold.

Toward projective science

What is clear to any researcher in this field is that the combined effects of an only ever imperfectly knowable past and an inconceivably complex environmental system make it, save in rare instances, impossible to apply the type of reasoning that arises from even post hoc experiments where cause and effect can be discriminated and variables considered in isolation. Some 20 years ago Oldfield tried to trace the evolving nature of scientific reasoning in research on past environmental change. This was prompted by the growing conviction that, as the succeeding 20 years have confirmed, the overarching need for a future-oriented research agenda would increasingly dominate funding priorities (Oldfield, 1993).

In that work, Oldfield contrasted both the more traditional and long-standing inductive approach exemplified by classic compilations such as those of Godwin (1956) and Berglund (1991) and the rather more rare but scientifically compelling deductive research exemplified above, with an emerging agenda in which, instead of through rigorously defined hypothesis testing (whether post hoc or through active experiments), validation had to be sought through the ever-increasing convergence between empirical data and models. Since the latter are all that we have for future projection beyond guesswork, expert opinion and extrapolation, data–model comparisons and interactions must be cornerstones of what Oldfield termed '*projective*' science. Transient and 'time frame' data are only available for the past but one important purpose of climate or Earth System models is to project the future. The best that can be done therefore is to test the model outputs against empirical data that reflect as wide a range of relevant processes and boundary conditions as possible, as well as to seek to increase understanding of the complex system interactions involved through model simulations.

Models are vital tools in our efforts to understand extremely complex systems such as the Earth System; in fact, that is their primary purpose. Thus, one of the essential features of any model used to project future changes in the global environment must be its ability to capture well those features and changes securely portrayed by the empirical evidence from the past. Future projections are therefore based on data–model comparisons, an interactive relationship subject to progressive refinement as both strands of the relationship gain in knowledge and skill. The uncertainties attached to projections often reflect, in part at least, the combined statistical 'errors' attached to both. It is hard to see how else to proceed. Certainly, this type of projective science falls outside the Popperian framework of straightforward hypothesis testing (Popper, 1963). Moreover, it will always fall short of 'proof' and be subject to varying degrees of uncertainty, but it will, with sufficient skill, be subject to refinement and increasing confidence in its explanatory and projective power. This is precisely what we are seeing in the IPCC assessments, with their increasing confidence in our understanding of past planetary changes; our strengthening ability to tease out the fundamental physical, chemical and biological (and increasingly human) processes in the climate system and combine them in the framework of complex systems; and our skill in building the quantitative models that capture this improved understanding. It is this emerging new model of science – or more precisely, the emerging understanding that science proceeds in an iterative rather than linear fashion – that underpins the whole business of future projection (University of California Museum of Paleontology, 2013).

Finally, alongside the type of 'projective' science outlined above lie future scenarios that include alternative pathways for human populations, their activities and the consequences of those activities. These rest on both quantitative science and plausible assumptions of human activity into the future. Whereas the former can be refined and filtered by the application of criteria based on the skill with which they capture current reality and past variations, the latter are not amenable to such rigorous evaluation. They too, though, are vital components of the Earth System and require the engagement of many areas of scholarship beyond those traditionally considered to be within the realm of Earth System science.

In the latest IPCC Summary for Policymakers (2013), these scenarios are portrayed as Representative Concentration Pathways (RCPs) rather than socio-economic scenarios. The only future projection that gives possible cause for complacency is RCP 2.6, which is theoretically possible provided all emission targets are met (van Vuuren et al., 2011). Current national trends, despite past, partial agreements on emission limitation and continuing rhetoric, seem unlikely to come anywhere near to meeting the targets required. In fact, our emissions are currently tracking nearest to RCP 8.5, the highest of the four pathways. The higher emission scenarios are thus much more probable, suggesting that the future does indeed hold challenges that, for much of humanity, will require a mix of mitigation and adaptation that still lies beyond most policy statements at national or international level. Moreover, for the high-end emission scenarios, the rates of change and projected outcomes may lie beyond the adaptive capacity of much of the human population as well as many aspects of Earth System functioning. The bottom line is clear. Denying the relevance and validity of Earth System science is a highly risky, and possibly catastrophic, approach for humanity to take towards its future.

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Short communication

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Problem solving in the Anthropocene

Anthony D Barnosky[1] and Elizabeth A Hadly[2]

Abstract
Despite the technological advances that characterize the Anthropocene, it will be necessary to address and solve some key environmental problems in order to mitigate societal risks and avoid undesirable impacts. Success will require more effective interactions between scientists, policy makers, the business community, technological innovators, thought leaders and the public-at-large about the key issues – climate change, extinctions, ecosystem loss, pollution and population overgrowth – and their practical solutions. Here we introduce one example of how such interactions can begin.

Keywords
Anthropocene, climate change, ecosystem loss, extinctions, human life support systems, pollution, population growth, scientific consensus

Problem solving in the Anthropocene

Given that human impacts already set aside the Anthropocene from all other time on Earth, and that those impacts are almost certain to increase as the human population grows from its present 7 billion to over 9 billion by the year 2050, it is inevitable that *Homo sapiens*' place in the biosphere will continue to evolve. A key question – in fact, a key challenge – is whether we will decide to simply continue business as usual and hope for the best, or try to actively guide the planet's future such that what is now healthy and productive for people and other species remains so, and what is now broken is repaired.

The second choice, to guide the future, is in many ways something new for humanity. In the past, it has worked pretty well to simply assume that the planetary resources we depend upon, such as abundant clean air and water, a climate that has varied relatively little and under which complex societies became established in their present configuration, and a diversity of other species and 'wild' places that provided what we want from them, are constants for the human experience. We

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[1]University of California, Berkeley, USA
[2]Stanford University, USA

Corresponding author:
Anthony D Barnosky, Department of Integrative Biology, University of California, Berkeley, 1005 Valley Life Sciences Bldg #3140, Berkeley, CA 94720, USA.
Email: barnosky@berkeley.edu

now know that not to be the case. A growing body of scientific studies going back more than three decades has firmly documented some human impacts that, if they keep going in the directions they have been, in the best case pose serious risks for maintaining a quality of life that is at least as satisfactory as humanity now finds it, and in the worst cases have great costs to people, other species and the planet in general.

Those impacts take the form of five dangerous trends, all of which are well substantiated with scientific data and observations, and all of which have been accelerating since about 1950: increasing climate disruption; growing numbers of extinctions; loss of non-human-dominated ecosystems; growing pollution of air, land and sea; and rapidly growing human populations. None of these are small problems, and combined they can synergize to create a maelstrom, yet all will require solution in the Anthropocene.

Solving such global issues will depend on much more than science and technology – solutions at the grand scale that is needed will require the actions of, and interactions between, people in all walks of life: scientists, policy makers, the business community, technological innovators, thought leaders and the public-at-large. In this issue, we publish one such effort at action and interaction, the ‘Scientific consensus on maintaining humanity’s life support systems in the 21st century: Information for policy makers’ (Barnosky et al., forthcoming, this issue). Developed by a team of 16 global change scientists in response to the need for information requested by the leader of the world’s 9th largest economy, Governor Edmund G ‘Jerry’ Brown, the statement was quickly endorsed by 522 leading scientists from 41 countries, and after its release on 23 May 2013, was translated into Chinese and Spanish, and promptly used in helping to forge greenhouse-gas and green technology agreements nationally and internationally, details of which will be presented in a later issue.

For now, the Consensus Statement continues to garner additional endorsements by practicing scientists and others, and to be used in communicating the basic scientific underpinnings of some of the Anthropocene’s most pressing problems and, importantly, their broad-brush solutions to those who need the information most (http://consensusforaction.stanford.edu/). It also offers a key lesson: making the Anthropocene the best it can be will require not only communicating across disciplinary boundaries within academia, but also making sure that what we learn in the Ivory Tower does not stay there.

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Introducing the *Scientific Consensus on Maintaining Humanity's Life Support Systems in the 21st Century: Information for Policy Makers*

Anthony D Barnosky,[1] James H Brown,[2] Gretchen C Daily,[3] Rodolfo Dirzo,[3] Anne H Ehrlich,[3] Paul R Ehrlich,[3] Jussi T Eronen,[4] Mikael Fortelius,[4] Elizabeth A Hadly,[3] Estella B Leopold,[5] Harold A Mooney,[3] John Peterson Myers,[6] Rosamond L Naylor,[3] Stephen Palumbi,[3] Nils Chr Stenseth[7] and Marvalee H Wake[1]

Abstract

The Anthropocene is recognized (though not yet formally defined) as the time when human impacts are widespread on Earth. While some of the impacts are essential to supporting large human populations and can be sustainable in the long run, others can irretrievably damage the life support systems upon which the global society has come to depend, or spark rapid changes to which societies cannot adapt fast enough. Among these dangerous trends are increasing climate disruption, extinctions, loss of non-human-dominated ecosystems, pollution, and population overgrowth. Interactions between these five trends exacerbate their potential to trigger harmful global change. Reducing the resultant risks requires effective cooperation between scientists and policy makers to develop strategies that guide for environmental health over the next few decades. To that end, the *Scientific Consensus on Maintaining Humanity's Life Support Systems in the 21st Century* was written to make accessible to policy makers and others the basic scientific underpinnings and widespread agreement about both the dangers of and the solutions to climate disruption, extinctions, ecosystem loss, pollution and population overgrowth. When it was released in May 2013, the document included endorsements by 522 global change scientists, including dozens of members of various nations' most highly recognized scientific bodies, from

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[1]University of California, USA
[2]University of New Mexico, USA
[3]Stanford University, USA
[4]University of Helsinki, Finland
[5]University of Washington, USA
[6]Environmental Health Sciences, USA
[7]University of Oslo, Norway

Corresponding author:
Anthony D Barnosky, Department of Integrative Biology, University of California, 1005 Valley Life Sciences Bldg #3140, Berkeley CA 94720, USA.
Email: barnosky@berkeley.edu

41 countries around the world. Since then, endorsements have grown to more than 1300 scientists plus more than 1700 others – business people, NGO representatives, students, and the general public – spanning more than 60 countries. Now also available in Spanish and Chinese, the document has proven useful in helping to stimulate national and international agreements. Further information about the genesis, uses, the signatories, and how to endorse it can be found at http://consensusforaction.stanford.edu/. Such communication between scientists, policy makers, and the public at large will be essential for effective guidance to address global change as the Anthropocene progresses.

Keywords
climate change, ecosystem loss, extinction, pollution, population growth

Essential points for policy makers

Scientific Consensus on Maintaining Humanity's Life Support Systems in the 21st Century

Earth is rapidly approaching a tipping point (Figure 1). Human impacts are causing alarming levels of harm to our planet. As scientists who study the interaction of people with the rest of the biosphere using a wide range of approaches, we agree that the evidence that humans are damaging their ecological life support systems is overwhelming.

We further agree that, based on the best scientific information available, human quality of life will suffer substantial degradation by the year 2050 if we continue on our current path.

Science unequivocally demonstrates the human impacts of key concern:

- *Climate disruption* – more, faster climate change than since humans first became a species.
- *Extinctions* – not since the dinosaurs became extinct have so many species and populations died out so fast, both on land and in the oceans.
- *Wholesale loss of diverse ecosystems* – we have plowed, paved, or otherwise transformed more than 40% of Earth's ice-free land, and no place on land or in the sea is free of our direct or indirect influences.
- *Pollution* – environmental contaminants in the air, water and land are at record levels and increasing, seriously harming people and wildlife in unforeseen ways.
- *Human population growth and consumption patterns* – the population, which stands at 7 billion people alive today, will likely grow to 9.5 billion by 2050, and the pressures of heavy material consumption among the middle class and wealthy may well intensify.

By the time today's children reach middle age, it is extremely likely that Earth's life support systems, critical for human prosperity and existence, will be irretrievably damaged by the magnitude, global extent, and combination of these human-caused environmental stressors, *unless we take concrete, immediate actions to ensure a sustainable, high-quality future*.

As members of the scientific community actively involved in assessing the biological and societal impacts of global change, we are sounding this alarm to the world. For humanity's continued health and prosperity, we all – individuals, businesses, political leaders, religious leaders,

Figure 1. Many indicators suggest that Earth is poised at a critical transition, or 'tipping point', that may cause widespread disruptions in natural landscapes and societal functions we now take for granted.
Source: Cheng (Lily) Li.

scientists, and people in every walk of life – must work hard to solve these five global problems, starting today:

1. climate disruption
2. extinctions
3. loss of ecosystem diversity
4. pollution
5. human population growth and resource consumption

Purpose of this Consensus statement

Since about 1950, the world has been changing faster, and to a greater extent, than it has in the past 12,000 years. Balancing the positive changes against the negative ones will be the key challenge of the 21st century.

Positive change has included the Green Revolution, which reduced world hunger (although one in eight people still do not have enough to eat); new medical breakthroughs that have reduced infant and childhood mortality and allow people to live longer and more productive lives; access to myriad goods and services that increase wealth and comfort levels; and new technological breakthroughs, such as computers, cell phones, and the internet, that now connect billions of people throughout the world into a potential global brain.

In contrast, other changes, all interacting with each other, are leading humanity in dangerous directions: *climate disruption, extinction of biodiversity, wholesale loss of vast ecosystems, pollution*, and *ever-increasing numbers of people* competing for the planet's resources. Until now, these have often been viewed as 'necessary evils' for progress, or collateral damage that, while unfortunate, would not ultimately stand in the way of serving the needs of people.

Several recent comprehensive reports by the scientific community, however, have now shown otherwise. Rather than simply being inconveniences, the accelerating trends of climate disruption, extinction, ecosystem loss, pollution, and human population growth in fact are threatening the life support systems upon which we all depend for continuing the high quality of life that many people already enjoy and to which many others aspire.

The vast majority of scientists who study the interactions between people and the rest of the biosphere agree on a key conclusion: that the five interconnected dangerous trends listed above are having detrimental effects and, if continued, the already-apparent negative impacts on human quality of life will become much worse within a few decades. The multitude of sound scientific evidence to substantiate this has been summarized in many recent position papers and consensus statements (a few samples are listed at the end of the References section), and documented in thousands of articles in the peer-reviewed scientific literature. However, the position papers and consensus statements typically focus only on one or a subset of the five key issues (for example, climate change, or biodiversity loss, or pollution), and access to the peer-reviewed literature is often difficult for non-scientists. As a result, policy makers faced with making critical decisions can find it cumbersome both to locate the pertinent information and to digest the thousands of pages through which it is distributed.

Here we provide a summary intended to:

- be useful to policy makers and others who need to understand the most serious environmental-health issues that affect both local constituencies and the entire planet
- clearly voice the consensus of most scientists who study these issues that:
  - *climate disruption, extinction, ecosystem loss, pollution*, and *population growth* are serious threats to humanity's wellbeing and societal stability, and
  - these five major threats do not operate independently of each other.

We also outline broad-brush actions that, from a scientific perspective, will be required to mitigate the threats. The intent is to provide information that will be necessary and useful if the desire of the general public, governments, and businesses is to maximize the chance that the world of our children and grandchildren will be at least as good as the one in which we live now.

Overview of problems and broad-brush solutions

Climate disruption

Reduce effects of climate disruption by decreasing greenhouse gas emissions, and by implementing adaptation strategies to deal with the consequences of climate change already underway. Viable approaches include accelerating development and deployment of carbon-neutral energy technologies to replace fossil fuels; making buildings, transportation, manufacturing systems, and settlement patterns more energy-efficient; and conserving forests and regulating land conversion to maximize carbon sequestration. Adapting to the inevitable effects of climate change will be crucial for coastal areas threatened by sea-level rise; ensuring adequate water supplies to many major population centers; maintaining agricultural productivity; and managing biodiversity and ecosystem reserves.

Extinctions

Slow the very high extinction rates that are leading to a global loss of biodiversity. Viable approaches include assigning economic valuation to the ways natural ecosystems contribute to human wellbeing and managing all ecosystems, both in human-dominated regions and in regions far from direct human influence, to sustain and enhance biodiversity and ecosystem services. It will be critical to develop cross-jurisdictional cooperation to recognize and mitigate the interactions of global pressures (for example, climate change, ocean acidification) and local pressures (land transformation, overfishing, poaching endangered species, etc.).

Ecosystem transformation

Minimize transformation of Earth's remaining natural ecosystems into farms, suburbs, and other human constructs. Viable agricultural approaches include increasing efficiency in existing food-producing areas; improving food-distribution systems; and decreasing waste. Viable development approaches include enhancing urban landscapes to accommodate growth rather than encouraging suburban sprawl; siting infrastructure to minimize impacts on natural ecosystems; and investing in vital 'green infrastructure', such as through restoring wetlands, oyster reefs, and forests to secure water quality, flood control, and boost access to recreational benefits.

Pollution

Curb the manufacture and release of toxic substances into the environment. Viable approaches include using current science about the molecular mechanisms of toxicity and applying the precautionary principle (verification of no harmful effects) to guide regulation of existing chemicals and design of new ones. We have the knowledge and ability to develop a new generation of materials that are inherently far safer than what is available today.

Population growth and consumption

Bring world population growth to an end as early as possible and begin a gradual decline. An achievable target is no more than 8.5 billion people by 2050 and a peak population size of no more than 9 billion, which through natural demographic processes can decrease to less than 7 billion by 2100. Viable approaches include ensuring that everyone has access to education, economic opportunities, and healthcare, including family planning services, with a special focus on women's rights.

Decrease per-capita resource use, particularly in developed countries. Viable approaches include improving efficiency in production, acquisition, trade, and use of goods and promoting environmentally friendly changes in consumer behavior.

Planning for the future

Overall, we urge the use of the best science available to anticipate most-likely, worst-case, and best-case scenarios for 50 years into the future, in order to emplace policies that guide for environmental health over the long term as well as adapting to immediate crises.

Background information: Dangerous trends in our life support systems

People have basic needs for food, water, health, and a place to live, and additionally have to produce energy and other products from natural resources to maintain standards of living that each culture considers adequate. Fulfilling all of these needs for all people is not possible in the absence of a healthy, well-functioning global ecosystem. The 'global ecosystem' is basically the complex ways that all life forms on Earth – including us – interact with each other and with their physical environment (water, soil, air, and so on). The total of all those myriad interactions compose the planet's, and our, life support systems.

Humans have been an integral part of the global ecosystem since we first evolved; now we have become the dominant species in it. As such, we strongly influence how Earth's life support systems work, in both positive and negative ways. A key challenge in the coming decades is to ensure that the negative influences do not outweigh the positive ones, which would make the world a worse place to live. Robust scientific evidence confirms that five interconnected negative trends of major concern have emerged over the past several decades:

- *Disrupting the climate* that we and other species depend upon.
- *Triggering a mass extinction* of biodiversity.
- *Destroying diverse ecosystems* in ways that damage our basic life support systems.
- *Polluting our land, water, and air* with harmful contaminants that undermine basic biological processes, impose severe health costs, and undermine our ability to deal with other problems.
- *Increasing human population rapidly* while relying on old patterns of production and consumption.

These five trends interact with and exacerbate each other, such that the total impact becomes worse than the simple sum of their parts.

Ensuring a future for our children and grandchildren that is at least as desirable as the life we live now will require accepting that we have already inadvertently pushed the global ecosystem in dangerous directions, and that we have the knowledge and power to steer it back on course – if we act now. Waiting longer will only make it harder, if not impossible, to be successful, and will inflict substantial, escalating costs in both monetary terms and human suffering.

The following pages summarize the causes of each of the five dangerous trends, why their continuation will harm humanity, how they interact to magnify undesirable impacts, and broad-brush solutions necessary to move the human race toward a sustainable, enjoyable future.

Rising to the challenge

Defusing the five global crises summarized on the following pages will not be easy, but past experience demonstrates that problems of this huge scale are indeed solvable – if humanity is ready to rise to the challenge. Solutions will require the same things that worked successfully in dealing with past global crises: individual initiative, cooperation both within and across national boundaries, technological advances, and emplacing new infrastructure. Individual initiative has seldom been in short supply and continues to be a powerful human resource. Successful global-through-local cooperation resulted in ending World War II and rebuilding afterwards; banning use of nuclear weapons; dramatically increasing global food production with the Green Revolution and averting food crises through United Nations initiatives; greatly reducing the use of persistent toxic chemicals such as DDT; reversing stratospheric ozone depletion (the 'ozone hole'); and diminishing infectious diseases such as malaria and polio worldwide.

Likewise, past technological advances and the building of new infrastructure have been remarkable and commensurate in scale with what is needed to fix today's problems. For instance, in just 7 years, responding to the demands of World War II, the USA built its airplane fleet from about 3100 to 300,000 planes, and beginning in the 1950s, took less than 50 years to build 47,000 miles (75,639 km) of interstate highways – enough paved roads to encircle Earth almost twice. Over about the same time, 60% of the world's largest rivers were re-plumbed with dams. In about 30 years, the world went from typewriters and postage stamps to hand-held computers and the internet, now linking one-third of the world's population. During the same time we leapfrogged from about 310 million dial-up, landline phones to 6 *billion* mobile phones networked by satellites and presently connecting an estimated 3.2 billion people.

In the context of such past successes, the current problems of climate disruption, extinction, ecosystem loss, pollution, and growing human population and consumption are not too big to solve in the coming 30 to 50 years. Indeed, the scientific, technological, and entrepreneurial pieces are in place, and encouraging initiatives and agreements have begun to emerge at international, national, state, and local levels. Moreover, today's global connectivity is unprecedented in the history of the world, offering the new opportunity for most of the human population to learn of global problems and to help coordinate solutions.

Three key lessons emerge from the examples given above. The first is that global-scale problems must be acknowledged before they can be solved. The second is that fixing them is eminently possible through 'win-win' interactions between local communities, where solutions are actually developed and always emplaced, and higher levels of government, which define priorities backed by clear incentives. The third very important lesson is that big problems cannot be fixed overnight. Given inherent lag times in changing climate, building infrastructure, changing societal norms, and slowing population growth, actions taken today will only begin to bear full fruit in a few decades. If, for example, we move most of the way towards a carbon-neutral energy system by 2035, climate still will not stabilize before 2100, and it will still be a different climate than we are used to now. But, if we delay action to 2035, not only will climate disruption continue to worsen, but efforts at mitigation and adaptation will cost dramatically more; climate would not stabilize until well after the year 2100, and when it did, it would be at an average climate state that is far more disruptive to society than would have been the case if we had acted earlier. Similar costs of delay accrue for the other problems as well; indeed, delaying action on those problems will lead to irretrievable losses of species, ecosystems, and human health and prosperity. Starting *today* to diffuse the global crises we now face is therefore crucial.

Climate disruption

It is now clear that people are changing Earth's climate by adding greenhouse gases to the atmosphere primarily through the burning of coal, oil (and its by-products such as gasoline,

Figure 2. The main greenhouse gases emitted by human activities are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (NO). Of these, CO_2 is particularly important because of its abundance. Human-produced ozone-forming chemicals also are contributing to climate change.
Source: AD Barnosky.

diesel, etc.), and natural gas (Figure 2). The overall trend, still continuing, has been to raise the average temperature of the planet over the course of the last century, and especially the last 60 years. Raising average global temperature causes local changes in temperature, in amount and timing of rainfall and snowfall, in length and character of seasons, and in the frequency of extreme storms, floods, droughts, and wildfires (IPCC, 2007, 2012). Sea-level rise is a particular concern in coastal areas (IPCC, 2007, 2012; Pfeffer et al., 2008; Rahmstorf, 2007). Such impacts directly influence the wellbeing of people through damaging their livelihoods, property, and health, and indirectly through increasing potentials for societal conflict. Recent examples include the flooding from superstorm Sandy on the east coast of the USA, record wildfires and drought throughout the western USA and Australia, heat waves and drought in Europe, and floods in Pakistan, all of which occurred in 2012 and 2013.

Causes for concern

Even best-case emissions scenarios (the IPCC B1 scenario) (IPCC, 2007) project that Earth will be hotter than the human species has ever seen by the year 2070, possibly sooner (Barnosky et al., 2012; IPCC, 2007). Continuing current emission trends (PriceWaterhouseCoopersLLP, 2012) would, by the time today's children grow up and have grandchildren (the year 2100), likely cause average global temperature to rise between 4.3°F and 11.5°F (2.4–6.4°C), with a best estimate being 7.2°F (4°C) (IPCC, 2007). The last time average global temperature was 7.2°F hotter was some 14 million years ago. The last time it was 11.5°F hotter was about 38 million years ago (Zachos et al., 2008). [Note: The IPCC AR5 report was released after this document was written; its RCP 8.5 scenario suggests a mean warming of 6.7°F (3.7°C) by 2100, with a likely range of 4.7–8.6°F (2.6–4.8°C) (IPCC, 2013)].

Impacts that would be detrimental to humanity by 2100, if not before, should greenhouse gas emissions continue at their present pace, include the following.

- *Longer and more intense heat waves*. The 1-in-20 year hottest day is likely to become a 1-in-2 year event by the end of the 21st century in most regions (for the IPCC B1, A1B, and A2 emissions scenarios; IPCC, 2012). Such effects already are being observed – in 2013, temperatures in Australia rose so much that weather maps had to add two new colors to express the new hot extremes. Some models indicate that the current trajectory of warming, if continued to the year 2100, would cause some areas where people now live to be too hot for humans to survive (Sherwood and Huber, 2010). (Note: The term 'likely' in this context implies that there is a 66–100% chance of the effect occurring. Usage here follows definitions explained in IPCC publications.)
- *More frequent damaging storms*. The 1-in-20 year annual maximum daily precipitation amount is likely to become a 1-in-5 to1-in-15 year event by the end of the 21st century in many regions (IPCC, 2012). Cyclone wind speeds are likely to increase. Cities would experience the extent of damage caused by superstorm Sandy on a more frequent basis.
- *Major damage to coastal cities as sea level rises*. The extent of sea-level rise will depend in part on how fast glaciers melt. Low-end projections (IPCC, 2007) call for a rise in sea level of 0.6–1.9 feet (0.18–0.59 m) by 2100; high-end projections suggest seas rising as high as 2.6–13.1 feet (0.8–4.0 m) (Pfeffer et al., 2008; Rahmstorf, 2007; Solomon et al., 2011). Raising sea level to even the lower estimates would flood large parts of major cities worldwide and force the permanent resettlement of millions of people; about 100 million people now live less than 3.3 feet (1 m) above mean sea level (Dow and Downing, 2007).
- *Water shortages in populous parts of the world*. Cities and farmlands that rely on the seasonal accumulation of snow pack and slow spring melt, arid regions that apportion water from major rivers, and regions that depend on water from glacier melt all are at risk (Dow and Downing, 2007).
- *Local reduction of crop yields*. New climate patterns will change which crops can be grown in which areas. Some regions are projected to experience overall declines: for instance, cereal crop production is expected to fall in areas that now have the highest population density and/or the most undernourished people, notably most of Africa and India (Dow and Downing, 2007). Key crop-growing areas, such as California, which provides half of the

fruits, nuts, and vegetables for the USA, will experience uneven effects across crops, requiring farmers to adapt rapidly to changing what they plant (Kahrl and Roland-Holst, 2012; Lobell et al., 2006).

- *Economic losses, social strife and political unrest*. Damage to coastal areas, flooding of ports, water shortages, adverse weather and shifts in crop-growing areas, creation of new shipping lanes, and competition for newly accessible arctic resources all will complicate national and international relations, and cost billions of dollars (Lobell et al., 2006; Shearer, 2005; Solomon et al., 2011; Steinbruner et al., 2012). For instance, the *New York Times* reported that by the first months of 2013, United States taxpayers had already paid US$7 billion to subsidize farmers for crops that failed because of extreme drought, and that figure was anticipated to rise as high as US$16 billion.
- *Spread of infectious disease*. As temperate regions warm, costly and debilitating mosquito-borne diseases such as malaria are expected to increase in both developed and developing nations (World Health Organization (WHO), 2013a). Indeed, expansion of West Nile virus into the USA beginning in 1999 has already occurred, and bluetongue virus, a costly livestock disease carried by midges, has expanded northward into central and northern Europe in the past decade. Besides human suffering, the human-health costs caused by climate change are anticipated to be US$2–4 billion per year by 2030 (WHO, 2013a).
- *Pest expansions that cause severe ecological and economic losses.* For example, over the past two decades, millions of acres of western North American forests have been killed by pine beetles whose populations have exploded as a result of warmer winter temperatures – previously, extreme winter cold prevented abundant beetle survival (Kurz et al., 2008). The beetle kill reduces wood production and sales, and lowers property values in developed areas.
- *Major damage to unique ecosystems*. Warming and acidification of ocean water is expected to destroy a large portion of the world's coral reefs, essentially the 'rainforests of the sea', so-called because they host most of the oceans' biodiversity (Morel et al., 2010; Solomon et al., 2011). On land, forests worldwide face drought-induced decline, both in dry and wet regions (Choat et al., 2012). This is especially problematic in many tropical and subtropical forests (Salazar et al., 2007), which are the cradles of most terrestrial biodiversity.
- *Extinction of species*. Currently at least 20–40% of assessed species – amounting to a minimum of 12,000–24,000 species – are possibly at increased risk of extinction if mean global temperature increases 2.7–4.5°F (1.5–2.5°C) (Dow and Downing, 2007; IPCC, 2007). Current emissions trends are on track for a 7.2°F (4°C) rise in global mean temperature by 2100, which would put many more species at risk (Solomon et al., 2011). The situation with population extinctions is much worse, with much higher extinction rates in the basic unit of biodiversity that supplies ecosystem services (Hughes et al., 1997).

Solutions

Avoiding the worst impacts of human-caused climate change will require reducing emissions of greenhouse gases substantially (PriceWaterhouseCoopersLLP, 2012; Solomon et al., 2011) and quickly (Rogelj et al., 2012). For instance, in order to stabilize atmospheric concentrations of CO_2 at 450 parts per million by the year 2050, which would give a 50% chance of holding global temperature rise to 2°C, emissions would have to be decreased 5.1% per year for the next 38 years. This rate of reduction has not been achieved in any year in the past six decades, which puts the magnitude and urgency of the task in perspective (PriceWaterhouseCoopersLLP, 2012).

> The world needs another industrial revolution in which our sources of energy are affordable, accessible and sustainable. Energy efficiency and conservation, as well as decarbonizing our energy sources, are essential to this revolution. (Chu and Majumdar, 2012)

However, reducing emissions to requisite values over the next 50 years appears possible through coordinated innovation and deployment of new transportation and energy systems, which can be accomplished largely with existing technology (Chu and Majumdar, 2012; Davis et al., 2013; Jacobson and Delucchi, 2009, 2011). This will require rapid scaling up of carbon-neutral energy production (solar, wind, hydro, geothermal, hydrogen fuel-cells, nuclear, microbe-based biofuels) to replace energy production from fossil fuels. In the transitional decades when fossil fuels will continue to be in widespread use, increased efficiency in energy use (better gas mileage for cars and trucks, more energy-efficient buildings, etc.) will be necessary, as will phasing out coal-fired power plants in favor of lower-emissions facilities (natural gas). While fossil fuels remain in use during the transitional period, carbon capture and storage (CCS) from major emitters such as cement and steel plants will probably be necessary. Scaling up carbon-neutral energy production fast enough will likely require legislation and government policies designed to stimulate the right kinds of innovations and realign the economic landscape for energy production (Chu and Majumdar, 2012; Delucchi and Jacobson, 2011).

Some effects of climate change already are underway (sea-level rise, higher frequency of extreme weather, etc.). Plans to adapt to unavoidable climate changes will need to be developed and implemented for cities and public lands. Keeping agricultural areas productive will require changing the crops grown in some places, and ensuring seed stocks that are adapted to new climates. Ultimate monetary costs for climate mitigation and adaptation grow substantially each year action is postponed (Kahrl and Roland-Holst, 2012; Rogelj et al., 2012).

Extinctions

Biological extinctions cannot be reversed and therefore are a particularly destructive kind of global change. Even the most conservative analyses indicate that human-caused extinction of other species is now proceeding at rates that are 3–80 times faster than the extinction rate that prevailed before people were abundant on Earth (Barnosky et al., 2011), and other estimates are much higher (Pimm and Raven, 2000; Pimm et al., 1995, 2006; World Resources Institute (WRI), 2005). If the current rate of extinction is not slowed for species and their constituent populations, then within as little as three centuries the world would see the loss of 75% of vertebrate species (mammals, birds, reptiles, amphibians, and fish), as well as loss of many species of other kinds of animals and plants (Barnosky et al., 2011). Earth has not seen that magnitude of extinction since an asteroid hit the planet 65 million years ago, killing the dinosaurs and many other species. Only five times in the 540 million years since complex life forms dominated Earth have mass extinctions occurred at the scale of what current extinction rates would produce; those mass extinctions killed an estimated 75–96% of the species known to be living at the time.

Currently, sound scientific criteria document that at least 23,000 species are threatened with extinction, including 22% of mammal species, 14% of birds, 29% of evaluated reptiles, as many as 43% of amphibians, 29% of evaluated fish, 26% of evaluated invertebrate animals, and 23% of plants (Collen et al., 2012; GBO3, 2010; International Union for Conservation of Nature (IUCN), 2010). Populations – groups of interacting individuals that are the building blocks of species – are dying off at an even faster rate than species. The extinction of local populations, in fact, represents the strongest pulse of contemporary biological extinction. For example, since 1970 some 30% of all vertebrate populations have died out (McRae et al., 2012), and most species have experienced loss of connectivity between populations because of human-caused habitat fragmentation. Healthy species are composed of many, interconnected populations; rapid population loss, and loss of connectivity between populations, are thus early warning signs of eventual species extinction.

Causes for concern

The world's plants, animals, fungi, and microbes are the working parts of Earth's life support systems. Losing them imposes direct economic losses, lessens the effectiveness of nature to serve our needs ('ecosystem services', see below), and carries significant emotional and moral costs.

- *Economic losses.* At least 40% of the world's economy and 80% of the needs of the poor are derived from biological resources (Dow and Downing, 2007). In the USA, for example, commercial fisheries, some of which rely on species in which the majority of populations have already gone extinct, provide approximately one million jobs and US$32 billion in income annually (National Oceanic and Atmospheric Administration (NOAA), 2013b). Internationally, ecotourism, driven largely by the opportunity to view currently threatened species such as elephants, lions, and cheetahs, supplies 14% of Kenya's GDP (in 2013) (United States Agency for International Development (USAID), 2013) and 13% of Tanzania's (in 2001), and in the Galapagos Islands, ecotourism contributed 68% of the 78% growth in GDP that took place from 1999 to 2005 (Taylor et al., 2008). Local economies in the USA also rely on revenues generated by ecotourism linked to wildlife resources: for example, in the year 2010 visitors to Yellowstone National Park, which attracts a substantial number of tourists lured by the prospect of seeing wolves and grizzly bears, generated US$334 million and created more than 4800 jobs for the surrounding communities (Stynes, 2011). In 2009, visitors to Yosemite National Park created 4597 jobs in the area, and generated US$408 million in sales revenues, US$130 million in labor income, and US$226 million in value added (Cook, 2011).
- *Loss of basic services in many communities*. Around the world, indigenous and rural communities depend on the populations of more than 25,000 species for food, medicine, and shelter (Dirzo and Raven, 2003).
- *Loss of ecosystem services*. Extinctions irreversibly decrease biodiversity, which in turn directly costs society through loss of ecosystem services (Cardinale et al., 2012; Daily et al., 2000; Ehrlich et al., 2012). 'Ecosystem services' (see the quote below) are attributes of ecological systems that serve people. Among the ecosystem services that support human life and endeavors are: moderating weather; regulating the water cycle, stabilizing water supplies; filtering drinking water; protecting agricultural soils and replenishing their nutrients; disposing of wastes; pollinating crops and wild plants; providing food from wild species (especially seafood); stabilizing fisheries; providing medicines and pharmaceuticals; controlling spread of pathogens; and helping to reduce greenhouse gases in the atmosphere . In contrast to such directly quantifiable benefits promoted by high biodiversity, reducing biodiversity generally reduces the productivity of ecosystems, reduces their stability, and makes them prone to rapidly changing in ways that are clearly detrimental to humanity (Cardinale et al., 2012). For example, among other costs, the loss of tropical biodiversity from deforestation often changes local or regional climate, leading to more frequent floods and droughts and declining productivity of local agricultural systems. Tropical deforestation can also cause new diseases to emerge in humans, because people more often encounter and disrupt animal vectors of disease (Patz et al., 2004; Quammen, 2012).

The world's ecosystems are *Natural Capital* that provides vital benefits called *Ecosystem Services* necessary for *Production of Goods* (crops, timber, seafood); *Life-Support Systems* (provision and purification of water, buffering against storms, floods, and droughts); *Life-Fulfilling Amenities* (beauty, opportunity for recreation, and the associated physical and mental health benefits); and *Options* for the future (genetic diversity for use in agriculture, energy, pharmaceuticals and other industries). Modified from Daily et al., (2000)

- *Intangible values.* Continuing extinction at the present pace would considerably degrade quality of life for hundreds of millions of people who find emotional and aesthetic value in the presence of iconic species in natural habitats. In this context species are priceless, in the sense of being infinitely valuable. An apt metaphor is a Rembrandt or other unique work of art that evokes exceptional human feelings, and whose loss would be generally recognized as making humanity poorer.

Chief drivers of extinction

The main drivers of human-caused extinction as follows (Barnosky et al., 2011; GBO3, 2010; Pimm and Raven, 2000; Pimm et al., 1995; Vié et al., 2009; WRI, 2005) (Figure 3).

- *Habitat destruction from ecosystem transformation.* Such practices as unsustainable forestry and conversion of land to agriculture, suburban sprawl, and roads, all cause both habitat destruction and habitat fragmentation. In particular, logging and clearing of tropical rainforests for ranching or farming permanently destroys the habitats for vast numbers of species. Such areas are among the most important reservoirs of terrestrial biodiversity, harboring thousands of unique species and plant and animal functional groups (ecological niches) found

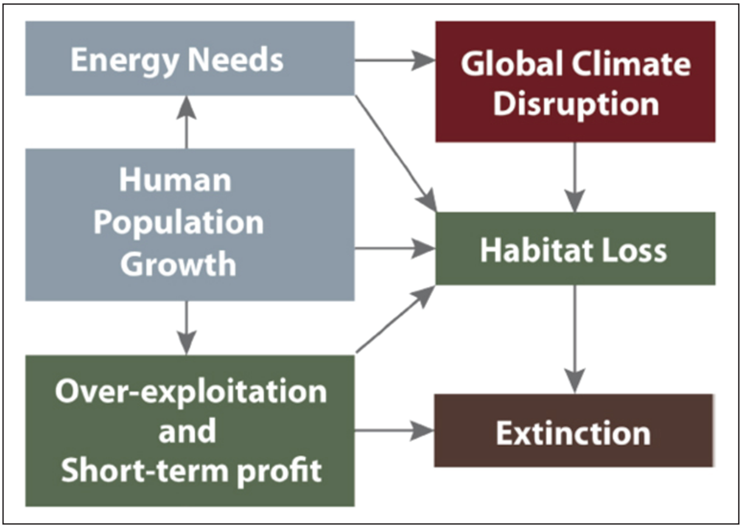

Figure 3. Extinction rates are now too high because old models of natural resource use are no longer sustainable. Supplying 7 billion people (9.5 billion by 2050) with a high quality of life requires investing in nature's capital, rather than spending down its principal.

Figure 4. If current rates of elephant poaching continue, there would be no more wild elephants on Earth within 20–30 years. (This assumes continuation of the annual rate of about 25,000 elephants killed in 2011, and a world population of between 420,000 and 650,000 African elephants plus about 50,000 Asian elephants (IUCN, 2008).) The bulk of the short-term profits go to organized crime and terrorist groups. In contrast, revenues from ecotourism are sustainable for the long run and contribute directly to local economies.
Source: AD Barnosky.

nowhere else (Dirzo and Raven, 2003). In the oceans, habitat destruction and fragmentation results from pollution, trawling, shipping traffic, and shipping noise (sonar, etc.).

- *Environmental Contamination*. Environmental contamination from human-made chemicals contributes to extinction pressures by destroying habitats (for instance, mine dumps, oil spills and agricultural runoff), by direct toxic effects of pollutants, and through subtle effects on animals' immune and reproductive systems.
- *Climate change*. Extinctions result when species cannot move fast enough to find climatic refuges as the climate becomes unsuitable where they now live; when climate changes such that it exceeds their physiological, developmental, or evolutionary tolerances; or when critical species interactions (the way one species depends on the next) are disrupted (Cahill et al., 2012). On land, models predict that by the year 2100, between 12% and 39% of the planet will have developed climates that no living species has ever experienced, and conversely, the climate that many species currently live in will disappear from 10% to 48% of Earth's surface (Williams et al., 2007). These changes will be most pronounced in areas that currently harbor most of the world's biodiversity. In the oceans, acidification, a by-product of climate change that disrupts growth and development of marine organisms, is of particular concern, because it prevents marine shelly animals such as clams and oysters from building their shell, and causes collapse of the physical reef infrastructure on which most marine species ultimately depend.
- *Intensive exploitation of wild species for profit.* Some iconic species, such as elephants (Figure 4), rhinoceroses, and tigers are being hunted to extinction to sell their tusks, horns, or other body parts to be made into curios or for purported health products. For example, the demand for ivory from elephant tusks, primarily from Asian markets, has driven the price high enough that elephant poaching has now become a lucrative source of income for international crime rings and terrorist organizations. Other species are being overutilized as marketable food – this is especially a problem for many ocean fisheries, such as those for

> Bluefin tuna and Atlantic cod. Demand is outstripping supply for such species – there are now seven times as many humans on the planet as there are wild salmon (Greenburg, 2011). In the same vein, the dramatic and rapid clearing of rainforests is motivated by immediate economic yield. In all of these cases, the one-time gain in profit (which benefits relatively few people) is a pittance compared with the loss of natural capital, which supplies important benefits locally and globally for the long term. In economic terms, it is analogous to spend down the principal of an investment rather than living off the interest.

> Many actions in support of biodiversity have had significant and measurable results in particular areas and amongst targeted species and ecosystems. This suggests that with adequate resources and political will, the tools exist for loss of biodiversity to be reduced at wider scales. (GBO3, 2010)

Solutions

Because species losses accrue from global pressures, and species and ecosystem distributions transcend political boundaries, solutions to the extinction crisis require coordination between local actions, national laws, and international agreements, as well as strict enforcement of policies (CBD, 2011; GBO3, 2010). Such a multi-jurisdictional approach is essential to prevent illegal trafficking in wildlife products; enhance protection of species in public reserves; and develop effective policies to ensure sustainable fisheries (GBO3, 2010). Management plans for individual species, as well as for public lands and marine protected areas, will need to include adaptation to climate change (Barnosky et al., 2011, 2012; GBO3, 2010; McLachlan and Hellmann, 2007; Solomon et al., 2011). Assessment of species risks will need to be accelerated (IUCN, 2010), particularly for invertebrate species (Collen et al., 2012) and fish.

In addition, it will be necessary to address the root causes of climate change and unnecessary ecosystem transformation (see those sections of this consensus statement). An important part of the solution will be economic valuation of natural capital and ecosystem services, such that global, regional, and local economies account for the benefits of banking natural capital for the long run, rather than irretrievably depleting finite species resources for short-term economic gain (Daily and Ellison, 2002; Ehrlich et al., 2012). Workable examples already exist in China, where 120 million farmers are being paid to farm in ways that not only yield crops and timber but also stabilize steep slopes, control floods, and maintain biodiversity (Ehrlich et al., 2012); in Costa Rica (Daily et al., 2000), where a national payment system for ecosystem services has helped to change deforestation rates from among the highest in the world to among the lowest; and in New York City, where maintaining natural landscapes for water filtration is more economical than building filtration plants (Daily and Ellison, 2002).

Ecosystem transformation

As humans have become more abundant, we have transformed large parts of the Earth’s surface from their pre-human ‘natural’ state into entirely different landscapes and seascapes (Vitousek et al., 1997b). Some of these transformations have been necessary to support basic human needs; others have been inadvertent and unanticipated.

As of 2012, somewhat more than 41% of Earth’s ice-free lands (36% of total land surface) have been commandeered for farms, ranches, logging, cities, suburbs, roads, and other human constructs (Foley et al., 2005, 2011; Vitousek et al., 1986) (Figure 5). This equates to an average of a little less than 2 acres of transformed land for each person on Earth. Conversion for agriculture accounts for

Figure 5. Almost half of Earth's ice-free land has already been changed completely by human activities. Nowhere on the land or in the sea is completely free of human influence.
Source: AD Barnosky.

most of the landscape change, with crops covering about 12% and pastureland about 26% of ice-free land (the percentages are about 10% and 22%, respectively, for the proportion of all Earth's land). Urban lands account for another 3%. On top of that are vast road networks that fragment habitats across some 50% of the entire land surface, dams that modify water flow in more than 60% of the world's large rivers and in many smaller ones (WWF, 2012), and continuing deforestation that has been proceeding at the rate of about 30,000 km^2 (= 11,000 square miles) per year for the past 16 years (FAO, 2012b). This per-year loss is roughly the equivalent of clear-cutting the entire country of Belgium or, in the USA, the states of Massachusetts or Hawaii in one year.

Measuring the percentage of the oceans that have been transformed is much more challenging, but it is clear that pollution, trawling, and ship traffic and noise have caused major changes along most of the world's coastlines (Jackson, 2008; Jackson et al., 2001). For example, bottom trawling alone has been estimated to annually destroy an area of seabed equivalent to twice the area of the continental USA (Hoekstra et al., 2010). Human debris, particularly plastics, also is ubiquitous in ocean waters, even far offshore (NOAA, 2013a).

The human footprint extends even outside of the ecosystems that have been transformed wholesale by people. Nearly every terrestrial ecosystem in the world now integrates at least a few species that ultimately were introduced by human activities (Ellis, 2011; Ellis et al., 2012; Vitousek et al., 1997a), sometimes with devastating losses in ecosystem services (Pejchar and Mooney, 2009), and invasive species now number in the hundreds in most major marine ports (Bax et al., 2003; Cohen and Carlton, 1998) and in the thousands on most continents (DAISIE, 2012; Thuilier, 2012; Vitousek et al., 1997a). All told, 83% of the entire land surface exhibits human impact defined as influenced by at least one of the following factors: human population density greater than 1 person/km^2 (= 1 person/0.4 square miles, or 247 acres); agricultural activity; built-up areas or settlements;

being within 15 km (9.3 miles) of a road or coastline; or nighttime light bright enough to be detected by satellites (Ewing et al., 2010; Sanderson et al., 2002). Adding in the effect of climate change, every place on Earth exhibits at least some human impact, even the most remote parts of the land and oceans (Halpern et al., 2008).

Causes for concern

There are two conflicting concerns with respect to ecosystem transformation.

- *The need to minimize the human footprint to prevent extinction of other species and degradation of essential ecosystem services.* Ecological 'tipping points', where whole ecosystems change suddenly and unexpectedly to become less biodiverse and in many cases less productive (Scheffer et al., 2009), are known to be triggered by transforming threshold percentages of their areas. Many studies document that when 50% to 90% of patches within a landscape are disturbed, the remaining undisturbed patches undergo rapid, irreversible changes as well (Barnosky et al., 2012; Bascompte and Solé, 1996; Noss et al., 2012; Pardini et al., 2010; Swift and Hannon, 2010). Therefore, wholesale ecological transformation of more than half of Earth's ecosystems by direct human impacts is prone to trigger unanticipated, irreversible degradation even in ecosystems that are not directly utilized by humans. Such changes already are becoming evident in nitrogen deposition in remote arctic lakes (Holtgrieve et al., 2011), by dwindling populations of once-common species in some nature reserves (McMenamin et al., 2008), by millions of acres of beetle-killed forests (Kurz et al., 2008), and by invasive species such as zebra mussels (Pejchar and Mooney, 2009; Vitousek et al., 1997a).
- *The need to feed, house, and provide acceptably high standards of living* for the 7 billion people that are now on the planet plus 2.5 billion more that probably will be added over the next three decades (PRB, 2012; UNDESA, 2011) means that the demands for land use will accelerate (see the 'Population growth' section for more details on this). Nearly 70% of the arable land that has not yet been converted to agricultural use is in tropical grasslands and forests, which include some of the world's most important biodiversity reservoirs and so far are among the lands least impacted by humans (Hoekstra et al., 2010). Farming less arable lands would take even more acres per person than at present, because of lower productivity per acre (Ehrlich and Ehrlich, 2013).

> Cities, regions, or countries that are not able to provide a high quality of life on a low [Ecological] Footprint will be at a disadvantage in a resource-constrained future. (Ewing et al., 2010)

Solutions

Because food production is the chief transformer of natural ecosystems, a key challenge will be feeding more people without significantly adding to the existing agricultural and fisheries footprint. Valuing natural capital (as explained above in the 'Extinctions' section) is a promising approach that can lead to significant gains in both biodiversity and crop yields; for instance, as has been shown by integrating coffee farms with natural landscapes in Costa Rica (Ricketts et al., 2004). Slowing and ultimately stopping the encroachment of agriculture into currently uncultivated areas (especially the few remaining tropical rainforests and savannahs) will probably require regulatory policies and incentives for conservation. Recent studies indicate that even without

Figure 6. The brown haze of air pollution is pernicious in and around many cities, and causes at up to 6 million deaths each year. Pictured is the smog accumulating south of San Francisco, California, on a cool winter day.
Source: EA Hadly.

increasing the agricultural footprint, it is feasible to increase food production adequately in an environmentally sound way through (Ausubel et al., 2012; Foley et al., 2011): (a) improving yields in the world's currently less productive farmlands; (b) more efficiently using the water, energy, and fertilizer necessary to increase yields; (c) eating less meat; and (d) reducing food waste through better infrastructure, distribution, and more efficient consumption patterns – some 30% of the food currently produced is discarded or spoiled. Adapting crop strains to changing climate will also be required to maximize yields (Lobell et al., 2008; Walthall et al., 2012). In the oceans, solutions lie in enhanced fisheries management; sustainable aquaculture that focuses on species for which farming does not consume more protein than is produced; and reduction of pollution, especially along coasts (Naylor et al., 2000, 2009).

It will be necessary to avoid losing more land to suburban sprawl through emphasizing development plans that provide higher-density housing and more efficient infrastructure in existing built-up areas, rather than carving new communities wholesale out of less disturbed surrounding lands.

Climate change will affect all places on the planet – those that are currently little impacted by humanity, as well as those now intensively used for agriculture or cities and towns – and the effects will be more pronounced with greater amounts of warming. Avoiding global ecosystem transformation will therefore also require keeping climate change to a minimum.

Pollution

There are few, if any places on Earth where human-produced environmental contaminants are not being deposited. Traces of pesticides and industrial pollutants are routinely found in samples of soil or tree bark from virtually any forest in the world, in the blubber of whales, in polar bear body tissues, in fish from most rivers and oceans, and in the umbilical cords of newborn babies (Dodds, 2008; Hoekstra et al., 2010). Smog in many cities is far above levels considered safe (WHO, 2011) (Figure 6). In the worst cases – such as in Beijing during January 2013 – polluted air can be seen from space. Other air pollutants, such as greenhouse gases and ozone, are invisible but cause serious global-scale problems, notably climate disruption. Oil spills routinely contaminate oceans and coastlines, as well as inland waters and land areas. Nuclear waste, and especially radioactive contamination from accidents at nuclear plants, is a growing problem, as is the ubiquity of hormone-disrupting or cancer-causing chemicals such as bisphenol-A (commonly known as BPA) (Guillette and Iguchi, 2012). Activities such as mining, manufacturing, and recycling of electronic equipment have not only concentrated dangerous pollutants locally, but also distributed them worldwide, notably harmful substances such as lead, chromium, mercury, and asbestos (Qiu, 2013; Staff, Blacksmith Institute, 2012).

Causes for concern

- *Health impacts.* The health costs of pollution are enormous. At least 125 million people are now at direct risk from toxic wastes produced by mining and manufacturing (Staff, Blacksmith Institute, 2012). As of 2010 air pollution caused up to 6 million premature deaths per year (Lim et al., 2012; WHO, 2011). Environmental exposures are thought to contribute to 19% of cancer incidence worldwide (Staff, Blacksmith Institute, 2012). Millions of people drink groundwater contaminated with cancer-causing arsenic or harmful microbes (Fendorf et al., 2010). All total, as of 2010, the number of years lost through illness, disability or early death (disability-adjusted life years, or DALYS) from environmental hazards is probably greater than those lost to malaria, tuberculosis, and HIV/AIDS combined (Lim et al., 2012). An emerging concern is the effect of hormone-simulating chemicals, such as endocrine disruptors, which may be affecting human growth, development, and health on a large scale. For instance, endocrine disruptors have been linked to earlier onset of puberty and obesity (Guillette and Iguchi, 2012). The latter also leads to increased incidence of heart disease and type II diabetes (Newbold et al., 2009).
- *Dead zones*. Excess nitrogen from farm fertilizers, sewage plants, livestock pens, and coal plants eventually ends up in waterways and makes its way to the oceans, where it stimulates prodigious algal growth. Decay of the dead algae then sucks all the oxygen out of the water (Dodds, 2008; Hoekstra et al., 2010). The result is a dead zone where marine life is greatly reduced. Most coasts of the world now exhibit elevated nitrogen flow, with large dead zones occurring near major population centers (Diaz and Rosenberg, 2008; NASA, 2010) (Figure 7).
- *Environmental devastation.* Greenhouse gas pollutants – primarily human-produced carbon dioxide (CO_2), nitrous oxide (NO), and methane (CH_4) – are the causes of one of the biggest environmental problems, climate disruption (IPCC, 2007). Herbicides, pesticides, and various chemicals used in plastic production contaminate many waterways directly, and then are taken up by organisms and bioamplified through food chains. Virtually all human beings on Earth carry a burden of these persistent chemicals, many of which are endocrine disruptors. Pharmaceuticals meant for humans or livestock, and subsequently flushed into drains or otherwise finding their way into rivers and lakes, disrupt growth and development of amphibians and fish. Sewage and excess fertilizer contribute significantly to damaging more than half of the world's coral reefs, and in some ecoregions, up to 90% of reefs (Dodds, 2008; Hoekstra et al., 2010).

Solutions

The pollution problem is not a new one. The sources of environmental contamination generally are well known, especially for the worst sources, such as lead-battery recycling, lead smelting, mining and ore processing, tannery operations, municipal and industrial dumpsites, product manufacturing, chemical manufacturing, petrochemical industry, electronic waste, agricultural pesticides and excess

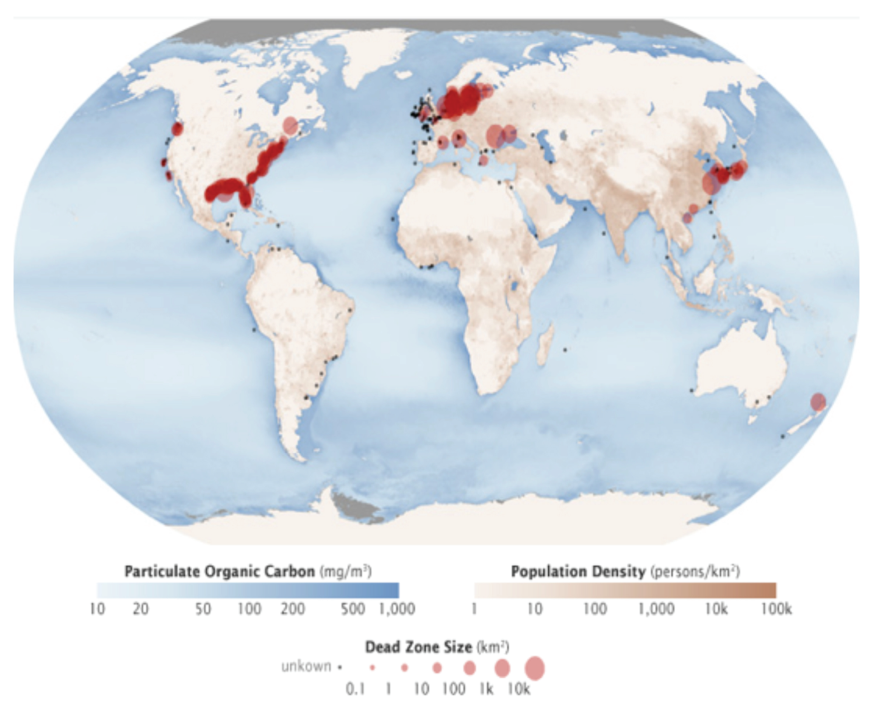

Figure 7. World distribution of dead zones in the ocean caused primarily by nitrogen pollution.
Source: NASA (2010).

fertilizers, and greenhouse gases (Dodds, 2008; Hoekstra et al., 2010; Staff, Blacksmith Institute, 2012). Viable prevention and cleanup solutions are available for most pollutants, but are often not employed because of cost. Significant reductions in pollution from manufacturing can be found in better regulation and oversight of industries using and producing hazardous wastes; better industry practices in controlling hazardous wastes and substances; educating local communities and hazardous industries in adverse effects of pollutants; enhancement of technology for management and treatment of pollutants; and minimizing location of potentially hazardous industries near population centers. Reducing air pollution (including greenhouse gases) requires phasing out coal-fired power plants and high-emissions vehicles immediately, and over time replacing fossil-fuel sources of energy with clean energy. Minimizing agricultural pollution requires maximizing efficiency in application of fertilizers, pesticides, and antibiotics.

Even more promising than these traditional approaches is to use our current scientific understanding of the mechanisms of toxicity to guide synthetic chemistry toward a new generation of inherently safer materials. This is now eminently feasible, and it promises to reward entrepreneurs who adopt these green chemistry approaches in the market (Schug et al., 2013).

Population growth and resource consumption

There are two aspects to the population problem. One is how many people are on Earth (Figure 8). The other is the wide disparity in the ‘ecological footprint’ among different countries and societal

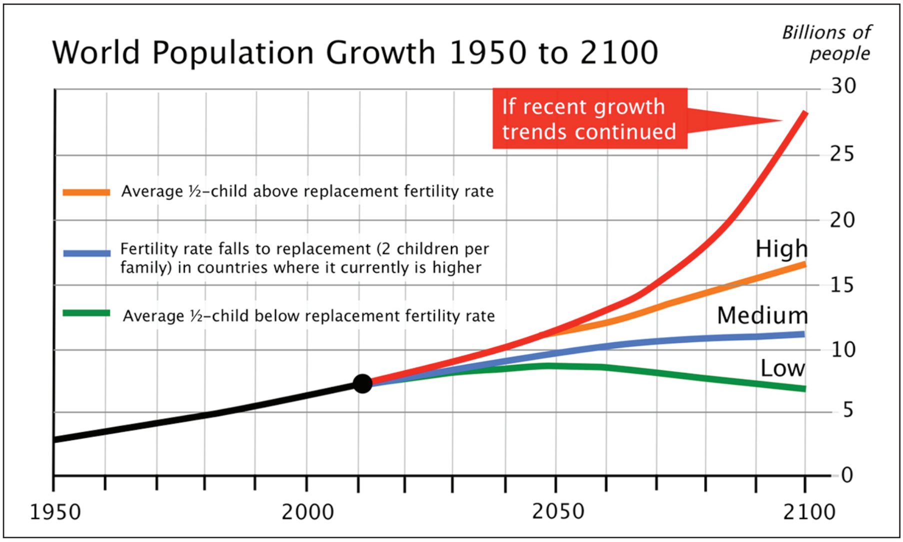

Figure 8. If the fertility rate in all countries rapidly changes so each family on average has one daughter, population will crest by 2050, then stabilize around 10.1 billion.
Source: Data from UNDESA (2011).

sectors, with a relatively small proportion of humanity inefficiently using and impacting an inordinately large proportion of ecological resources (Figure 9).

Today there are more than 7 billion people on the planet. Demographic projections of population growth indicate that some 2.5 billion more people may be added to the world population by 2050 (PRB, 2012; UNDESA, 2011), when today's children will be reaching middle age (see the population growth chart, Figure 8). How population actually changes in coming decades depends largely on what happens to fertility rates (the average number of children born per woman in the population in her lifetime), as well as mortality rates. If the global average fertility rate stayed at its present level, there could be 27 billion people on Earth in the year 2100, but that is extremely unlikely. If fertility changed worldwide to 'replacement rate' (in which parents just 'replaced' themselves in the next generation – about 2.1 children per woman) and mortality rates were those typical of developed countries, then there would be 10.1 billion people in 2100. With a global average fertility rate of ½ child above replacement rate, the population would reach 15.8 billion in 2100, and a rate of ½ child below replacement would lead to an early peak in population size and a decline to about 6.2 billion people by 2100.

There are very wide differences in fertility between countries today. At the low end, rates are just 1.2 or 1.3 in several developed countries, including Latvia, Portugal, South Korea, and Singapore. Some countries with slightly higher fertility rates now show declining rates, including Russia, Germany, and Japan. Virtually all developed countries and a number of developing countries, including China, Brazil, and Thailand, now have below-replacement fertility, and their populations are on track to stop growing within a few decades at most. By contrast, many very poor developing countries still have fertility rates as high as six or more children per family: e.g. Zambia, Somalia, Burundi, and Afghanistan, among others. It is the high fertility in these regions that may keep the world population growing for a century more unless population policies lower their fertility sooner rather than later.

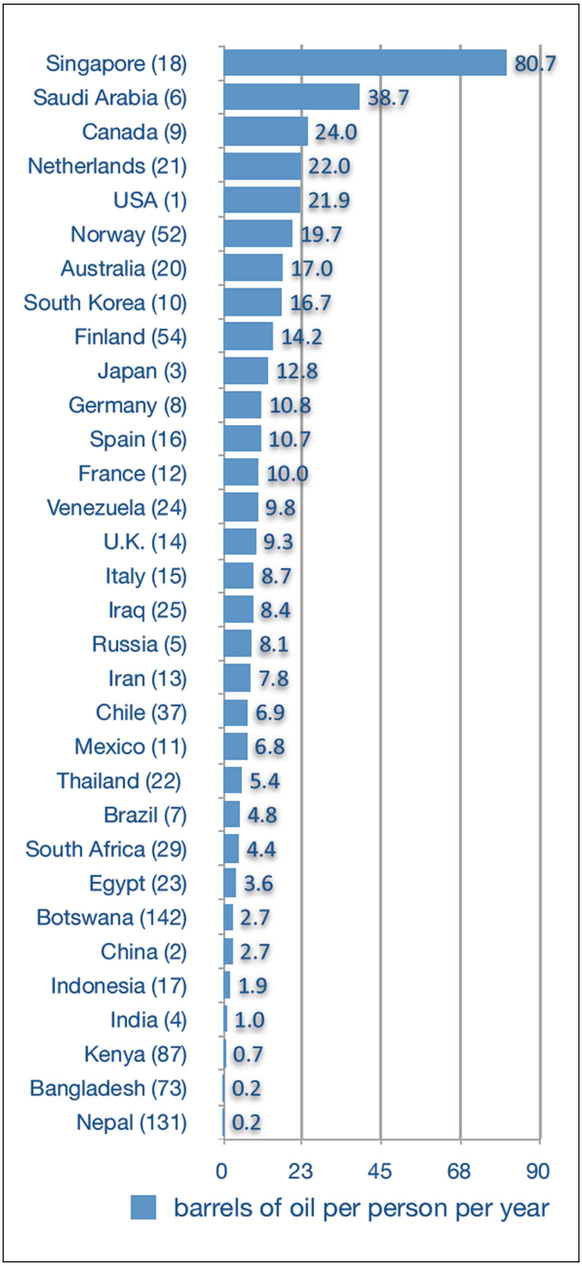

Figure 9. Consumption varies dramatically among countries, as illustrated by this graph of average barrels of oil used per person per year in some of the top oil-consuming countries compared with other representative nations. Numbers in parentheses give world rank in oil consumption. Numbers at right are barrels used per person per year. The challenge is bringing down per-capita consumption rates in countries in which rates are now too high, while allowing for growth in developing countries that are now at low consumption rates. In the case of fossil fuels, scaling up of renewables and new technological innovations will be required to solve the problem.
Source: Data from Central Intelligence Agency (CIA), 2013: ref. 115.

Causes for concern

Each of the 7 billion people now on Earth contributes at some level to climate disruption, extinctions, ecosystem transformation, and pollution. The actual contributions of course vary from region to region, country to country, and between rich and poor (Figure 9), with the general pattern being a much larger per capita footprint in highly industrialized, wealthier countries, and a lower per capita footprint in developing, poorer countries. Although each individual contribution to the global-change footprint can be tiny, when multiplied by billions, the effect becomes inordinately large. Among the key ways population growth contributes to world problems are the following.

- *Climate disruption.* On average each person on Earth produces about 4.9 tonnes of CO_2 per year, as of 2011 (Olivier et al., 2012); thus, as population grows, greenhouse gases and consequent climate disruption increase proportionately.
- *Extinctions*. Direct causes of extinction (habitat destruction, overexploitation) can be expected to increase as billions more people occupy and use more and more of the planet (Hoekstra et al., 2010). Further extinctions are likely to result from climate change. In addition, there are serious indirect impacts, notably the amount of net primary productivity, or NPP, that humans consume or co-opt. (NPP is a measure of the ‘natural energy’ available to power the global ecosystem. It is technically defined as the net amount of solar energy converted to plant organic matter through photosynthesis.) Humans now appropriate about 28% of all NPP (although estimates range from 23% to 40%) (Haberl et al., 2007; Running, 2012; Smith et al., 2012; Vitousek et al., 1986, 1997b). There are limits to the amount of NPP that can be produced on Earth, so the more NPP that humans use, the less is available for other species. That means that as the human population grows, populations of other species inevitably go extinct (unless special conservation measures mitigate the losses) because of global energy constraints. Calculations that assume no change in human consumption patterns indicate that the amount of NPP required by 20 billion people – which would occur by the year 2085 if fertility rates stayed the same as they are now – would cause the extinction of most other species on Earth (Maurer, 1996). Clearly, a human population of that size is untenable.
- *Ecosystem transformation*. A little less than 2 acres of land has already been converted for each person on Earth (Barnosky et al., 2012; Foley et al., 2011; Vitousek et al., 1997b). If that per capita rate of land conversion continued, adding 2.5 billion more people to the planet means that the majority of Earth’s lands – a little over 50% – would have been changed into farms, pastures, cities, towns, and roads by 2050. Continuing to use land at the rate of 2 acres per person would mean that 85% of Earth’s lands would have to be used – including inhospitable places such as deserts, the Arctic, and the Antarctic – if the population hit 15 billion. Such unworkable scenarios underscore that population cannot grow substantially without reducing the human footprint.
- *Pollution*. All of the most dangerous sources of pollution result from per capita demand for goods and services and, given current practices, will increase proportionately with the number of people on Earth. Additionally, there is the problem of treating and disposing of human waste (sewage and garbage), which multiplies roughly in proportion to numbers of people.

An important consideration is that basic needs – a place to live, food, water, and adequate healthcare – are difficult to provide even for the 7 billion people already alive today. Although international programs have been making significant gains in bringing these basic needs to more people and places, about 80% of the world’s population still lives below poverty level (i.e. on less than US$10 per day; 1.4 billion people still live on less than US$1.25 per day) (Shah, 2013); 2.6 billion people lack basic sanitation services (more than one-third of all the people on the planet) (Shah, 2013); 1.1 billion people have inadequate access to water (Shah, 2013); about 870 million people (1 in 8) lack enough food (FAO, 2012a); and 1 billion people lack access to basic healthcare systems (Shah, 2011). Addition of 2.5 billion more people by 2050, and more after that, would make these already-challenging problems even more difficult to solve, particularly since the highest fertility rates currently are in the poorest countries. For example, despite an overall decrease in malnourished children from 1990 to 2011, the number of underfed children in Africa – where populations have grown substantially and most countries are relatively poor – rose from about 46 million to 56 million in those two decades (WHO, 2013b).

Solutions

Two strategies will be required to avoid the worst impacts of population growth. The first involves recognizing that sustaining at least the quality of life that exists today while still adding some billions of people will require reducing the per capita human footprint – for example, developing and implementing carbon-neutral energy technologies, producing food and goods more efficiently, consuming less, and wasting less. This amounts to a dual challenge of reducing the per capita use of resources in economically developed countries, while still allowing growth in quality of life in developing countries. For example, the average US citizen used about 22 barrels of oil per year in 2011, whereas the average person in China and India used only about 3 and 1 barrels, respectively (Figure 9) (CIA, 2013). Evening out such disparities while still preserving quality of life will require a transformation of energy and resource-consumption regimes in both rich and poor nations, as well as major technological breakthroughs in some areas. Especially in the energy sector, policy changes will be needed to ensure that developing countries can ‘leap-frog’ over outdated technologies, as occurred with the mobile phone industry. Overall, per capita consumption can be reduced by using state-of-the-art science for designing, developing, and commercializing the materials that are used by billions of people.

The second strategy involves ensuring that the lower population-growth projections are the ones that prevail (Brown et al., 2011; Ehrlich et al., 2012). The medium-fertility variant worldwide (on average one daughter per family) would stabilize world population at about 10 billion; that would actually entail a large *increase* in fertility in all developed countries plus China and dozens of other developing countries. Therefore the 10-billion benchmark clearly can be improved upon. Today, about 40% of the population lives in countries where fertility is already near replacement, and another 42% lives in countries where the fertility rate is significantly lower. The ‘low’ projection (Figure 8) is achievable and should be the goal. Ending world population growth at about 8 billion requires bringing down fertility rates in the 18% of the population (UNDESA, 2011) that live mostly in economically disadvantaged countries, where people still lack ready access to education and healthcare. Raising levels of education, particularly among women, and providing access to safe and effective means of contraception to those who want it, have been proven to reduce fertility rates substantially (Ehrlich et al., 2012; Speidel et al., 2009).

Interactions

While climate disruption, extinctions, ecosystem transformation, pollution, and population growth all are serious problems on their own, they interact with each other in ways that make their total effects much more than simply the sum of their parts. For example, pollution leads to local losses

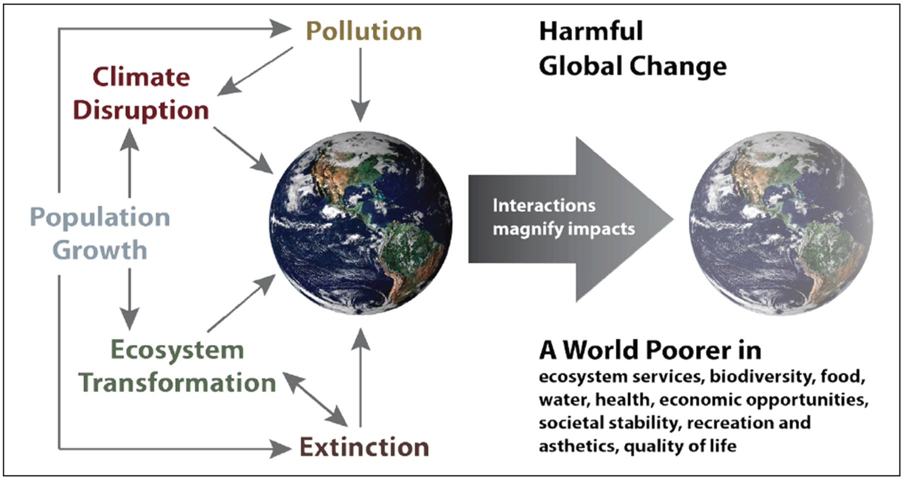

Figure 10. The interactions between climate disruption, population growth and consumption, ecosystem transformation, pollution, and extinction greatly magnify the potential for undesirable global change.

of biodiversity, which in turn leads to major ecological changes. Cutting down old-growth rainforests permanently transforms local climate by making it effectively drier, which in turn permanently changes the local ecosystem from forest to grassland. At the same time global climate disruption is magnified as a result of removing a major source of carbon sequestration. Scaling up, as global climate reaches critical thresholds of change, rapid disappearance of whole biomes, such as boreal forests (Scheffer et al., 2012), may result. Some pressures are tied intimately to others: for instance, increasing human population size, and especially increasing per capita consumption, multiplies the impacts of all four of the other problems.

Causes for concern

Interaction effects markedly increase the chances that crossing critical thresholds will lead to irreversible change (Peters et al., 2009; Scheffer et al., 2009) (Figure 10). That means that multiple global pressures can combine to cause undesirable changes to occur more unexpectedly, faster and more intensely than what would be predicted from considering each pressure separately (Folke et al., 2011; Lenton, 2011; Rockström et al., 2009; Steffen et al., 2011; Wang et al., 2012). Such unanticipated changes in essential resources – food, water, climate predictability, biodiversity – are likely to result in social strife.

The pressures of each dangerous trend on its own, combined with the multiplying effect of combining them, makes it highly plausible that disruptive societal changes would occur within decades if business as usual continues (Barnosky et al., 2012; Rockström et al., 2009; Steffen et al., 2011). Even taken individually, the current trajectories of climate change, extinctions, ecosystem transformation, pollution, and population growth are faster and greater than the planetary pressures that triggered so-called ‘planetary state-changes’ in the past (Barnosky et al., 2012). Essentially, those were times when the Earth system hit a ‘tipping point’, that is, suddenly switched to a new condition that precipitated abrupt, major, and permanent changes, including losses of species and shifts in ecological structure and ecosystem services that affected all places on the planet. The last time this happened was nearly 12,000 years ago, when the last glaciation ended. In general, ‘tipping points’ are characteristic of how biological systems respond to continued pressures, and they are well documented at a variety of spatial and temporal scales (Scheffer et al., 2001, 2009).

Solutions

Minimizing the chances that unanticipated global changes will result from interaction effects requires flattening the trajectories of all five dangerous trends. An important part of the solution lies in relieving the global pressures that have the strongest interaction effects, namely population growth, per capita resource consumption, and greenhouse gas emissions. These affect conditions in all parts of the planet, because the extent of ecosystem transformation, extinctions, and pollution inevitably multiply as population grows, as people consume more, and as climate changes, and climate disruption becomes more pronounced as more people use energy derived from fossil fuels.

While the science is clear that continuing the negative trends of climate disruption, extinction, ecosystem loss, pollution, population growth and growing per capita consumption are harmful to humanity, actually solving these problems will require recognition of their urgency by people and governments at all levels. The technological expertise is available to mitigate many of the harmful impacts, but ultimately, science and technology only provide the tools; it is up to society to decide whether or not they want to use them. Therefore, a crucial next step in diffusing these problems is societal recognition of their urgency and willingness to commit human ingenuity and resources towards implementing solutions (Ehrlich and Ehrlich, 2013). This will entail enhanced education about these issues at all levels, including schools, businesses, the media, and governments, and sustainable development goals that acknowledge that human wellbeing depends on planetary wellbeing (Griggs et al., 2013).

The window of time for this global effort to begin is short, because the science also demonstrates that with each passing year of business as usual, the problems not only become worse, they become more expensive and difficult to solve, and our chances of avoiding the worst outcomes diminish. Put another way, starting now means we have a good chance of success; delaying even a decade may be too late.

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