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The cost of living in the Anthropocene

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Abstract

The most recent epoch, the Holocene, has been a period of relative environmental stability, allowing humans to develop agriculture and establish settlements, culminating in modern civilization. Human activities have now reached such a scale that we are having significant impacts on planetary systems, and these effects are of sufficient magnitude to suggest that we have triggered a new geological epoch, the Anthropocene. Neither climatic nor biogeochemical stability is likely to continue in the Anthropocene, and the Earth systems we rely on to provide a liveable environment for human society are likely to become much less predictable. The stability of our infrastructure, the reliability of our production systems and the liveability of our cities will all be much less certain in the future. More research on the diverse aspects of global change will certainly help to improve predictions on the timing and extent of changes, but will not alter the basic conclusion that global change is upon us. There is now a pressing need for much more interdisciplinary work, addressing such questions as the global societal changes that must accompany responses to environmental change, and dealing with the true economic consequences of a less predictable environment. Conceptualizing the challenges that face humanity under the umbrella of the Anthropocene should allow different disciplines to collaborate and develop strategies for dealing with global change in a coherent and rational manner. Researchers in diverse fields must work together with primary producers, politicians, business interests, policy makers and the public to formulate strategies to minimise or mitigate the risks that face all of humanity over the next centuries. Here we provide a summary of the environmental triggers that are pushing us into the Anthropocene, and outline the consequences of transgressing the boundaries beyond which earth systems are likely to become unstable.

Keywords: Climate change; Ocean acidification; Biogeochemistry; Anthropocene; Natural capital; Governance; Economics

Background

The history of Earth is divided into geological periods. The most recent period is the Quaternary, which spans the last 2.5 million years, and corresponds roughly to the time that hominids have occupied the Earth. In turn, periods are subdivided into epochs. For instance, the Quaternary is divided into the Pleistocene and the Holocene epochs. Transitions between Periods or Epochs are defined by major geological or paleontological events that leave a signature in the geological record. Such signatures are caused by significant changes in climate, atmosphere or biota. The best-known example of such a transition is the catastrophic event that ended the Cretaceous period and coincided with the extinction of the dinosaurs.

For the last 10,000 years, humans have been living in the Holocene epoch. This has been an interglacial period of relative environmental stability, where temperature, atmospheric conditions and biogeochemical cycles have exhibited only minor fluctuations (Dansgaard et al. 1993; Rioual et al. 2001; Young and Steffen 2009). This stability allowed humans to develop agriculture and form settled communities, culminating in the complex societies of modern times. The very stability of the Holocene has helped humans to abandon a mobile lifestyle that exploited natural resources, in favour of permanent settlements with complex infrastructure (van der Leeuw 2008).

Modern societies are highly dependent on the physical and electronic links between larger and larger regions, and especially upon the transport of matter and energy. The timeliness and reliability of such systems is dependent on the predictability of environmental conditions. However, our infrastructure and agriculture have been developed to function under the benign conditions that

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have typified the Holocene, and the last 10,000 years. It is thus of considerable concern that human activities have begun to alter the Earth's climate and biogeochemistry, threatening to plunge us into an era of unpredictability in all Earth systems. It is not certain that we will be able to adapt quickly enough to accommodate these changes. The scale and speed of change has led to the proposal that we are moving into a new epoch, termed the Anthropocene, or literally, the 'Age of Man' (Crutzen 2002; Steffen 2006; Steffen et al. 2007).

So what is the evidence that we should recognize the current era as a new geological epoch? What are the key atmospheric, biotic and environmental changes that have already occurred, and what changes can we expect in the future? Can we actually predict the unpredictable? The destabilization of key planetary systems may have catastrophic consequences for humanity, and yet current policies of social and economic development often operate in an arena of selective blindness to looming planetary disasters (Stern 2007). Strategies for policy and governance must be far more responsive to the current and ongoing destabilization of planetary scale processes if humanity is to deal successfully with the predicted rate of environmental change (Biermann 2012). Furthermore, the science of global change must be communicated in language that is concise and clear, such that non-specialists can understand it, yet still be accurate. Here we review recent literature on the Anthropocene, and the interactions between the various phenomena contributing to global change.

The History of the Anthropocene

The idea that human activities have the power to affect Earth's systems was recognized in the late 1800s by the geologist Antonio Stoppani, who coined the term 'Anthropozoic Era' to highlight this conclusion (Crutzen 2002). The term 'Anthropocene' was first used by Eugene Stoermer, and subsequently popularized by the atmospheric chemist and Nobel Prize laureate Paul Crutzen (Crutzen 2002). The Anthropocene may soon become an official epoch, since a proposal to formalise it was made to the Stratigraphy Commission of the Geological Society of London in 2008, resulting in serious consideration for its acceptance as an epoch in the geological time scale (Zalasiewicz et al. 2008; Zalasiewicz et al. 2010).

Crutzen dates the beginning of the Anthropocene to the late 18th century when atmospheric concentrations of carbon dioxide and methane began to rise significantly. Other writers have suggested that the Anthropocene could be dated to as long as 8,000 years ago, driven by clearing of forests and agriculture (Ruddiman 2003; Ruddiman 2013). However, the 18th century date seems a reasonable compromise, since this date coincides with the invention of the steam engine and the industrial revolution, and corresponds to increased carbon emissions by humans.

Biotic and Geochemical Markers of the Anthropocene

The most compelling argument for the erection of the Anthropocene as a new epoch relies on projecting ourselves forward in time, and asking if future geologists will be able to detect a stratigraphic boundary that defines a transition from the Holocene (Zalasiewicz et al. 2011; Gale and Hoare 2012; Brown et al. 2013). To this end, a number of key processes have been identified as 'Planetary Boundaries', representing thresholds below which humanity can safely operate, and beyond which the stability of planetary-scale systems cannot be relied upon (Rockstrom et al. 2009a; Rockstrom et al. 2009b). Transgressing these boundaries may leave a clear record in the geological column.

Nine distinct planetary boundaries have been suggested, each based on the unacceptable economic, social and environmental risks that humanity faces should they be crossed. For each of these boundaries attempts have been made to estimate the tipping points, beyond which abrupt and irreversible environmental changes might occur. There is uncertainty about many of these boundaries, because we do not have enough data and we lack a comprehensive understanding of the complex feedback mechanisms that maintain resilience and stability in biophysical systems (Rockstrom et al. 2009a). Nevertheless, we should operate from the precautionary principle that abrupt and catastrophic changes in earth systems are likely if humanity continues its current scale of activities.

The key planetary boundaries, and their potential consequences, are as follows:

Climate change

Humans have had a significant effect on global carbon cycling. Emissions of carbon dioxide into the atmosphere have raised its concentration to a level higher than at any time in the last 800,000 years. Carbon isotope chemistry was used to mark the boundary between the Paleocene and Eocene epochs, so a carbon signature also seems appropriate to mark a transition to the Anthropocene (Steffen et al. 2011a).

Thirty years ago there were suggestions that the Earth was warming, based on the known linkage between global mean temperature and the atmospheric concentration of carbon dioxide. Despite political opposition and the efforts of climate sceptics, this conclusion is now certain (Agnihotri and Dutta 2013; IPCC 2007). The boundary for deleterious climate change forced by accumulation of carbon dioxide was set at 350 ppm, and this boundary has already been transgressed (Steffen et al. 2007; Rockstrom et al. 2009a).

Climate change has the potential to affect every aspect of our economy and society. Extreme weather events, such as hurricanes, heatwaves and droughts will increase in intensity and frequency over the next decades (Repetto and Easton 2010; Coumou and Rahmstorf 2012). Around the globe, weather related events already cause more casualties than other catastrophes (Bouwer 2012), and have serious human health consequences (Knowlton et al. 2011). In addition to the direct human toll, extreme weather disrupts or destroys infrastructure. For instance, in October 2012, Hurricane Sandy resulted in the cancellation of almost 20,000 airline flights and the closure of bus, rail and ferry services (Kaufman et al. 2012). Total damages from Sandy were estimated to lie between 30 and 50 billion dollars (Tollefson 2012). Globally, economic losses caused by extreme weather events are rapidly increasing, and will continue to rise over the next decades (Bouwer 2012). Strategic decision making by businesses should anticipate and incorporate the need for organizational adaptation in the face of this rapidly changing climate (Linnenluecke et al. 2012).

Predicting the impacts of climate change is difficult because the likely effects are not uniform in either location or direction. For instance, weather in north-western Europe is dependent on the effect of the warm North Atlantic Drift. Changes in this thermohaline circulation caused by alterations in rainfall patterns could, ironically, lower temperatures by as much as 10°C across NW Europe, and such changes might be irreversible (Rahmstorf 2000).

The last decade has seen an increase in the frequency and severity of heatwaves and droughts (Coumou and Rahmstorf 2012), both of which have serious implications for food production, human health, and infrastructure (Fischer and Schar 2010; Anderson and Bell 2011; Battisti and Naylor 2009). There will also be a substantial increase in the frequency of intense tropical cyclones and the attendant damage to cities and coastal settlements. Category 4 and 5 storms are expected to double in frequency by the end of the century (Bender et al. 2010; Knutson et al. 2010). There is also good evidence that the frequency of great floods has increased significantly over the last 100 years (Milly et al. 2002). Such floods damage settlements, impact agriculture and promote the spread of waterborne diseases (Few 2012).

Rising global temperatures lead to proportional rises in sea level, due to thermal expansion of the oceans and melting of ice fields (Hodgson 2011; Nicholls and Cazenave 2010). Rates of sea level rise are currently 3.4 mm/year with an estimate of a total rise of between 0.5 and 1.4 m by 2100 (Rahmstorf 2007; Rahmstorf 2010; Schaeffer et al. 2012). Impacts on humans will include inundation of low lying areas and loss of islands with low elevation. Although such effects are restricted to coastal areas, these are often highly productive ecosystems with a consequently high population density. Densely populated cities such as Tokyo, Shanghai and Bangkok exhibit the additional problem of land subsidence, exacerbating the effects of rising sea levels (Nicholls and Cazenave 2010). Estimates suggest that some 10 to 50 million people in the Southeast Asian region alone will become refugees from sea level rise (Wetzel et al. 2012). Many of the regions most at risk also have an inherently low capacity for adaptation to rising sea levels (Nicholls and Cazenave 2010), and the greatest impacts will disproportionately affect those least responsible for climate change.

Worldwide, populations in the hazard zone for 1000 year storm surges are estimated to reach 400 to 600 million by 2050. As a contemporary example, in October 2012 Hurricane Sandy caused record storm surges in New Jersey, NY City, Connecticut, and Rhode Is. Other significant effects of sea level rise include loss of wetlands, erosion and salt-water intrusion into freshwater systems (Nicholls and Tol 2006), thus having flow-on effects on other planetary boundaries such as biodiversity, land use and fresh water resources.

Further effects of climate change include an increase in the frequency and severity of fires, loss of alpine habitats, movement of vegetation zones and disruption to agriculture (Hughes 2003). Declines in crop yields due to climate change are already apparent, with a global drop in wheat and maize production of 5.5 and 3.8% respectively, despite improvements in agricultural technology over the last 30 years (Lobell et al. 2011). Modelling suggests that climate change will result in yield declines of 30-80% in US production of corn and soybeans by the turn of the century (Schlenker and Roberts 2009). Long term global trends are more difficult to predict because effects differ significantly from region to region (Piao et al. 2010; Schlenker and Lobell 2010). World production of food may remain stable, but declines in yield will disproportionately affect developing nations, resulting in higher prices, increased risks of food shortages and increasing inequity in food distribution (Parry et al. 2004; Lobell et al. 2008).

Ocean acidification

Nearly one third of the carbon dioxide released by anthropogenic activity is absorbed by the oceans. But for this fact, current atmospheric CO_2 concentrations would be higher than they already are. However, CO_2 uptake lowers the pH and alters the chemical balance of the oceans, in particular the solubility of calcium salts (Doney et al. 2009). This phenomenon is called ocean acidification, and is occurring at a rate faster than at any time in the last 300 million years (Hönisch et al. 2012). We are now at risk of transgressing the pH boundary where the calcium carbonate and aragonite skeletons of marine life will simply dissolve (Rockstrom et al. 2009a). It is a sobering thought that the great Permian extinction event, where 96% of species were lost, was associated with ocean acidification (Barnosky et al. 2011; Harnik et al. 2012).

The economic costs of ocean acidification encompass a number of biological effects, including decalcification of the skeletons of molluscs, echinoderms, foraminifera, coralline red algae and tropical corals, and effects on reproduction of plankton, molluscs and echinoderms (Doney et al. 2009; Lurling and De Senerpont Domis 2013; Schlegel et al. 2012). Many of these groups contain keystone species, whose loss will permanently alter marine ecosystems.

Corals reefs harbor a significant proportion of marine diversity. Ocean acidification threatens to dissolve coral skeletons and convert reefs into algal dominated systems (Hoegh-Guldberg et al. 2007; Pandolfi et al. 2011). The economic impact on ecosystem services provided by reefs are difficult to assess (Stoeckl et al. 2011), but there will be serious consequences for fisheries, tourism and coastal protection (Hoegh-Guldberg et al. 2007). Estimates suggest that current global loss in shellfish production due to ocean acidification amounts to some 6 billion dollars (US) per annum, and that this could rise to \$100 billion, based on increased demand in the Asia-Pacific region (Narita et al. 2012). Degradation of marine habitats, loss of ecosystem services and the resultant decline in harvests are likely to have disproportionate effects in some regions, particularly those with high dependency on marine resources (Cooley and Doney 2009). The number of peer-reviewed analyses on the economic impact of ocean acidification is still small, but is likely to increase sharply, given the rapid rise in research papers now being published in this area. Appropriate methods for estimating costs have been identified and applied to ecosystem services in Norwegian waters. There were both positive and negative effects of acidification, but overall there was a large net negative outcome (Armstrong et al. 2012). In the final analysis, protection of the ocean may be more important than protection of atmosphere or land because it stores more carbon, mediates climate variability and provides essential ecosystem services (Steffen et al. 2011b).

Ozone depletion

The original appearance of the ozone layer allowed the emergence of life on land, because ozone in the stratosphere filters out ultraviolet radiation from the sun. Human use of chlorofluorocarbons and other compounds has depleted ozone, and resulted in the thinning of the ozone layer in the polar stratosphere. This exposes humans to health risks and has negative effects on marine ecosystems. Ozone depletion is also the major cause of changes in the pattern of atmospheric circulation in the southern hemisphere (Portmann et al. 2012). Climate models suggest that ozone depletion led to a significant increase in rainfall across SE South America during the last 40 years of the 20th century. Any recovery of the ozone layer in the future may thus lead to a drying of this region, with consequent adverse effects on agriculture and economies (Gonzalez et al. 2013).

Recognition of the ozone depletion problem led to an international agreement (the Montreal Protocol), and as a consequence, ozone-depleting halocarbons have declined from their peak in 1992–1994. Globally, we are now unlikely to pass the tipping point for ozone depletion, largely based on acceptance of key scientific findings, and the resulting international agreements (Velders et al. 2007; Mäder et al. 2010). Although ozone depleting chemicals will take many decades to degrade, informed science and political will have changed human behaviour so successfully as to avoid transgressing the tipping point for ozone depletion (Rockstrom et al. 2009a). However, the reduction of halocarbon emissions will not solve the problem entirely, since anthropogenic nitrous oxide emission also affects ozone levels (Portmann et al. 2012).

Atmospheric aerosol loading

Aerosols are particles suspended in the atmosphere. Since the industrial revolution the concentration of aerosols has doubled (Tsigaridis et al. 2006). There is considerable evidence that aerosols alter the way precipitation forms from clouds, and hence human emissions of aerosols have the potential to significantly change rainfall and weather patterns (Rockstrom et al. 2009a). Simulations suggest that aerosol loading of the atmosphere will change the timing, intensity and extent of the South Asian monsoon, affecting rainfall over East Asia (Lau et al. 2006; Lewis et al. 2011). Thus one of the most densely populated regions of the planet will suffer most from unpredictable rainfall. Aerosols may also alter the distribution of primary production in marine ecosystems, either enhancing or lowering production dependent on the metal content of the aerosol (Paytan et al. 2009).

Some 80% of populations in Asia are exposed to aerosol concentrations that exceed WHO guidelines (Carmichael et al. 2009). Exposure to the particulate matter in polluted air causes cardiac and respiratory disease, amounting to some 500,000 deaths per year (Nel 2005). The combined health costs due to particulate pollution in Beijing amount to between US\$1.6 and 3.6 billion annually, equivalent to over 6% of this cities gross domestic product (Zhang et al. 2007). Globally, the health impacts and consequent economic costs of aerosol emissions are estimated to lie between US\$120 and 510 billion annually (Selin et al. 2011). Aerosols also affect other organisms, including crops, forests and aquatic animals, primarily through the acid rain generated by nitrogen and sulphur oxides. Because aerosols are composed of diverse compounds with different origins, half-lives and potential impacts, it is difficult to predict their effects with any certainty, although some progress is being made (Jimenez et al. 2009).

Phosphorus and Nitrogen cycles

Phosphorus and nitrogen are key elements for growth of living things. Humans have successfully manipulated their availability to improve the productivity of agricultural systems. Prior to the industrial era, the vast majority of biologically available nitrogen was fixed from atmospheric nitrogen via bacterial activity. By tapping into fossil fuels and as a result of agricultural activities, humans now fix more atmospheric nitrogen into biologically available forms than the quantity fixed by all natural processes combined (Rockstrom et al. 2009a; Gruber and Galloway 2008). Industrial fixation of nitrogen is accomplished via the energy intensive Haber-Bosch process, while other human-driven processes such as cultivation of legumes, fossil fuels and burning of biomass add to the total. The planetary boundary for the nitrogen cycle has already been passed (Rockstrom et al. 2009a).

Nitrogen flux through the biosphere is primarily a biological process, while phosphorus availability arises slowly through geological weathering. Humans sidestep the phosphorus bottleneck by mining and distribution of fertilizer onto agricultural lands, thus inadvertently increasing the flow of phosphorus into the oceans. While the planetary boundary for phosphorus is unlikely to be passed in the near future (Rockstrom et al. 2009a), the production of phosphorus for fertilizer will peak in 2030, before peak demand occurs. In a world where phosphorus supply is limited, there are serious implications for global food security (Cordell et al. 2009).

Increasing levels of phosphorus and nitrogen in soils and waters causes soil acidification, eutrophication of waterways and is associated with harmful algal blooms (Anderson et al. 2008; Bennett et al. 2001). Eutrophication affects waterfront real estate values, recreational water use, freshwater availability and expenditure on species recovery programs. In the US, the combined costs arising from eutrophication have been estimated as US$2.2 billion per year (Dodds et al. 2008). In England and Wales, the damage costs of eutrophication are in the range of US$105-160 million per year (Fankhauser 2009). Excess phosphorus flowing into the oceans also causes oceanic anoxia, associated with mass extinction events (Barnosky et al. 2011; Handoh and Lenton 2003). Guidelines and protocols for lowering the release of nutrients into ecosystems must be widely adopted to lessen the economic impact of eutrophication (Lewis et al. 2011; Fulweiler et al. 2012).

Global freshwater use

Humans die in several days if water is not available. Because of this, access to fresh water is regarded as a universal human right (Füssel et al. 2012). The water bodies that we depend on also connect the atmosphere, soils, and the oceans, and are indispensable for the functioning of terrestrial ecosystems. However, freshwater systems can no longer be thought of as being naturally regulated. Human use of freshwater and our control of river flows have fundamentally altered the water cycle at both local and regional scales (Meybeck 2003). Extraction of water by humans results in 25% of rivers running dry before they reach the ocean (Falkenmark and Molden 2008; Molden 2007). Further, water bodies are subject to a variety of environmental insults including salinization, acidification, and contamination with chemical and microbial pollutants (Meybeck 2003).

Fresh water resources are running out. Many populations live under water stress, and 80% of the world's population face threats to water security (Vorosmarty et al. 2000; Vorosmarty et al. 2010). Limitations on water availability have led to the concept of 'peak water', split into three components: renewable freshwater flow; non-renewable groundwater resources; and peak 'ecological' water. Once the damage cost of any additional human use of water exceeds the benefits, we have passed the point of peak ecological water. Peak water use for at least one of these three components has been passed for major river basins and aquifers all across the globe (Gleick and Palaniappan 2010).

The uncertainty of climate change places the predictability and reliability of water resources in doubt (Piao et al. 2010; Füssel et al. 2012), and the economic impacts scale with climate change. Damage costs for North America are estimated at about US$3 billion for a 1°C increase in global mean temperature, scaling to US$7 - 16 billion at 2.5°C. Globally, costs to water resources are estimated at some US$47 - 84 billion under a 4°C temperature increase (Tol 2002).

In addition to the central role of water in food production, aquatic systems harbour valuable biodiversity and provide essential ecosystem services (Vorosmarty et al. 2010; Wilson and Carpenter 1999). Increasing pressure on water availability will have serious economic consequences for food production and human health. Because of the transnational nature of rivers and water bodies, action to protect this resource requires inter-regional and international agreements (Falkenmark and Lundqvist 1998). Adaptive responses to less reliable and diminishing water resources will require critical improvements in governance (Hill 2013).

Land system change

As human population increases, there is more pressure to convert landscapes into croplands, pastures and urban landscapes. Expansion of agriculture increases the risk of undermining sustainability by threatening biodiversity and affecting both climatic and hydrological cycles (Pielke et al. 2003; Sterling et al. 2013). Changes to land cover driven by deforestation or urbanization interact with climate and temperature, in some cases forcing climate change to the same degree as carbon dioxide emissions. Land use change complicates global climate predictions, but its inclusion may improve modelling at more regional levels (Avila et al. 2012).

Some 12% of the land surface is now under cultivation (Foley et al. 2005), and the suggested planetary boundary of 15% is likely to be surpassed in the near future (Rockstrom et al. 2009a). The current reserves of land suitable for conversion cropping are predicted to be exhausted some time between 2020 and 2050 (Lambin and Meyfroidt 2011). Consequently, some expansion is likely to be forced onto more marginal land, creating further unpredictable feedbacks on biodiversity, hydrology and climate. Additional land use change will be forced upon us by flooding of low lying land during sea level rise. Conversion of dryland by such flooding, and the subsequent cost to ecosystems amount to US$14 billion and $41 billion per year respectively (Fankhauser 1995).

Conversion of biomes to undesirable states, for example forest to desert, can occur rapidly and unpredictably when thresholds are crossed. For instance, small increases in the clearing of Amazonian rainforest may cause an irreversible conversion into semi-arid savannah (Rockstrom et al. 2009a; Foley et al. 2005). Attention to minimising land degradation, conservation of irrigation water and protection of the most productive croplands from urban development will partially mitigate the problem. Similarly, the development of agricultural practices that mimic complex natural ecosystems will minimise the impact of land use (Ericksen et al. 2009). Improved efficiency of land use has dual outcomes of increased agricultural production and forest conservation (Lambin and Meyfroidt 2011). However, continuing human effects on land systems are likely to combine with climate change to convert land systems into less desirable states.

Loss of biodiversity

Transitions between major geological eras are often characterized by loss of species. When more than 75% of species are lost in a geologically short time period, this is known as a mass extinction. There have been five such mass extinction events over the last 540 million years. In modern times, global biodiversity is declining, via species extinction, at rates that are orders of magnitude higher than might be expected from the fossil record. The rate of decline is not slowing, despite recognition of the problem (Butchart et al. 2010). This has led some scientists to suggest that we are currently in a sixth mass extinction, fully comparable with those in the geological past. Recent analysis suggests that the current loss of species, while dramatic, does not yet qualify as a mass extinction. However, ongoing losses, particularly of species currently recognized as critically endangered, would push us into a state of mass extinction similar in magnitude to the ‘big five’. Recovery from such catastrophic species loss would probably take millions of years (Barnosky et al. 2011). It is a sobering thought that the causes of past mass extinctions are eerily similar to key environmental pressures now facing humanity. These include ocean acidification, climate change, changes in atmospheric CO_2 levels, loss of habitat, and deep water anoxia (Barnosky et al. 2011; Harnik et al. 2012).

Extinction of species and loss of biodiversity have multiple impacts on humanity. There is now consensus that biodiversity increases the efficiency of communities in key ecosystem processes, improves the stability of ecosystem functions, and that diverse communities are more productive. Loss of biodiversity has direct economic effects including decreasing the yield in commercial crops, fodder, forestry and fisheries (Cardinale et al. 2012). Overexploitation of natural resources puts further pressure on biodiversity. For instance, there has been a significant decline in fisheries catches since 1990, despite a doubling of effort (Worm and Branch 2012).

There are numerous conceptual issues surrounding the costs of saving species versus the benefits. Extinction is irreversible, and the effects of individual species loss are uncertain, so the economic costs cannot be accurately estimated. It is difficult to place a value on an ecosystem or a species, but rough estimates based on usage and existence can be used to calculate that a global increase in temperature of 1°C will cost US$50 billion per year in terms of lost biodiversity and resultant ecosystem services (Tol 2002).

The existence value of a species is essentially unmeasurable (Bishop 1978). Further, the effects of losing even one species from an ecosystem are difficult to predict. The magnitude of effects on ecosystem functions increases in a non-linear manner as ever more biodiversity is lost, in part because the majority of species depend on symbioses with other species. Simplification of ecosystems by loss of species may alter their functioning, such that the net effect might be equivalent to effects wrought by ocean acidification and climate change (Reich et al. 2012). Consequently, loss of biodiversity drives changes in ecosystem productivity, decreasing stability and resilience (Hooper et al. 2012).

Chemical pollution

Humans synthesize and distribute an enormous variety of xenobiotic compounds, with some 80,000 chemicals available in the marketplace. We also mine and disseminate various toxic compounds. In the past, this has resulted in local or regional pollution with heavy metals, synthetic organic compounds and radioactive materials. The extent of such activity means that signatures of chemical pollution are now evident at a global scale, and will be detectable in the geological record.

Because of the diversity of potential pollutants and uncertainty as to their effects, it is difficult to set a universal planetary boundary for chemical pollutants (Rockstrom et al. 2009a). Since chemical pollution encompasses diverse compounds in diverse habitats, there are no universal estimates of the costs of anthropogenic pollution, but rather, key studies dealing with single types of pollutants in particular regions. The global costs of air pollution by nitrogen and sulfur oxides were estimated at US$15 billion per year (Fankhauser 1995), excluding the costs of acid deposition. Clearly this estimate overlaps with the costs of aerosols, of which these oxides are major components. Useful global estimates could be made from the clean-up costs for legacy sites and the costs of pollutant capture, but the ongoing and diffuse nature of chemical pollution makes economic calculations problematic.

We should be particularly concerned about pollutants that have direct biological effects at low concentrations, such as endocrine disrupting chemicals (Diamanti-Kandarakis et al. 2009) and antibiotics (Gillings 2013; Gillings and Stokes 2012), since these have the potential to alter population assemblages and affect biodiversity. There have been successful bans on particular organic pollutants, such as dioxins, PCBs, DDT, and other pesticides. These bans have been based on investigations into their effects on humans and other organisms. Assembling equivalent information for the enormous diversity of compounds currently generated by humans is a daunting task, and is complicated by the potential for interactions between compounds. Certainly pollutants have effects on both ecosystem functioning and on human welfare. Exposure of children to low concentrations of compounds with neurotoxic effects may be leading to a global epidemic of developmental disorders (Grandjean and Landrigan 2006; Grandjean et al. 2008), and many pollutants have the potential for bioaccumulation at higher trophic levels (Arnot and Gobas 2004).

Conclusions

Humans are having significant effects at a global scale, and the magnitude of these effects is sufficient to suggest we are entering a new geological epoch, the Anthropocene. This new epoch will be characterized by a shift away from the stable conditions that have typified the last 10,000 years, and usher in a period of unpredictability that threatens to destabilise human economics and society. It is clear that the comparative stability that has typified the last 10,000 years will not continue into this century, and that we face a future where business as usual will not be possible.

Attempting to estimate the absolute costs of living in the Anthropocene is difficult, largely because the potential magnitude of environmental effects are hard to quantify, as are the flow-on costs of unpredictability in weather, nutrient cycling and ecosystem services. Here we have dealt with these potential costs via the framework of the planetary boundaries defined by Rockstrom *et al.* (Rockstrom et al. 2009b), however this framework does not encompass all the costs inherent in the transition to the Anthropocene. For instance, the contributions of cultural heritage such as landscape aesthetics, the cultural significance of particular sites, or the intrinsic value of outdoor recreation are not well integrated into analyses of ecosystem services (Daniel et al. 2012). A number of groups are actively working to incorporate such values into ecosystem assessments (Tengberg et al. 2012; Chan et al. 2012).

The terms ‘ecology’ and ‘economics’ both use the same Greek root as a prefix (oikos = home), and it is surprising that there has not been more cross-disciplinary work between the two fields. Indeed, the value of ecosystem services, essential for human welfare, was not estimated until 1997 (Costanza and Déarge 1997). The value of such services was placed in the range of US$16-54 trillion dollars, most of which lay outside the market. By comparison, at that time the global gross national product was US$18 trillion.

Since 1997, there has been more attention paid to valuing the world’s natural capital, and examining the trade-offs between human welfare and the environment (Farber et al. 2002; Fisher et al. 2011). Particular attention has been paid to biodiversity and conservation (Naidoo et al. 2008), and the costs associated with loss of forest ecosystem services (Chiabai et al. 2011). There has also been critical analysis of the interactions between ecosystem services, policy and economics, and linking these to the costs of human activities (Balmford et al. 2011; Farley 2012; Kinzig et al. 2011). It is clear that much more attention needs to be paid to the real costs resulting from human exploitation of natural resources, and this in turn will require closer collaboration between environmental scientists and economists. Finally, while science can inform and predict, its practitioners will increasingly have to deal with the more difficult issues of value, amenity and ethics (Seidl et al. 2013).

Dealing with the instability and environmental consequences of the Anthropocene will require cooperation and coordination between scientists, policy makers, governments and the general public. However, governance is required at time scales beyond past experience, because the earth systems we are affecting operate at a time scale that is mismatched with human decision making and our economic systems (Steffen et al. 2007). The time lag between cause and effect for complex earth systems mean that likely effects are already mortgaged into the future, and preventing the causes now will not stop the changes that are already in train (Steffen et al. 2011a). Nevertheless, whole society and global responses are needed to prevent even more catastrophic changes to earth systems. Such responses must include population control, greatly reduced consumption of resources, sustainable energy generation, conservation of the natural world and generally better management of all human activities. These actions are essential if we are to maintain human welfare on a less predictable planet (Tickell 2011).

Effective management of earth systems will require changes to both national and international organizations (Biermann et al. 2012), and to aid this process an Earth System Governance Project has been proposed (Biermann et al. 2010). Clearly, adaptive responses have to be examined at local, regional and global scales, and further, because the concept of planetary boundaries crosses environmental, social and economic systems, communication between different fields must be improved, to adequately represent each discipline's perspectives (Nilsson and Persson 2012; Veldkamp et al. 2011). The Anthropocene concept offers the ripe opportunity, and indeed, the necessity, for truly transdisciplinary research that transcends sociology, politics, economics and environmental science (Seidl et al. 2013; Hoban and Vernesi 2012; Palsson et al. 2013). The planetary boundaries central to the Anthropocene concept imply social tipping points that accompany the planetary tipping points, creating a research opportunity for fusing the work of those interested in politics, governance, human psychology and ecology (Biermann 2012). The true economic costs of the Anthropocene are yet to be properly quantified for any one of the planetary boundaries, and this is also an area that needs immediate attention from diverse research standpoints. Finally, solutions based on geoengineering rather than attitudinal and social change need to be examined in terms of their ecological, social and economic cost (Galaz 2012).

Many human civilizations have collapsed in the past, usually due to complex combinations of environmental, social and economic factors (Butzer and Endfield 2012; Diamond 1994). However, modern society has the advantage of hindsight, and knows the kinds of disasters that have overtaken previously successful civilizations. We owe it to future generations to not repeat the mistakes made in the past (Lawson 2011), and to invest in the future of our planet now, rather than pay a higher price later. Acceptance of the risks we face is a significant hurdle to overcome, since individuals and institutions are in a state of collective cognitive dissonance (Steffen et al. 2011a), where unpalatable facts are actively ignored, or worse, distorted and ridiculed. The folly of using growth as a measure of success needs to be more widely appreciated, since continuous growth in human activity is inimical to the natural processes upon which human welfare depends (Kosoy et al. 2012). Current policies tend to ignore intangible and long-term costs, including those of environmental degradation. Unless we consider the true costs of consumption by placing real values on natural capital, we run the unacceptable risk of squandering our inheritance.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
MRG and ELH conceived and designed the manuscript, assembled and reviewed the literature. MRG wrote the manuscript drafts, and ELH provided critical revisions. Both authors have read and approved the final manuscript.

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