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Avoiding collapse: Grand challenges for science and society to solve by 2050

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Abstract

We maintain that humanity's grand challenge is solving the intertwined problems of human population growth and overconsumption, climate change, pollution, ecosystem destruction, disease spillovers, and extinction, in order to avoid environmental tipping points that would make human life more difficult and would irrevocably damage planetary life support systems. These are not future issues: for example, detrimental impacts of climate change (increased wildfires and extreme weather, sea-level rise, ocean acidification), pollution (contaminated drinking water in many parts of the world), rapid population growth in some areas (contributing to poverty, war, and increasingly frequent migration) and overconsumption in others (a main driver of overexploitation of resources and greenhouse gas emissions), and new disease outbreaks (Ebola, Zika virus) already are apparent today, and if trends of the past half century continue, even more damaging, long-lasting impacts would be locked in within three decades. Solving these problems will require some scientific and technological breakthroughs, but that will not be enough. Even more critical will be effective collaboration of environmental and physical scientists with social scientists and those in the humanities, active exchange of information among practitioners in academics, politics, religion, and business and other stakeholders, and clear communication of relevant issues and solutions to the general public. This special feature offers examples of how researchers are addressing this grand challenge through the process of discovering new knowledge and relevant tools, transferring insights across disciplinary boundaries, and establishing critical dialogues with those outside academia to help effect positive global change.

Introduction

Until recently, the planet was so big compared to humanity's impacts that Earth's resources seemed limitless. We now know that is not the case (Barnosky et al., 2014; Barnosky and Hadly, 2015; Brown et al., 2011; Ehrlich and Ehrlich, 2013; GFN, 2013; Rockström et al., 2009). The human population has nearly tripled in just one human lifetime, and, at 7.3 billion people and counting, is still growing rapidly (Ehrlich and Ehrlich, 2013; PRB, 2015; UNDESA, 2013a, 2013b), with almost a quarter of a million more people added every day: the equivalent of a new Hong Kong every month and more than a new Pakistan every two years. Provisioning the food, housing, water, and other goods and services desired by these ever-growing numbers of people has transformed more than 50% of the planet into human constructs like farms, pastures, cities, towns, roads, and dams (Barnosky et al., 2012; Foley, 2011; Foley et al., 2011; Hooke et al., 2012). Virtually all of the world's most productive land is already being used to grow food (Ehrlich and Ehrlich, 2013; Foley et al., 2011), and more than 60% of the world's big rivers have been dammed (Hoekstra et al., 2010). Humans now co-opt more than one third of the energy that photosynthesis provides for all the species in the world to share, measured as Net Primary Productivity (NPP), mostly for food and biofuel production (Grosso et al., 2008; Haberl et al., 2007; Running, 2012; Smith et al., 2012; Vitousek et al., 1986, 1997). Even so, about one in nine people in the world go hungry each day, about a third are malnourished, and more than one in seven get by on a bare minimum of water (Barnosky et al., 2014; FAO, 2012, 2015; Shah, 2011, 2013; WHO, 2013). In some regions these problems reflect lack of adequate resources with respect to local population sizes—for example, a shortage of arable land, adequate rainfall, and NPP in the Sahel (Abdi et al., 2014). But, on a global scale, the obstacle to many people obtaining adequate life-support resources also arises from political, economic, and social factors (Gower et al., 2012), including large inequalities in economic opportunities and land tenure rights, or poor infrastructure—as is the case for food production, for example. Although global crop yields are sufficient to feed the world (so far), distribution mechanisms are inadequate to transport it where it is needed (FAO, 2015; Foley et al., 2011).

Producing what billions of people need to survive requires energy in amounts that now far exceed what terrestrial photosynthesis can provide (Barnosky, 2008, 2014; Smil, 2011), a shortfall that will continue to grow with human population growth, and will be exacerbated even further with increasing levels of production and consumption of goods. Since the Industrial Revolution, we have produced most of the extra energy the global society needs by burning massive amounts of fossil fuels—in effect, prehistoric net primary productivity. Relying on fossil fuels to augment the global energy budget has input CO_2 (and other greenhouse gases) into the atmosphere at a pace that is 200 times faster than what was normal for Earth's pre-industrial carbon cycle (Archer et al., 2009; Berner, 2003; DePaolo et al., 2008). The richest one billion of us—only 15% of the human population—consume half of the energy produced by fossil fuels (Ramanathan et al., 2015), and consequently have been responsible for 60% of the CO_2 problem. In contrast, the poorest 3 billion people account for only about 5% of CO_2 emissions (Ramanathan et al., 2015). Because of greenhouse gas emissions, the net effect of relying on fossil fuels is that we are now changing climate faster than people have ever experienced since our ancestors became *Homo sapiens* (Blois and Hadly, 2009; Diffenbaugh and Field, 2013; IPCC, 2007, 2013). Already the changing climate is manifesting as more frequent floods, wildfires and heat waves that kill thousands of people annually; rising sea levels that displace whole communities and cost hundreds of billions of dollars for coastal infrastructure building and repair; and as increasingly acid oceans, which in some places are becoming so acidic that oyster and scallop fisheries are beginning to collapse (Barnosky and Hadly, 2015; Barton et al., 2012; Gazeau et al., 2011; Liu et al., 2012; Miller et al., 2009). Air pollution from burning fossil fuels also has long been recognized as a growing problem, to the extent that more than six million people die from it each year (Lim et al., 2012; WHO, 2011).

The gases and particulates from burning fossil fuels are but one example of globally distributed pollutants. By-products of the fertilizers, herbicides and pesticides we presently rely on to grow food for the world, the pharmaceuticals we use, the chemicals utilized in manufacturing and mining, and the trash we discard have contaminated even the most remote environments of the world (Diaz and Rosenberg, 2008; Hayes et al., 2003; Lim et al., 2012; Newbold et al., 2009; Qiu, 2013; Staff, 2012). Many of these toxins have recently been shown to mimic hormones important in the metabolism of people and other animals, and may be much more dangerous in small rather than large concentrations – reversing the old slogan that "the dose makes the poison." Whales and polar bears harbor such toxins in their tissues; arctic lakes far from any human settlements exhibit elevated nitrogen levels; Texas-sized trash gyres swirl in the middle of the oceans; and both macro and microscopic plastic debris has become a ubiquitous constituent of the marine sediments (Andrady, 2011; Barnes et al., 2009, 2010; Cole et al., 2011; Fendall and Sewell, 2009; Ng and Obbard, 2006; Ryan et al., 2009; Zarfl et al., 2011; Zarfl and Matthies, 2010).

Increasing encroachment of humans into previously little-touched ecosystems is disrupting non-human communities and leading to more frequent and severe 'spillovers' of disease (Barnosky and Hadly, 2015; Quammen, 2012). Our limited knowledge of the reservoirs and vectors of these potential killers means that we can only guess from where and when they will emerge. Climatic change is further increasing the odds that novel diseases will crop up in humans and the plants and animals on which we depend: most of the world's diseases are tropical in origin, and as we build roads and destroy habitats there, we disrupt the native systems leading to an increased probability of exposure risk to us. Spillover from humans to animals is increasing as well—many of our wild, and sometimes migratory, animals are afflicted with antibiotic resistant forms of bacteria such as MRSA.

All of these human impacts add up to losses or serious degradation of more than half of the habitats (Hooke et al., 2012) that once supported many non-human species, and along with poaching, overfishing, and generally exploiting nature for short-term profit, have accelerated the extinction rate of wild animals and plants to levels not seen since the dinosaurs died out (Barnosky, 2014; Barnosky et al., 2011; Ceballos et al., 2015; Dirzo and Raven, 2003; GBO3, 2010; Pimm et al., 2006, 2014; Urban, 2015). The resulting loss of benefits to humankind already includes reduction in direct ecosystem services such as water filtration, pollination of crops, control of pests, food production, and emotional fulfillment, and indirect impacts like the spread of pathogens ranging from Lyme disease to Ebola (Barnosky and Hadly, 2015; Cardinale et al., 2012; Daily et al., 2000; Ehrlich et al., 2012; Foley et al., 2005, 2011; Jackson, 2008; McCauley et al., 2015; Tercek and Adams, 2013; Tyrrell, 2011; Vitousek et al., 1986, 1997; Young et al., 2014). Table 1 highlights the six crucial environmental problems on which this Special Feature focuses.

Table 1. Environmental issues of key concern[a]

Issue	Description
Climate disruption	More, faster climate change has occurred than since humans first became a species.
Extinctions	Not since the dinosaurs went 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 50% 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	More than seven 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.
Disease	More contact through destruction of intact ecosystems combined with dramatically changed environments are leading to increases in the rates and types of sicknesses that harm humans, other animals and plants.

[a]Adapted from Scientific Consensus Statement 2013.

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A large body of science now documents that if these problems continue to grow as they have over the past half-century, the result will be substantial harm to human wellbeing by 2050 (**Scientific Consensus on Maintaining Humanity's Life Support Systems in the 21st Century**), (Barnosky et al., 2012, 2014; Brown et al., 2011; Ehrlich and Ehrlich, 2013), even the possible collapse of civilization as we know it.

The next four decades

At the root of all of the threats listed above are the numbers of people in the world and the ecological footprint of each (GFN, 2013; Rockström et al., 2009; WWF, 2012), especially the excessively large per capita ecological footprints in high income countries (WWF et al., 2014). With respect to population growth, the best-case scenarios indicate that by 2050, the planet will have to support at least two billion to three billion people more than it does today (PRB, 2015; UNDESA, 2013a, 2013b). In order to feed that many more people, business-as-usual food production, distribution, and wastage would require converting even more of Earth's lands to agriculture, and overfishing more of the sea—but, there simply isn't enough productive land left to accomplish that, or enough of the species we presently like to eat left in the ocean (Ehrlich and Ehrlich, 2013; Foley, 2011; Foley et al., 2011; Jackson, 2008; Jackson et al., 2001; McCauley et al., 2015). Under business-as-usual burning of fossil fuels, the increased food production would have to take place under climate stresses that agriculture and aquaculture have not yet witnessed (Challinor et al., 2014; Lobell et al., 2008; Moore and Lobell, 2014; Ray et al., 2013; Trnka et al., 2014; West et al., 2014; White et al., 2013). Our present commensal animal population (cows, sheep, etc.) is more than three times the biomass than humans account for, and all of those animals require food and water, not to mention waste management (Barnosky, 2008; Barnosky and Hadly, 2015; Smil, 2011). Present emissions trajectories would, by mid-century, heat the planet to a level that humans and most other vertebrate species have never experienced (Blois and Hadly, 2009), inhibiting not only food production, but also greatly multiplying other climate-change problems already apparent (IPCC, 2013, 2014; IPCC-SREX, 2012; White et al., 2013), including exacerbating global conflict and national security concerns (CNA, 2007, 2014; Steinbruner et al., 2012). Indeed, if the present climate-change trajectory continued to 2100, Earth would be hotter than it has been in at least 14 million years, and large regions would be too hot to support human life outdoors (Sherwood and Huber, 2010). Even now, heat waves kill thousands of people increasingly frequently. Using presently accepted norms of manufacturing the goods and services to maintain present rates of consumption—not even accounting for the desirability of raising standards of living for billions of poor people today—would dramatically increase what already are dangerous levels of environmental contamination worldwide, and deplete critical natural resources we depend upon today—including water (Barnosky and Hadly, 2015). And, should present rates of extinction continue, in as little as two human lifetimes, Earth would lose three out of every four familiar species forever—a so-called Sixth Mass Extinction that is now beginning, an interruption of life so rare that it has occurred only five times since complex animals evolved half a billion years ago (Barnosky, 2014; Barnosky et al., 2011; Ceballos et al., 2015; Pimm et al., 2014). Already biodiversity is under such pressure that wildlife has suffered gigantic losses: more than half of all the Earth's vertebrate animals have been killed within four decades – a "defaunation" unprecedented in the history of humanity (WWF et al., 2014).

In reality, of course, the six problems listed in Table 1 are intertwined and feed back on one another (Barnosky et al., 2014; Barnosky and Hadly, 2015; Barnosky et al., 2012; Rockström et al., 2009; Steffen et al., 2011). As they act in concert, the risks of detrimental outcomes become greatly magnified.

The grand challenge

The grand challenge for science and society, then, is how to solve the intertwined problems of human population growth and overconsumption, climate change, pollution, ecosystem destruction, disease spillovers, and extinction, in order to avoid environmental tipping points that would make human life infinitely more difficult. Researchers in many disciplines have long recognized this challenge, and discussed it widely, especially in academic circles, for more than four decades, both from the perspective of the natural sciences (Table 2) and the social sciences (Leach et al., 2013; Raworth, 2012). However, understanding the problems stops short of fixing them, if the inter-related facets of seemingly distinct issues are not recognized, and if few outside the scientific community realize or accept that the problems are serious and that solutions are at hand. Therefore, a huge challenge within academia is working across traditional disciplinary boundaries to connect different pieces of the solutions puzzle that are emerging from practitioners spread across many different specialties (Cash et al., 2003; Ramanathan et al., 2015). And, an even bigger challenge is to take the knowledge developed within academia and collaborate closely with stakeholders in ways that elicit significant action (Ehrlich et al., 2012; Gibbons, 1999; Klenk et al., 2015). This is especially important, since guiding the planet for the future will likely require some fundamental changes—not just in human economic and governance systems—but also in societal values. Engagement with religious leaders, local communities and businesses, subnational groups and the military and security sectors of society, recently starting to burgeon, are critically important to further these necessary conversations and impel action (CNA, 2007, 2014; PAS and PASS, 2014; Ramanathan et al., 2015; Under2MOU, 2015; Vatican, 2015; WBSCD, 2013a, 2013b).

Table 2. Broad-brush solutions to key environmental problems[a]

Problem	Solution
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 for 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 well-being 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 health care, 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.
Disease	*Limit road-building and penetration of intact tropical forests.* Designate remaining tropical regions for limited dissection and extraction of resources. Better on-the-ground monitoring of the areas under resource extraction will help us ascertain where and when outbreaks are likely to occur. Since most global disease is a subset of tropical diseases, our focus should be on those areas in particular, but even temperate regions require vigilance—chronic wasting disease, for example, threatens wild and farmed animals alike in North America. *Anticipate global disease outbreaks and increase collaboration for containment and treatment.* Our experience with Ebola taught the world that we are woefully underprepared to coordinate and contain even very infectious diseases. Increased communication and collaboration here is critical.

[a]Reproduced from Scientific Consensus Statement 2013; see that document for elaboration.

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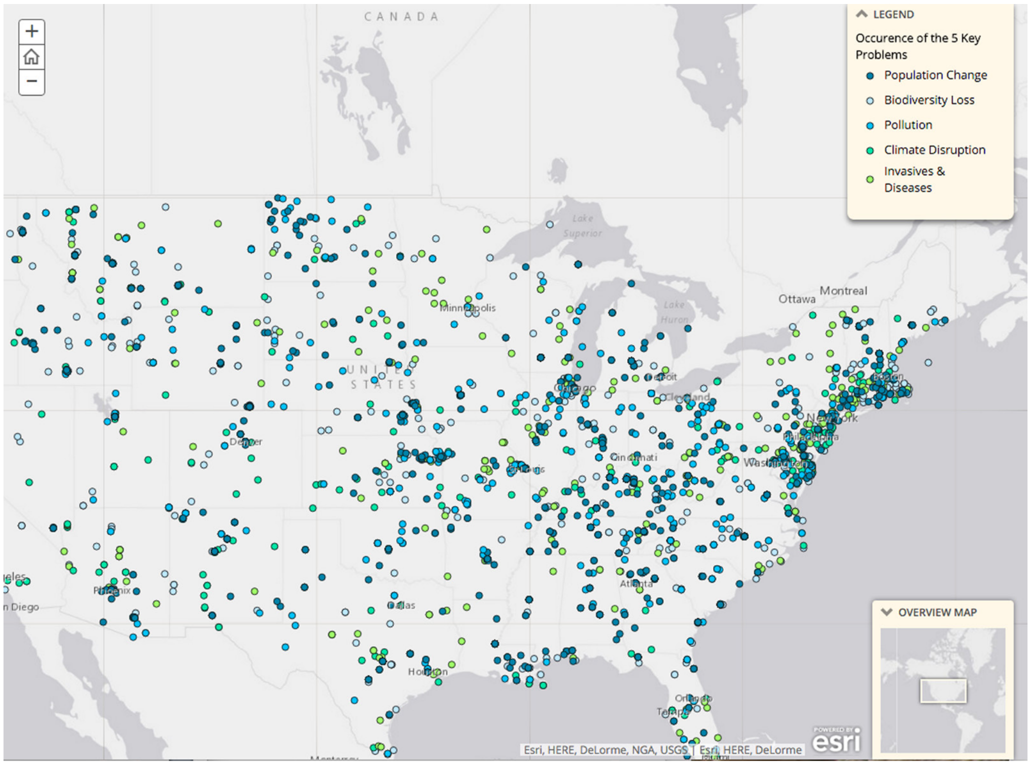

Figure 1

Mapping the stories of U.S. global change: The 5 key problems

This map shows the distribution of news articles about global change, categorized by the key problem it exemplifies. Source: Alexis Mychajliw, Sarah Truebe, Shane Johnson, Charlie Jiang, Simone Barley-Greenfield, Laura Cussen, and Elizabeth A. Hadly (Team Leaders), 2016, Mapping the Impacts of Global Change: Stories of Our Changing Environment as Told by U.S. Citizens. Stanford. maps.arcgis.com

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In this Special Feature, we offer six examples of how researchers are addressing these challenges through the process of discovering new knowledge and relevant tools within academia, and sharing knowledge and learning from stakeholders outside the Ivory Tower. The examples take the form of three articles and three web sites. The Special Feature arose from the symposium "Avoiding Collapse: Human Impacts on the Biosphere," at the 2015 American Association for the Advancement of Science Annual Meeting in San Jose, California, and the three articles are extensions of presentations that were conveyed there. To illustrate the key role of science and industry in developing new information technology that will be critical in identifying and responding to global change, Dawn Wright shares insights on digital resilience, and what that means for policy-making and conservation. Tyrone Hayes and Martin Hansen highlight the intersections between food production, environmental contamination, and some social and economic obstacles that stand in the way of sustainable agriculture. And Vice Admiral Lee Gun (Ret.) bridges the divide between science and society by assessing the national security implications of climate change—and expresses a view increasingly echoed at the highest levels of the national security community.

The three websites were constructed specifically to bridge the science-society divide. The Millennium Alliance for Humanity and the Biosphere was founded to connect scientists, humanists, activists and civil society in order to foster positive global change. The Consensus For Action website is an outgrowth of the Scientific Consensus on Maintaining Humanity's Life Support Systems in the 21st Century: Information for Policy Makers (Barnosky et al., 2014) a document which has been circulated to political leaders worldwide and used in discussions leading to international climate agreements. The website provides a venue for policy makers to quickly digest why it is essential to immediately address the issues of climate change, extinctions, ecosystem loss, pollution, and population overgrowth; for scientists to indicate to policy makers throughout the world the importance of dealing with those key environmental issues; and for the general public to voice their support to policy makers for taking action. The third website (Figure 1), "Mapping the Impacts of Global Change: Stories of Our Changing Environment as Told By U.S. Citizens," was developed to provide rapid and locally relevant information to everyone, from the general public to political leaders, about how these threats to humanity's life support systems play out, and resulted from dialogues between university students and faculty, policy makers at the state through national levels, and everyday citizens (Mychajliw et al., 2015).

These six examples illustrate that there is no one-size-fits all approach for researchers to address today's grand environmental challenges, but two common themes emerge. The first is that it is no longer enough to simply do the science and publish an academic paper; that is a necessary first step, but moves only halfway towards the goal of guiding the planet towards a future that is sustainable for both human civilization and the biosphere. To implement knowledge that arises from basic research, it is necessary to establish dialogues and collaborations that transcend narrow academic specialties, and bridge between academia, industry, the policy community and society in general. The second theme is that now is the time to rise to these scientific and communication challenges. The trajectories of population overgrowth, climate change, ecosystem loss, extinctions, disease, and environmental contamination have been rapidly accelerating over the past half-century. If not arrested within the next decade, their momentum may prevent us from stopping them short of disaster.

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Contributions

- Substantial contributions to conception and design: ADB, EAH, PRE
- Acquisition of data: ADB, EAH, PRE
- Analysis and interpretation of data: ADB, EAH, PRE
- Drafting the article or revising it critically for important intellectual content: ADB, EAH, PRE
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Competing interests

The authors declare no competing interests.