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

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

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## 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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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 ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ) and nitrous oxide ( $\text{NO}$ ). Of these,  $\text{CO}_2$  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 to 1-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<sub>2</sub> 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).

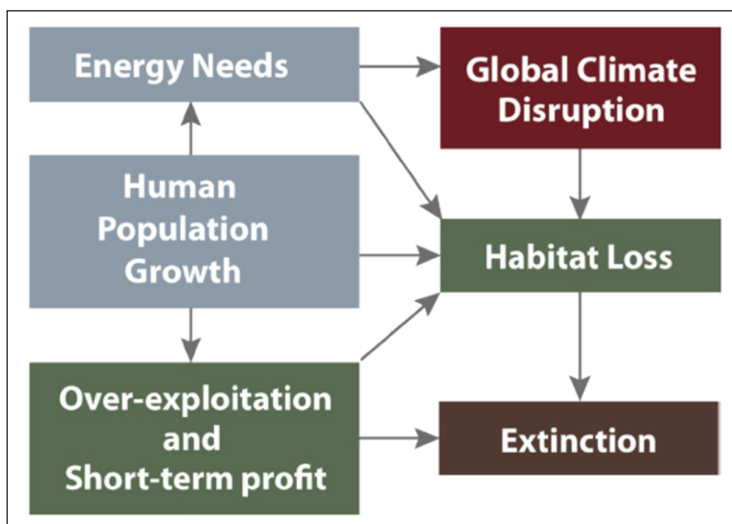
The world's ecosystems are *Natural Capital* that provides vital benefits called *Ecosystem Services* necessary for *Production of Goods* (crops, timber, seafood); *Life-Support Systems* (provision and purification of water, buffering against storms, floods, and droughts); *Life-Fulfilling Amenities* (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<sup>2</sup> (= 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<sup>2</sup> (= 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

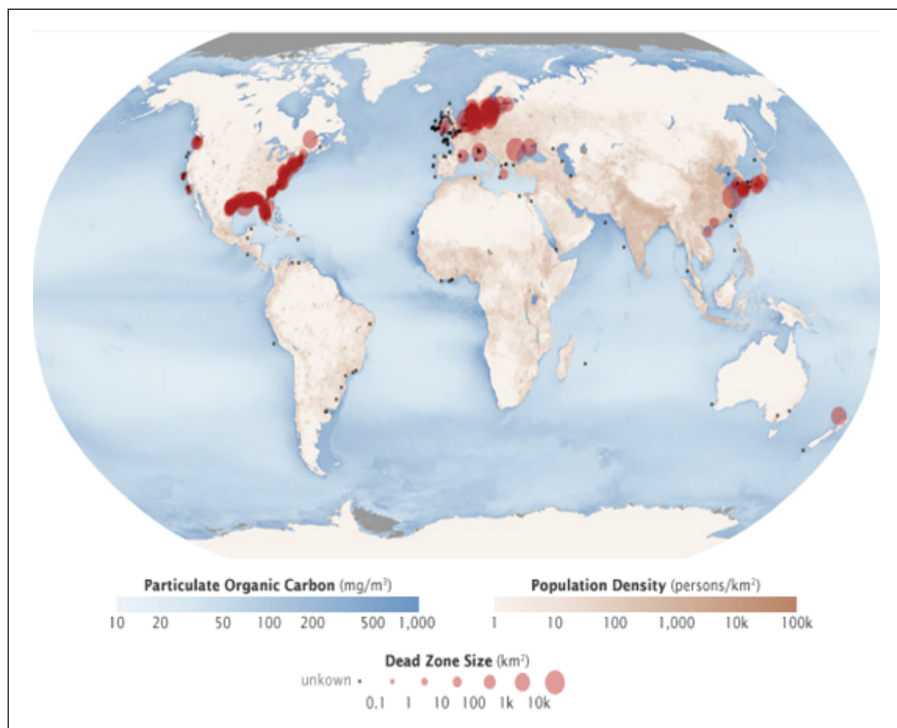
and Iguchi, 2012). Activities such as mining, manufacturing, and recycling of electronic equipment have not only concentrated dangerous pollutants locally, but also distributed them worldwide, notably harmful substances such as lead, chromium, mercury, and asbestos (Qiu, 2013; Staff, Blacksmith Institute, 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<sub>2</sub>), nitrous oxide (NO), and methane (CH<sub>4</sub>) – 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



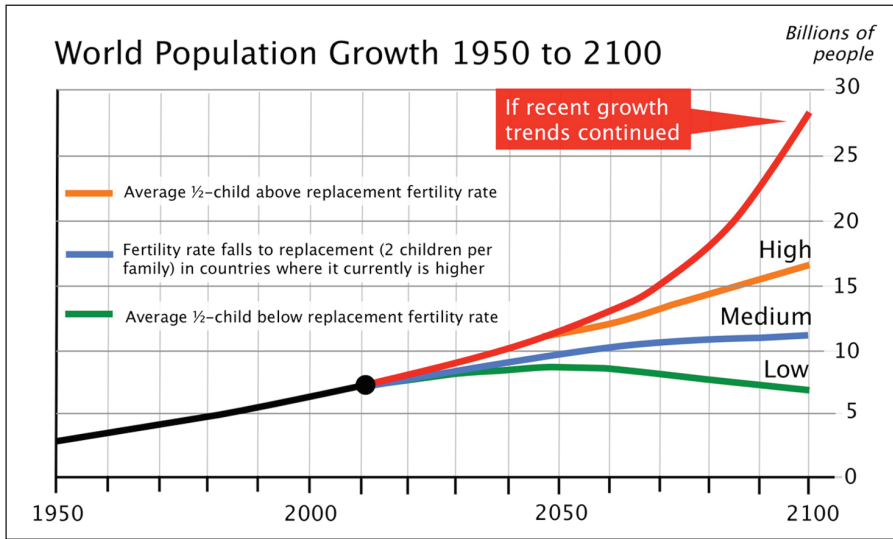
**Figure 7.** World distribution of dead zones in the ocean caused primarily by nitrogen pollution. Source: NASA (2010).

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

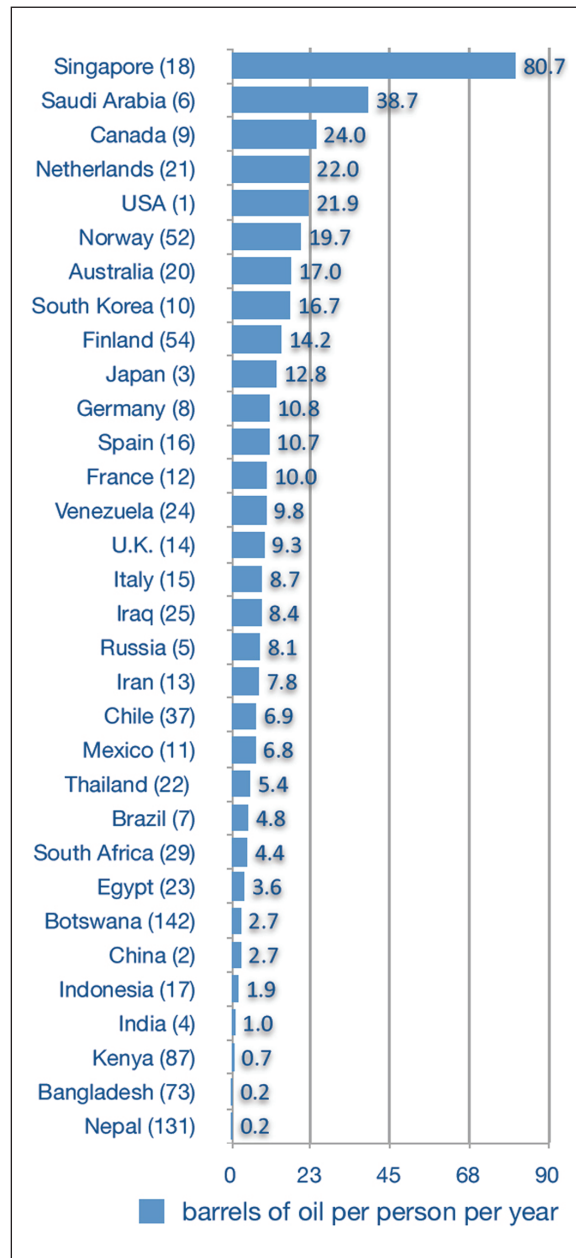


**Figure 8.** If the fertility rate in all countries rapidly changes so each family on average has one daughter, population will crest by 2050, then stabilize around 10.1 billion.  
Source: Data from UNDESA (2011).

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  $\frac{1}{2}$  child above replacement rate, the population would reach 15.8 billion in 2100, and a rate of  $\frac{1}{2}$  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<sub>2</sub> 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).

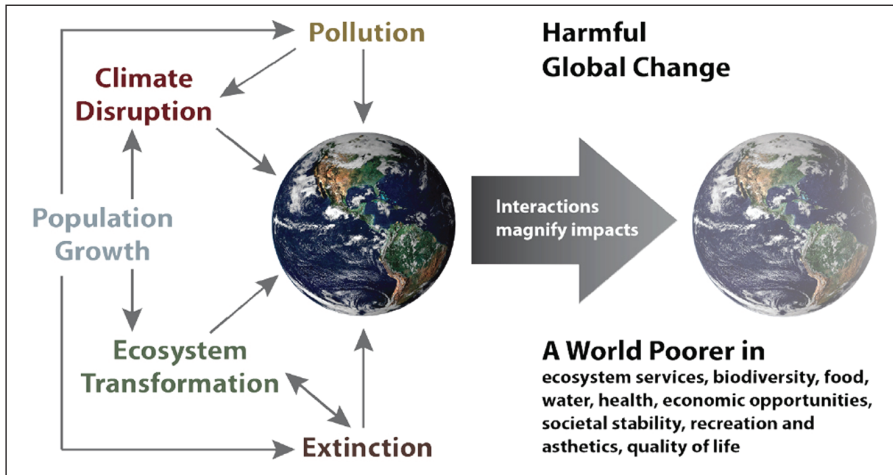
## Solutions

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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## References

- Ausubel JH, Wernick IK and Waggoner PE (2012) Peak farmland and the prospect for land sparing. *Population and Development Review* 38: 221–242.
- Barnosky AD, Hadly EA, Bascompte J et al. (2012) Approaching a state-shift in Earth's biosphere. *Nature* 486: 52–56.
- Barnosky AD, Matzke N, Tomiya S et al. (2011) Has the Earth's sixth mass extinction already arrived? *Nature* 471: 51–57.
- Bascompte J and Solé RV (1996) Habitat fragmentation and extinction thresholds in spatially explicit models. *Journal of Animal Ecology* 65: 465–473.
- Bax N, Williamson A, Aguero M et al. (2003) Marine invasive alien species: A threat to global biodiversity. *Marine Policy* 27: 313–323.
- Brown JH, Burnside WR, Davidson AD et al. (2011) Energetic limits to economic growth. *Bioscience* 61: 19–26.

- Cahill AE, Aiello-Lammens ME, Fisher-Reid MC et al. (2012) How does climate change cause extinction? *Proceedings of the Royal Society B – Biological Sciences* 280: 20121890. Available at: <http://dx.doi.org/10.1098/rspb.2012.1890>.
- Cardinale BJ, Duffy JE, Gonzalez A et al. (2012) Biodiversity loss and its impact on humanity. *Nature* 486: 59–67.
- Central Intelligence Agency (2013) *The World Factbook*. Washington, DC: CIA.
- Choat B, Jansen S, Brodribb TJ et al. (2012) Global convergence in the vulnerability of forests to drought. *Nature* 491: 752–756.
- Chu S and Majumdar A (2012) Opportunities and challenges for a sustainable energy future. *Nature* 488: 294–303.
- Cohen AN and Carlton JT (1998) Accelerating invasion rate in a highly invaded estuary. *Science* 279: 555–558.
- Collen B, Böhm M, Kemp R et al. (2012) *Spineless: Status and Trends of the World's Invertebrates*. London: Zoological Society of London.
- Convention on Biological Diversity (2011) *Strategic Plan for Biodiversity 2011–2020*. Available online at: [www.cbd.int/sp/](http://www.cbd.int/sp/) (accessed 28 March 2011).
- Cook PS (2011) *Impacts of Visitor Spending on the Local Economy: Yosemite National Park, 2009*. Natural Resource Report NPS. Available at: <http://www.nps.gov/yose/parkmgmt/upload/YOSE-09-MGM.pdf>.
- Daily GC and Ellison K (2002) *The New Economy of Nature: The Quest to Make Conservation Profitable*. Washington, DC: Island Press.
- Daily GC, Söderqvist T, Aniyar S et al. (2000) The value of nature and the nature of value. *Science* 289: 395–396.
- DAISIE (2012) *Delivering Alien Invasive Species Inventories for Europe*. European Commission under the Sixth Framework Programme through the DAISIE project. Available online at: <http://www.europe-aliens.org/> (accessed 8 December 2013).
- Davis SJ, Cao L, Caldeira K et al. (2013) Rethinking wedges. *Environmental Research Letters* DOI:10.1088/1748-9326/8/1/011001.
- Delucchi MA and Jacobson MZ (2011) Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy* 29: 1170–1190.
- Diaz RJ and Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926–929.
- Dirzo R and Raven PH (2003) Global state of biodiversity and loss. *Annual Review of Environment and Natural Resources* 28: 137–167.
- Dodds WK (2008) *Humanity's Footprint*. New York: Columbia University Press.
- Dow K and Downing TE (2007) *The Atlas of Climate Change*. Berkeley, CA: University of California Press.
- Ehrlich PR and Ehrlich AH (2013) Can a collapse of global civilization be avoided? *Proceedings of the Royal Society B – Biological Sciences* 280. Available at: <http://dx.doi.org/10.1098/rspb.2012.2845>.
- Ehrlich PR, Kareiva PM and Daily GC (2012) Securing natural capital and expanding equity to rescale civilization. *Nature* 486: 68–73.
- Ellis EC (2011) Anthropogenic transformation of the terrestrial biosphere. *Philosophical Transactions of the Royal Society A* 369: 1010–1035.
- Ellis EC, Antill EC and Kref H (2012) Plant biodiversity in the Anthropocene. *PLOS ONE* 7: e30535.
- Ewing B, Moore D, Goldinger S et al. (2010) *Ecological Footprint Atlas 2010*. Oakland, CA: Ecological Footprint Network.
- Fendorf S, Michael HA and vanGeen A (2010) Spatial and temporal variations of groundwater arsenic in South and Southeast Asia. *Science* 328: 1123–1127.
- Foley JA, DeFries R, Asner GP et al. (2005) Global consequences of land use. *Science* 309: 570–574.
- Foley JA, Ramankutty N, Brauman KA et al. (2011) Solutions for a cultivated planet. *Nature* 478: 337–342.
- Folke C, Jansson Å, Rockström J et al. (2011) Reconnecting to the biosphere. *AMBIO: A Journal of the Human Environment* 40: 719–738.

- Food and Agriculture Organization (FAO) (2012a) *The State of Food Insecurity in the World 2012*. Rome: Food and Agriculture Organization of the United Nations.
- Food and Agriculture Organization (FAO) (2012b) *State of the World's Forests, 2012*. Rome: Food and Agriculture Organization of the United Nations.
- Global Biodiversity Outlook 3 (2010) *Global Biodiversity Outlook 3*. Montréal: Secretariat of the Convention on Biological Diversity.
- Greenburg P (2011) *Four Fish, the Future of the Last Wild Food*. Penguin.
- Griggs D, Stafford-Smith M, Gaffney O et al. (2013) Sustainable development goals for people and planet. *Nature* 495: 305–307.
- Guillette LJ Jr and Iguchi T (2012) Life in a contaminated world. *Science* 337: 1614–1615.
- Haberl H, Erb K-H, Krausmann F et al. (2007) Quantifying and mapping the human appropriation of net primary production in Earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences* 104: 12,942–12,947.
- Halpern BS, Walbridge S, Selkoe KA et al. (2008) A global map of human impact on marine ecosystems. *Science* 319: 948–952.
- Hoekstra JM, Molnar JL, Jennings M et al. (2010) *The Atlas of Global Conservation*. Berkeley, CA: University of California Press.
- Holtgrieve GW, Schindler DE, Hobbs WO et al. (2011) A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the northern hemisphere. *Science* 334: 1545–1548.
- Hughes JB, Daily GC and Ehrlich PR (1997) Population diversity: Its extent and extinction. *Science* 278: 689–692.
- Intergovernmental Panel on Climate Change (IPCC) (2007) *Intergovernmental Panel on Climate Change: Fourth Assessment Report (AR4)*. Available at: [http://www.ipcc.ch/publications\\_and\\_data/ar4/syr/en/contents.html](http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html).
- Intergovernmental Panel on Climate Change (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the IPCC. Field CB, Barros V, Stocker TF et al. (eds). New York: Cambridge University Press, pp.1–594.
- Intergovernmental Panel on Climate Change (IPCC) (2013) *Summary for Policymakers, AR5*. In: Stocker TF, Qin D, Plattner G-K et al. (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York, NY: Cambridge University Press, pp. 1–27. Available at: [http://www.climatechange2013.org/images/uploads/WGI\\_AR5\\_SPM\\_brochure.pdf](http://www.climatechange2013.org/images/uploads/WGI_AR5_SPM_brochure.pdf)
- International Union for Conservation of Nature (IUCN) (2008) *Elephas maximus*. *IUCN Red List*. Available at: <http://www.iucnredlist.org/details/7140/0>.
- International Union for Conservation of Nature (IUCN) (2010) *International Union for Conservation of Nature Red List*. Available at: [http://www.iucn.org/about/work/programmes/species/red\\_list/](http://www.iucn.org/about/work/programmes/species/red_list/) (accessed 28 March 2011).
- Jackson JBC (2008) Ecological extinction and evolution in the brave new ocean. *Proceedings of the National Academy of Science* 105: 11,458–11,465.
- Jackson JBC, Kirby MX, Berger WH et al. (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629–638.
- Jacobson MZ and Delucchi MA (2009) A path to sustainable energy by 2030. *Scientific American* November: 58–65.
- Jacobson MZ and Delucchi MA (2011) Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 29: 1154–1169.
- Kahrl F and Roland-Holst D (2012) *Climate Change in California*. Berkeley, CA: University of California Press.
- Kurz WA, Bymond CC, Stinson G et al. (2008) Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452: 987–990.
- Lenton TM (2011) Early warning of climate tipping points. *Nature Climate Change* 1: 201–209.

- Lim SS, Vos T, Flaxman AD et al. (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 380: 2224–2260.
- Lobell DB, Burke MB, Tebaldi C et al. (2008) Prioritizing climate change adaptation needs for food security in 2030. *Science* 319: 607–610.
- Lobell DB, Field CB, Cahill KN et al. (2006) Impacts of future climate change on California perennial crop yields: Model projections with climate and crop uncertainties. *Agricultural and Forest Meteorology* 141: 208–218.
- McLachlan JS and Hellmann JJ (2007) A framework for the debate of assisted migration in an era of climate change. *Conservation Biology* 21: 297–302.
- McMenamin SK, Hadly EA and Wright CK (2008) Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. *Proceedings of the National Academy of Sciences of the United States of America* 105: 16,988–16,993.
- McRae L, Collen B, Deinet S et al. (2012) The Living Planet Index. In: Grooten M (ed.) *Living Planet Report*. Gland: World Wildlife Fund, pp. 1–161.
- Maurer BA (1996) Relating human population growth to the loss of biodiversity. *Biodiversity Letters* 3: 1–5.
- Morel FMM, Archer D, Barry JP et al. (2010) *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Washington, DC: National Academies Press.
- National Aeronautics and Space Administration (NASA) (2010) Aquatic dead zones. *Earth Observatory*. Available at: <http://earthobservatory.nasa.gov/IOTD/view.php?id=44677>
- National Oceanic and Atmospheric Administration (NOAA) (2013a) *Marine Debris*. National Oceanic and Atmospheric Administration. Available at: <http://marinedebris.noaa.gov/welcome.html>
- National Oceanic and Atmospheric Administration (NOAA) (2013b) *State of the Coast*. National Oceanic and Atmospheric Administration. Available at: [http://stateofthecoast.noaa.gov/com\\_fishing/welcome.html](http://stateofthecoast.noaa.gov/com_fishing/welcome.html).
- Naylor RL, Goldburg RJ, Primavera JH et al. (2000) Effect of aquaculture on world fish supplies. *Nature* 405: 1017–1024.
- Naylor RL, Hardy RW, Bureau DP et al. (2009) Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences* 106: 15,103–15,110.
- Newbold RR, Padilla-Banks E and Jefferson WN (2009) Environmental estrogens and obesity. *Mol Cell Endocrinology* 304: 84–89.
- Noss RF, Dobson AP, Baldwin R et al. (2012) Bolder thinking for conservation. *Conservation Biology* 26: 1–4.
- Olivier JGJ, Janssens-Maenhout G and Peters JAHW (2012) *Trends in Global CO<sub>2</sub> Emissions 2012 Report*. The Hague/Bilthoven: PBL Netherlands Environmental Assessment Agency.
- Pardini R, Bueno AdA, Gardner TA et al. (2010) Beyond the fragmentation threshold hypothesis: Regime shifts in biodiversity across fragmented landscapes. *PLOS ONE* 5: e13666, 13,661–13,610.
- Patz JA, Daszak P, Tabor GM et al. (2004) Unhealthy landscapes: Policy recommendations on land use change and infectious disease emergence. *Environmental Health Perspectives* 112: 1092–1098.
- Pejchar L and Mooney HA (2009) Invasive species, ecosystem services and human well-being. *Trends in Ecology and Evolution* 24: 497–504.
- Peters DPC, Bestelmeyer BT, Knapp AK et al. (2009) Approaches to predicting broad-scale regime shifts using changing pattern–process relationships across scales. In: Miao SL, Carstenn S and Nungesser MK (eds) *Real World Ecology*. New York: Springer, pp. 47–71.
- Pfeffer WT, Harper JT and O’Neel S (2008) Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* 321: 1340–1343.
- Pimm SL and Raven PH (2000) Extinction by numbers. *Nature* 403: 843–845.
- Pimm SL, Raven P, Peterson A et al. (2006) Human impacts on the rates of recent, present, and future bird extinctions. *Proceedings of the National Academy of Sciences of the United States of America* 103: 10,941–10,946.
- Pimm SL, Russell GJ, Gittleman JL et al. (1995) The future of biodiversity. *Science* 269: 347–350.

- Population Reference Bureau (PRB) (2012) *Population Projections 2050*. Population Reference Bureau. Available at: <http://www.prb.org/> (accessed 20 February 2012).
- PriceWaterhouseCoopersLLP (2012) *Too Late for Two Degrees? Low Carbon Economy Index 2012*. Available at: [http://www.pwc.com/en\\_GX/gx/low-carbon-economy-index/assets/pwc-low-carbon-economy-index-2012.pdf](http://www.pwc.com/en_GX/gx/low-carbon-economy-index/assets/pwc-low-carbon-economy-index-2012.pdf), pp. 1–16.
- Qiu J (2013) Tough talk over mercury treaty. *Nature* 493: 144–145.
- Quammen D (2012) *Spillover: Animal Infections and the Next Human Pandemic*. New York: W.W. Norton & Company.
- Rahmstorf S (2007) A semi-empirical approach to projecting future sea-level rise. *Science* 315: 368–370.
- Ricketts TH, Daily GC, Ehrlich PR et al. (2004) Economic value of tropical forest to coffee production. *Proceedings of the National Academy of Sciences* 101: 12,579–12,582.
- Rockström J, Steffen W, Noone K et al. (2009) A safe operating space for humanity. *Nature* 461: 472–475.
- Rogelj J, McCollum DL, Reisinger A et al. (2012) Probabilistic cost estimates for climate change mitigation. *Nature* 493: 79–83.
- Running SW (2012) A measurable planetary boundary for the biosphere. *Science* 337: 1458–1459.
- Salazar LF, Nobre CA and Oyama MD (2007) Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters* 34: L09708 09701–09706.
- Sanderson EW, Jaiteh M, Levy MA et al. (2002) The human footprint and the last of the wild. *Bioscience* 52: 891–904.
- Scheffer M, Bascompte J, Brock WA et al. (2009) Early-warning signals for critical transitions. *Nature* 461: 53–59.
- Scheffer M, Carpenter S, Foley JA et al. (2001) Catastrophic shifts in ecosystems. *Nature* 413: 591–596.
- Scheffer M, Hirota M, Holmgren M et al. (2012) Thresholds for boreal biome transitions. *Proceedings of the National Academy of Science* 109: 21,384–21,389.
- Schug TT, Abagyan R, Blumberg B et al. (2013) Designing endocrine disruption out of the next generation of chemicals. *Green Chemistry* 15: 181–198.
- Shah A (2011) Health issues. *Global Issues*. Available at: <http://www.globalissues.org/issue/587/health-issues>.
- Shah A (2013) Poverty facts and stats. *Global Issues*. Available at: <http://www.globalissues.org/article/26/poverty-facts-and-stats>
- Shearer AW (2005) Whether the weather: Comments on ‘An abrupt climate change scenario and its implications for United States national security’. *Futures* 37: 445–463.
- Sherwood SC and Huber M (2010) An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Science* 107: 9552–9555.
- Smith WK, Zhao M and Running SW (2012) Global bioenergy capacity as constrained by observed biospheric productivity rates. *Bioscience* 62: 911–922.
- Solomon S, Battisti D, Doney S et al. (2011) *Climate Stabilization Targets: Emissions, Concentrations, and Impacts of Decades to Millennia*. Washington, DC: National Academies Press.
- Speidel JJ, Weiss DC, Ethelston SA et al. (2009) Population policies, programmes and the environment. *Philosophical Transactions of the Royal Society B* 364: 3049–3065.
- Staff, Blacksmith Institute (2012) *The World's Worst Pollution Problems 2012*. New York: Blacksmith Institute.
- Steffen W, Persson Å, Deutsch L et al. (2011) The Anthropocene: From global change to planetary stewardship. *AMBIO: A Journal of the Human Environment* 40: 739–761.
- Steinbruner JD, Stern PC, Husbands JL et al. (2012) *Climate and Social Stress: Implications for Security Analysis*. Washington, DC: National Academies Press.
- Stynes DJ (2011) Economic benefits to local communities from national park visitation and payroll, 2010. *Natural Resource Report NPS/NRSS/EQD/NRR—2011/481*. Available at: <http://www.nature.nps.gov/socialscience/docs/NPSSystemEstimates2010.pdf>
- Swift TL and Hannon SJ (2010) Critical thresholds associated with habitat loss: A review of the concepts, evidence, and applications. *Biological Reviews* 85: 35–53.

- Taylor JE, Hardner J and Stewart M (2008) Ecotourism and economic growth in the Galapagos: an island economy-wide analysis. *Environmental and Developmental Economics* 14: 139–162.
- Thuillier C (2012) Introduced plants outnumber natives. *Australian Geographic* 14 August. Available at: <http://www.australiangeographic.com.au/journal/invasive-plants-outnumber-australian-natives.htm> (accessed 12 December 12).
- United Nations Department of Economic and Social Affairs (UNDESA) (2011) *World Population Prospects, the 2010 Revision*. United Nations Department of Economic and Social Affairs Population Division, Population Estimates and Projections Section. Available at: [http://esa.un.org/unpd/wpp/Analytical-Figures/htm/fig\\_1.htm](http://esa.un.org/unpd/wpp/Analytical-Figures/htm/fig_1.htm) (accessed 10 December 2011).
- United States Agency for International Development (USAID) (2013) *Kenya, Environment*. USAID Kenya. Available at: <http://kenya.usaid.gov/programs/environment>
- Vié J-C, Hilton-Taylor C, Stuart SN et al. (2009) *Wildlife in a Changing World – An Analysis of the 2008 IUCN Red List of Threatened Species*. Gland: IUCN.
- Vitousek PM, D'Antonio CM, Loope LL et al. (1997a) Introduced species: A significant component of human-caused global change. *New Zealand Journal of Ecology* 21: 1–16.
- Vitousek PM, Ehrlich PR, Ehrlich AH et al. (1986) Human appropriation of the products of photosynthesis. *Bioscience* 36: 368–373.
- Vitousek PM, Mooney HA, Lubchenco J et al. (1997b) Human domination of Earth's ecosystems. *Science* 277: 494–499.
- Walthall, CL JH, Backlund P et al. (2012) Climate change and agriculture in the United States: Effects and adaptation. *USDA Technical Bulletin* 1935: 1–186.
- Wang R, Dearing JA, Langdon PG et al. (2012) Flickering gives early warning signals of a critical transition to a eutrophic lake state. *Nature* 492: 419–422.
- Williams JW, Jackson ST and Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* 104: 5738–5742.
- World Health Organization (WHO) (2011) *Tackling the Global Clean Air Challenge*. World Health Organization Media Center. Available at: [http://www.who.int/mediacentre/news/releases/2011/air\\_pollution\\_20110926/en/index.html](http://www.who.int/mediacentre/news/releases/2011/air_pollution_20110926/en/index.html)
- World Health Organization (WHO) (2013a) *Climate Change and Health*. World Health Organization Fact Sheet 266. Available at: <http://www.who.int/mediacentre/factsheets/fs266/en/index.html>
- World Health Organization (WHO) (2013b) *Millennium Development Goals (MDGs), Health Topics, MDG 1: Eradicate Extreme Poverty and Hunger*. Millennium Development Goals. Available at: [http://www.who.int/topics/millennium\\_development\\_goals/hunger/en/index.html](http://www.who.int/topics/millennium_development_goals/hunger/en/index.html)
- World Resources Institute (WRI) (2005) *Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Biodiversity Synthesis*. Washington, DC: World Resources Institute.
- World Wildlife Foundation (WWF) (2012) *Free-flowing Rivers, Economic Luxury or Ecological Necessity?* World Wildlife Foundation, Available at: <http://awsassets.panda.org/downloads/freeflowingriversreport.pdf>
- Zachos JC, Dickens GR and Zeebe RE (2008) An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* 451: 279–283.

### Some other relevant reports

- Brundtland GH, Ehrlich P, Goldemberg J et al. (2012) *Environment and Development Challenges: The Imperative to Act*. Available at: [http://www.af-info.or.jp/bpplaureates/doc/2012jp\\_fp\\_en.pdf](http://www.af-info.or.jp/bpplaureates/doc/2012jp_fp_en.pdf)
- Carabias J, Molina M and Sarukhán J (2010) *Climate Change: Causes, Effects and Solutions*. Mexico City: Secretaría de Relaciones Exteriores/AHD-Fundación Coca Cola, pp. 1–197.
- Convention on Biological Diversity (2010) *Global Biodiversity Outlook 3*. Montréal: Secretariat of the Convention on Biological Diversity. Available at: <http://www.cbd.int/gbo3/>
- Convention on Biological Diversity (2011) *Strategic Plan for Biodiversity 2011–2020*. Available at: <http://www.cbd.int/sp/>



- Crowder L, Caldwell M, Barry J et al. (2012) *Consensus Statement on Climate Change and Coral Reefs*. Available at: <http://hopkins.stanford.edu/climate/fulltext.pdf>
- Ewing B, Moore D, Goldinger S et al. (2010) *Ecological Footprint Atlas 2010*. Oakland, CA: Ecological Footprint Network, pp. 1–113.
- Food and Agriculture Organization of the United Nations (2012) *The State of Food Insecurity in the World 2012*. Rome: Food and Agriculture Organization of the United Nations, pp. 1–65.
- Food and Agriculture Organization of the United Nations (2012) *State of the World's Forests, 2012*. Rome: Food and Agriculture Organization of the United Nations, pp. 1–60.
- Hoekstra JM, Molnar JL, Jennings M et al. (2010) *The Atlas of Global Conservation*. Berkeley, CA: University of California Press.
- McIntyre BD, Herren HR, Wakhungu J et al. (2009) *Agriculture at a Crossroads, International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): Synthesis Report with Executive Summary: A Synthesis of the Global and Sub-global IAASTD Reports*. Island Press.
- McRae L, Collen B, Deinet S et al. (2012) The Living Planet Index. In: Grooten M (ed.) *Living Planet Report*. Gland: World Wildlife Fund.
- National Research Council (1999) *Our Common Journey, A Transition Toward Sustainability*. Board on Sustainable Development, National Research Council. Washington, DC: National Academy of Sciences, pp. 1–380.
- Price Waterhouse Coopers LLP (2012) *Too Late for Two Degrees? Low Carbon Economy Index*. Available at: [http://www.pwc.com/en\\_GX/gx/low-carbon-economy-index/assets/pwc-low-carbon-economy-index-2012.pdf](http://www.pwc.com/en_GX/gx/low-carbon-economy-index/assets/pwc-low-carbon-economy-index-2012.pdf), pp. 1–16.
- Sarukhán J et al. (2012) *Capital Natural de México: Acciones Estratégicas Para su Valoración, Preservación y Recuperación*. Mexico City: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, pp. 1–91.
- Society for Conservation Biology Board of Governors (2008) *Recommendations for the Obama Administration to Advance the Scientific Foundation for Conserving Biological Diversity 2009–2013*. Washington, DC: Society for Conservation Biology, 24 pp. Available at: [http://www.conbio.org/images/content\\_policy/SCB2008TransitionTeamRecommendations.pdf](http://www.conbio.org/images/content_policy/SCB2008TransitionTeamRecommendations.pdf)
- Society for Conservation Biology Board of Governors (2013) *Recommendations for the Obama Administration to Advance the Scientific Foundation for Conserving Biological Diversity 2013–2017*. Washington, DC: Society for Conservation Biology, 24 pp. Available at: [http://www.conbio.org/images/content\\_policy/2013-4-22\\_SCB\\_Recommendations\\_to\\_Obama\\_Administration\\_2nd\\_Term.pdf](http://www.conbio.org/images/content_policy/2013-4-22_SCB_Recommendations_to_Obama_Administration_2nd_Term.pdf)
- Staff, Blacksmith Institute (2012) *The World's Worst Pollution Problems 2012*. New York: Blacksmith Institute, pp. 1–54.
- Sulston J, Bateson P, Biggar N et al. (2012) *People and the Planet*. London: The Royal Society, pp. 1–134.
- Union of Concerned Scientists (1992) *World Scientists' Warning to Humanity, Scientist Statement*. Union of Concerned Scientists. Available at: <http://www.ucsusa.org/about/1992-world-scientists.html>, pp. 1–5.
- United Nations Environment Programme (2012) *21 Issues for the 21st Century, Results of the UNEP Foresight Processon Emerging Environmental Issues*. Nairobi: United Nations Environmental Programme, pp. 1–56.
- Vié J-C, Hilton-Taylor C and Stuart SN (eds) (2009) *Wildlife in a Changing World – An Analysis of the 2008 IUCN Red List of Threatened Species*. Gland: IUCN, 180 pp.
- World Resources Institute (2005) *Millennium Ecosystem Assessment, Ecosystems and Human Well-being*. Washington, DC: Island Press. Available at: <http://www.unep.org/maweb/en/index.aspx>
- World Science Academies (1994) Science summit: On world population. A joint statement by 58 of the World's Scientific Academies. *Population and Development Review* 20: 233–238.
- World Wildlife Fund (2012) *Free-flowing Rivers, Economic Luxury or Ecological Necessity?* World Wildlife Foundation, <http://awsassets.panda.org/downloads/freeflowingriversreport.pdf>