The Rockefeller Foundation THE LANCET

The Rockefeller Foundation–*Lancet* Commission on planetary health

Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–*Lancet* Commission on planetary health

Sarah Whitmee, Andy Haines, Chris Beyrer, Frederick Boltz, Anthony G Capon, Braulio Ferreira de Souza Dias, Alex Ezeh, Howard Frumkin, Peng Gong, Peter Head, Richard Horton, Georgina M Mace, Robert Marten, Samuel S Myers, Sania Nishtar, Steven A Osofsky, Subhrendu K Pattanayak, Montira J Pongsiri, Cristina Romanelli, Agnes Soucat, Jeanette Vega, Derek Yach

Executive summary

Far-reaching changes to the structure and function of the Earth's natural systems represent a growing threat to human health. And yet, global health has mainly improved as these changes have gathered pace. What is the explanation? As a Commission, we are deeply concerned that the explanation is straightforward and sobering: we have been mortgaging the health of future generations to realise economic and development gains in the present. By unsustainably exploiting nature's resources, human civilisation has flourished but now risks substantial health effects from the degradation of nature's life support systems in the future. Health effects from changes to the environment including climatic change, ocean acidification, land degradation, water scarcity, over-exploitation of fisheries, and biodiversity loss pose serious challenges to the global health gains of the past several decades and are likely to become increasingly dominant during the second half of this century and beyond. These striking trends are driven by highly inequitable, inefficient, and unsustainable patterns of resource consumption and technological development, together with population growth.

We identify three categories of challenges that have to be addressed to maintain and enhance human health in the face of increasingly harmful environmental trends. Firstly, conceptual and empathy failures (imagination challenges), such as an over-reliance on gross domestic product as a measure of human progress, the failure to account for future health and environmental harms over present day gains, and the disproportionate effect of those harms on the poor and those in developing nations. Secondly, knowledge failures (research and information challenges), such as failure to address social and environmental drivers of ill health, a historical scarcity of transdisciplinary research and funding, together with an unwillingness or inability to deal with uncertainty within decision making frameworks. Thirdly, implementation failures (governance challenges), such as how governments and institutions delay recognition and responses to threats, especially when faced with uncertainties, pooled common resources, and time lags between action and effect.

Although better evidence is needed to underpin appropriate policies than is available at present, this should not be used as an excuse for inaction. Substantial potential exists to link action to reduce environmental damage with improved health outcomes for nations at all levels of economic development. This Commission identifies opportunities for action by six key constituencies: health professionals, research funders and the academic community, the UN and Bretton Woods bodies, governments, investors and corporate reporting bodies, and civil society organisations.

Depreciation of natural capital and nature's subsidy should be accounted for so that economy and nature are not falsely separated. Policies should balance social progress, environmental sustainability, and the economy. To support a world population of 9–10 billion people or more, resilient food and agricultural systems are needed to address both undernutrition and overnutrition, reduce waste, diversify diets, and minimise environmental damage. Meeting the need for modern family planning can improve health in the short term—eg, from reduced maternal mortality and reduced pressures on the environment and on infrastructure.

Planetary health offers an unprecedented opportunity for advocacy of global and national reforms of taxes and subsidies for many sectors of the economy, including energy, agriculture, water, fisheries, and health. Regional trade treaties should act to further incorporate the

Lancet 2015; 386: 1973–2028

Published Online July 16, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60901-1

This online publication has been corrected. The corrected version first appeared at thelancet.com on August 17, 2015

See **Comment** pages 1921, e36, e37, and e39

For **infographic** see http://www.thelancet.com/infographics/planetary-health

Centre for Biodiversity and Environment Research, University College London, London, UK (S Whitmee PhD, Prof G M Mace DPhil); **London School of Hygiene & Tropical Medicine, London, UK** (Prof A Haines FMedSci, R Marten MPH); **Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA** (Prof C Beyrer MD); **The Rockefeller Foundation, New York, NY, USA** (F Boltz PhD, R Marten); **International Institute for Global Health, United Nations University, Federal Territory of Kuala Lumpur, Malaysia** (Prof A G Capon PhD); **Convention on Biological Diversity, Montreal, QC, Canada** (B F de Souza Dias PhD, C Romanelli MSc); **African Population and Health Research Center, Nairobi, Kenya** (A Ezeh PhD); **School of**

Key messages

1 The concept of planetary health is based on the understanding that human health and human civilisation depend on flourishing natural systems and the wise stewardship of those natural systems. However, natural systems are being degraded to an extent unprecedented in human history.
2 Environmental threats to human health and human civilisation will be characterised by surprise and uncertainty. Our societies face clear and potent dangers that require urgent and transformative actions to protect present and future generations.
3 The present systems of governance and organisation of human knowledge are inadequate to address the threats to planetary health. We call for improved governance to aid the integration of social, economic, and environmental policies and for the creation, synthesis, and application of interdisciplinary knowledge to strengthen planetary health.
4 Solutions lie within reach and should be based on the redefinition of prosperity to focus on the enhancement of quality of life and delivery of improved health for all, together with respect for the integrity of natural systems. This endeavour will necessitate that societies address the drivers of environmental change by promoting sustainable and equitable patterns of consumption, reducing population growth, and harnessing the power of technology for change.

Public Health, University of Washington, Seattle, WA, USA (H Frumkin MD); **Center for Earth System Science, Tsinghua University, Beijing, China** (Prof P Gong PhD); **The Ecological Sequestration Trust, London, UK** (P Head BSc); **The Lancet, London, UK** (R Horton FMedSci); **Center for the Environment, Harvard University, Cambridge, MA, USA** (S S Myers MD); **Harvard T.H. Chan School of Public Health** (S S Myers); **Heartfile, Islamabad, Pakistan** (S Nishtar PhD); **Wildlife Conservation Society, Oakton, VA, USA** (S A Osofsky DVM); **Sanford School of Public Policy and Nicholas School of the Environment, Duke University, Durham, NC, USA** (Prof S K Pattanayak PhD); **US Environmental Protection Agency, Washington, DC, USA** (M J Pongsiri PhD); **The World Bank, Washington, DC, USA** (A Soucat PhD); **The National Chilean Public Health Insurance Agency, Santiago, Chile** (J Vega MD); **and The Vitality Group, New York, NY, USA** (D Yach MBChB)

Correspondence to: Dr Sarah Whitmee, Centre for Biodiversity and Environment Research, Department of Genetics, Evolution and Environment, University College London, London WC1E 6BT, UK **s.whitmee@ucl.ac.uk**

protection of health in the near and long term. Several essential steps need to be taken to transform the economy to support planetary health. These steps include a reduction of waste through the creation of products that are more durable and require less energy and materials to manufacture than those often produced at present; the incentivisation of recycling, reuse, and repair; and the substitution of hazardous materials with safer alternatives.

Despite present limitations, the Sustainable Development Goals provide a great opportunity to integrate health and sustainability through the judicious selection of relevant indicators relevant to human wellbeing, the enabling infrastructure for development, and the supporting natural systems, together with the need for strong governance.

The landscape, ecosystems, and the biodiversity they contain can be managed to protect natural systems, and indirectly, reduce human disease risk. Intact and restored ecosystems can contribute to resilience (see panel 1 for glossary of terms used in this report), for example, through improved coastal protection (eg, through wave attenuation) and the ability of floodplains and greening of river catchments to protect from river flooding events by diverting and holding excess water.

The growth in urban populations emphasises the importance of policies to improve health and the urban environment, such as through reduced air pollution, increased physical activity, provision of green space, and urban planning to prevent sprawl and decrease the magnitude of urban heat islands.

Transdisciplinary research activities and capacity need substantial and urgent expansion. Present research limitations should not delay action. In situations where technology and knowledge can deliver win–win solutions and co-benefits, rapid scale-up can be achieved if researchers move ahead and assess the implementation of potential solutions. Recent scientific investments towards understanding non-linear state shifts in ecosystems are very important, but in the absence of improved understanding and predictability of such changes, efforts to improve resilience for human health and adaptation strategies remain a priority. The creation of integrated surveillance systems that collect rigorous health, socio-economic, and environmental data for defined populations over long time periods can provide early detection of emerging disease outbreaks or changes in nutrition and non-communicable disease burden. The improvement of risk communication to policy makers and the public and the support of policy makers to make evidence-informed decisions can be helped by an increased capacity to do systematic reviews and the provision of rigorous policy briefs.

Health professionals have an essential role in the achievement of planetary health: working across sectors to integrate policies that advance health and environmental sustainability, tackling health inequities, reducing the environmental impacts of health systems, and increasing the resilience of health systems and populations to environmental change.

Humanity can be stewarded successfully through the 21st century by addressing the unacceptable inequities in health and wealth within the environmental limits of the Earth, but this will require the generation of new knowledge, implementation of wise policies, decisive action, and inspirational leadership.

Introduction

The environment has been the foundation for human flourishing

By most metrics, human health is better today than at any time in history. Life expectancy has soared from 47 years in 1950–1955, to 69 years in 2005–2010. Death rates in children younger than 5 years of age worldwide decreased substantially from 214 per thousand live births in 1950–1955 to 59 in 2005–2010.[14,15] Human beings have been supremely successful, staging a “great escape” from extreme deprivation in the past 250 years.[16] The total number of people living in extreme poverty has fallen by 0·7 billion over the past 30 years, despite an increase in the total population of poor countries of about 2 billion.[17] This escape from poverty has been accompanied by unparalleled advances in public health, health care, education, human rights legislation, and technological development that have brought great benefits, albeit inequitably, to humanity.

Humanity’s progress has been supported by the Earth’s ecological and biophysical systems. The Earth’s atmosphere, oceans, and important ecosystems such as forests, wetlands, and tundra help to maintain a constant climate, provide clean air, recycle nutrients such as nitrogen and phosphorus, and regulate the world’s water cycle, giving humanity freshwater for drinking and sanitation.[3] The land, seas, and rivers, and

Panel 1: **Glossary**

Holocene[1]
A geological epoch that began about 11 700 years ago and encompasses most of the time period during which humanity has grown and developed, including all its written history and development of major civilisations.

Anthropocene[2]
The proposed name for a new geological epoch demarcated as the time when human activities began to have a substantial global effect on the Earth's systems. The Anthropocene has to be yet formally recognised as a new geological epoch and several dates have been put forward to mark its beginning.

Ecosystem[3]
A dynamic complex of plant, animal, and microorganism communities and the non-living environment acting as a functional unit.

Ecosystem services[4]
The benefits provided by ecosystems that contribute to making human life both possible and worth living. Examples of ecosystem services include products such as food and clean water, regulation of floods, soil erosion, and disease outbreaks, and non-material benefits such as recreational and spiritual benefits in natural areas. The term services is usually used to encompass the tangible and intangible benefits that human beings obtain from ecosystems, which are sometimes separated into goods and services.

Biodiversity[5]
An abbreviation of biological diversity; biodiversity means the variability among living organisms from all sources, including inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part. This variability includes diversity within species, between species, and of ecosystems.

Wetland[6]
The Ramsar Convention defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres".

Representative Concentration Pathway (RCP)[7]
RCPs are trajectories of the concentrations of greenhouse gases in the atmosphere consistent with a range of possible future emissions. For the Fifth Assessment Report of Intergovernmental Panel on Climate Change, the scientific community has defined a set of four RCPs. They are identified by their approximate total radiative forcing (ie, warming effect) in the year 2100 relative to 1750. RCP 8·5 is a pathway with very high greenhouse gas emissions, but such emissions are in line with present trends.

Social–ecological systems[8]
Natural systems do not exist without people and social systems cannot exist totally in isolation from nature. These systems are truly interconnected and coevolve across spatial and temporal scales.

REDD+[9]
Reducing Emissions from Deforestation and Forest Degradation (REDD) tries to assign a financial value to the carbon stored in trees to help developing countries invest in low-carbon paths to sustainable development. REDD+ includes an added focus on conservation, sustainable management of forests, and enhancement of forest carbon stocks.

Externalities[10]
A benefit or cost that affects an individual or group of people who did not choose to incur that benefit or cost.

Circular economy[11]
A global economic model that decouples economic growth and development from the consumption of finite resources. Circular economy systems keep products in use for as long as possible, allow for the recycling of end products, and eliminate waste.

State shift[12]
Large, lasting changes in the structure and function of social–ecological systems, with substantial impacts on the ecosystem services provided by these systems.

Resilience[8,13]
"the capacity of any entity—an individual, a community, an organization, or a natural system—to prepare for disruptions, to recover from shocks and stresses, and to adapt and grow from a disruptive experience."

the plants and animals they contain, also provide many direct goods and benefits—chiefly food, fuel, timber, and medicinal compounds (figure 1).

Alongside the development of public health, the development of agriculture and industry have been major drivers of human success, harnessing the ability of the Earth to provide sustenance, shelter, and energy—underpinning the expansion of civilisation.[18] To achieve the gains in nutrition, health, and energy use needed to reach a population of more than 7 billion people has required substantial changes in many of these systems, often affecting their structure and function at a cost to their ability to provide other vital services and to function in ways on which humanity has relied throughout history.[19] In essence, humanity has traded off many of the Earth's supportive and regulating processes to feed and fuel human population growth and development.[20]

The scale of human alteration of the natural world is difficult to overstate (figure 2). Human beings have converted about a third of the ice-free and desert-free land surface of the planet to cropland or pasture[25] and annually roughly half of all accessible freshwater is appropriated

Ecosystem services		
Provisioning services	**Regulating services**	**Cultural services**
Food Freshwater Wood and fibre Fuel Medicines and new chemical compounds	Climate regulation Flood regulation Disease regulation Water regulation Pollination services Erosion prevention Air quality regulation	Aesthetic Cultural Recreational Spritual
Supporting services or habitat services		
Habitat maintenance Genetic diversity Soil formation Photosynthesis or primary productivity		

Figure 1: **Services provided by natural systems.**
Adapted from the Millennium Ecosystem Assessment.[3]

for human use.[22] Since 2000, human beings have cut down more than 2·3 million km² of primary forest.[26] About 90% of monitored fisheries are harvested at, or beyond, maximum sustainable yield limits.[27] In the quest for energy and control over water resources, humanity has dammed more than 60% of the world's rivers,[28] affecting in excess of 0·5 million km of river.[29] Humanity is driving species to extinction at a rate that is more than 100 times that observed in the fossil record[30] and many remaining species are decreasing in number. The 2014 Living Planet Report[24] estimates that vertebrate species have, on average, had their population sizes cut in half in the past 45 years. The concentrations of major greenhouse gases—carbon dioxide, methane, and nitrous oxide—are at their highest levels for at least the past 800 000 years.[7] As a consequence of these actions, humanity has become a primary determinant of Earth's biophysical conditions, giving rise to a new term for the present geological epoch, the Anthropocene (panel 1).[2]

In 2005, a landmark study by the Millennium Ecosystem Assessment (MEA) estimated that 60% of ecosystem services examined, from regulation of air quality to purification of water, are being degraded or used unsustainably (figure 2).[3] The authors of the MEA warned that "the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted".[31]

In 2006, a report published by WHO estimated that about a quarter of the global disease burden and more than a third of the burden in children was attributable to modifiable environmental factors.[32] These factors lead to a range of exposures that have adverse effects on health, including exposure to fine particulate air pollution, contaminated water, and some types of unintentional injury.[32] The 2012 Global Burden of Disease study by Lim and colleagues[33] has provided a more recent estimate of the disease burden from exposure to a range of environmental and other risk factors. Neither of these exercises examined the health impacts of global environmental change that can be direct (such as heat stress from climate change), secondary (due to the alteration of natural systems), or indirect or tertiary effects (for example due to social disruption; figure 3).[3] Many effects of global environmental change are difficult to quantify because they are mediated through complex systems that might have feedback loops and non-linear relationships between environmental change and health outcomes. Nevertheless, these effects have the potential to disrupt the progress of humanity because of their far reaching effects on vital ecosystem services (such as the provision of sufficient food) and their potential for compounding pre-existing socially-mediated threats, such as displacement, conflict, or civil disturbance.[34]

The importance of the natural environment in supporting human health and wellbeing is only becoming clear as the Earth's systems are degraded. For example, the ability of mangroves, coral reefs, and other types of wetland to provide wave attenuation and reduce damage from tsunamis and storm surges[35] has gained increased prominence since devastating events such as the tsunami caused by the 2004 Indian Ocean earthquake and hurricane Katrina in 2005.[36,37] The role of intact ecosystems and the suitability of climatic conditions in regulating the transmission of diseases is complex and not fully understood, but several new studies reporting an increased risk of zoonotic disease transmission in disturbed and degraded habitats emphasise the role of biodiversity in mediating exposure to infectious diseases.[38,39]

Many global assessments from the Global Environment Outlook[40,41] to the MEA[3] and the Intergovernmental Panel on Climate Change (IPCC) reports[42] have warned that accelerating change to the structure and function of the Earth's natural systems represents a substantial threat to global human health and that the threat will become increasingly severe over time if steps are not taken to remedy the situation. Nonetheless, policy makers have so far failed to respond decisively to the incremental changes in the Earth's natural systems that have occurred. However, despite these changes, human health has mainly improved around the world. What is the explanation for the overall improvements in global human health while natural systems have deteriorated?

The paradox of improved health and natural system deterioration

Throughout history, humanity has advanced by exploiting the environment to provide essential services and resources, but there is a growing awareness that humanity's historical patterns of development cannot be a guide for the future. At first sight, the fact that humanity is experiencing substantial and sustained improvements in life expectancy at a time when many ecosystems worldwide are degrading at unprecedented rates might seem contradictory.[43,44] In view of this apparent contradiction, an assessment[44] of the difference between environmental trends and human wellbeing has reported partial support for several possible explanations.

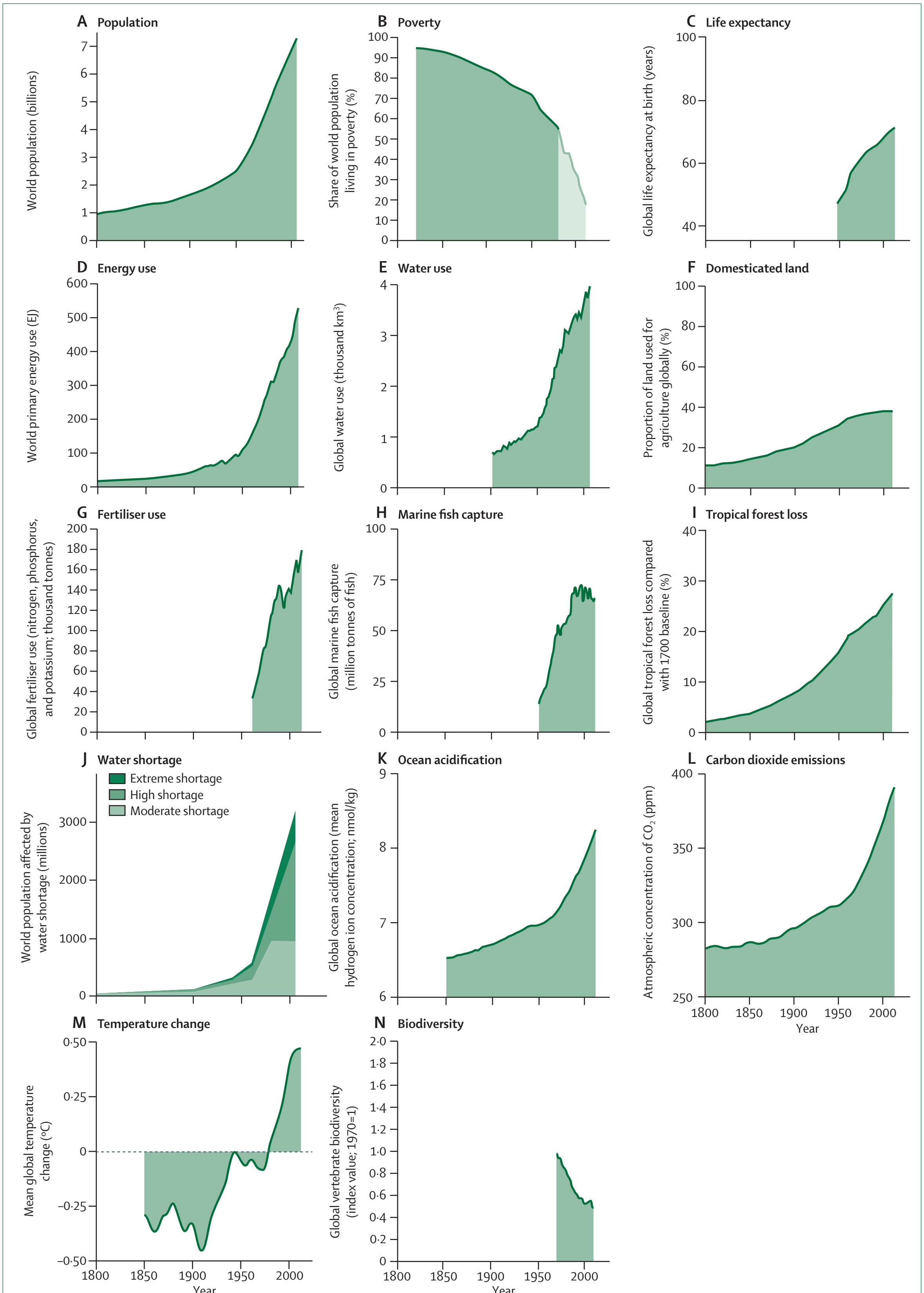

***Figure 2:* Characteristics of the Anthropocene epoch—global trends in population, consumption, health, and the environment**

(B) Poverty data is split between the share of the world's population living in poverty, defined as less than US$2 per day, in 1820–1980 (dark green) and the share of the world's population living below the international poverty line, defined as $1·25 per day, in 1984–2011 (light green). (C) The average number of years of life expected by a hypothetical cohort of individuals who would be subject throughout their entire lives to the mortality rates of a given period. (E) Global water use is the sum of irrigation, domestic, manufacturing, and electricity water withdrawals from 1900 to 2010 and livestock water consumption from 1961 to 2010. (F) Increase in agricultural land area, including cropland and pasture as a percentage of total land area. (G) Global fertiliser (nitrogen, phosphate, and potassium) consumption based on International Fertilizer Industry Association data. (I) Loss of tropical forests; area of tropical evergreen forest and tropical deciduous forest, which also includes woody parts of savannas and woodlands, compared with the area of these forests in the year 1700. (K) Ocean acidification expressed as global mean surface ocean hydrogen ion concentration from a suite of models (CMIP5) on the basis of observations of atmospheric carbon dioxide until 2005 and thereafter RCP8·5. (L) Carbon dioxide from firn and ice core records (Law Dome, Antarctica) and Cape Grim, Australia (deseasonalised flask and instrumental records); spline fit. (M) Global surface temperature anomaly (HadCRUT4: combined land and ocean observations, relative to 1961–1990, 20 year Gaussian smoothed). (N) Mean change in vertebrate population abundance relative to 1970 (see original source for uncertainty limits). EJ=exajoule. Data for graphs A and C are from World Population Prospects 2012.[15] Data for graph B are from Roser.[21] Data for graphs D–I and K–M are from Steffen and colleagues.[22] Data for graph J are from Kummu and colleagues.[23] Data for graph N are from the Living Planet Report 2014.[24]

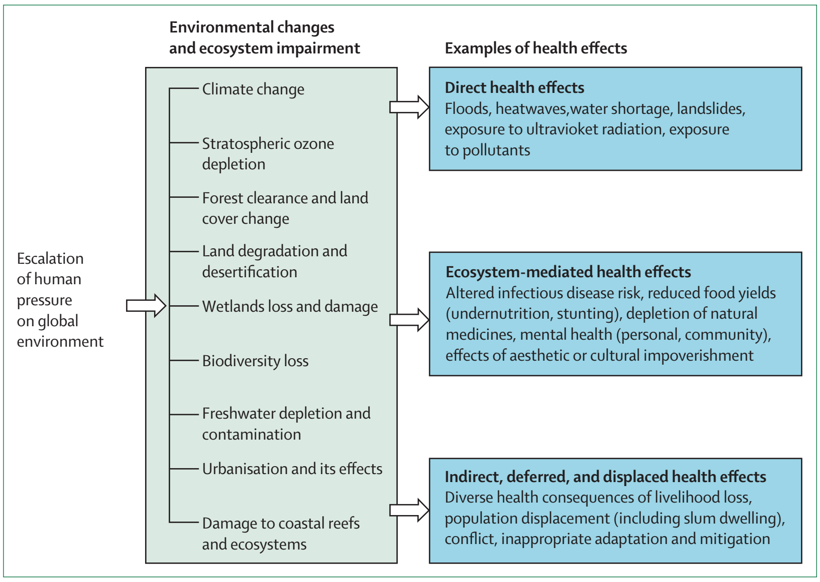

Figure 3: **Mechanisms by which the harmful effects of ecosystem change can affect human health**
Reproduced from Millennium Ecosystem Assessment,[3] by permission of WHO.

The first possible explanation is that wellbeing is dependent on food services, which are increasing, and not on other ecosystem services that are diminishing. So far, the increased productivity of food systems has probably outweighed the adverse effects from the deterioration of other ecosystem services.[45]

A second possible explanation is that technology and infrastructure have decoupled wellbeing from nature by increasing the efficiency with which humanity can exploit ecosystem services and by replacing nature's services (eg, intact ecosystems) that had provided ecosystem services such as food, safe drinking water, and household energy, with engineered infrastructure and markets—ie, the "ecological transition".[43]

A third possible explanation is that time lags might exist between the deterioration of function of some ecosystem services and the subsequent reductions in human wellbeing that they cause. Lags might also result from short-term adaptation to change until the limits to adaptation are reached.[44] Widely used measures such as life expectancy at birth are not a prediction of what will happen in the future but rather they represent the experience of those who have reached old age now, having benefited from the exploitation of the Earth's resources. As such some measures could give a false sense of reassurance.

Substantial health improvements might be one of the first outcomes associated with ecosystem conversion as threats are reduced and economic or provisioning goods are realised. Increasing wealth means populations can use ecosystem services from other locations through access to markets. Over time, however, resources are depleted, regulating services are compromised, and the potential to source food, water, and other ecosystem services from elsewhere will become increasingly difficult

Panel 2: The concept of planetary health

The concept of health is typically applied to individuals, communities, and populations or, on occasion, to nations but it does not take into account whether health gains are achieved at the cost of eroding the Earth's underpinning natural systems that provide essential services (eg, food, fuel, water, shelter) on which human civilisation depends. If a population attains a given level of health by exploiting the environment unsustainably then it is likely to be doing so at the expense of other populations—now or in the future, or both. The environmental impact of populations should therefore be represented in assessments of progress of human health and wellbeing.

An ecological public health model has been proposed that integrates the material, biological, social, and cultural aspects of public health and accepts the complexity and non-linearity of the dynamics of natural systems.[49] The model stresses not only how ecosystems underpin human health but also makes the case for widening the responsibility for health across disciplines and sectors beyond the traditional confines of the health sector.[49] The concept of planetary health builds on this approach to address the challenges of how best to protect and promote human health in the Anthropocene epoch.

According to the WHO definition, "health is a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity".[50] Our definition of planetary health is the achievement of the highest attainable standard of health, wellbeing, and equity worldwide through judicious attention to the human systems—political, economic, and social—that shape the future of humanity and the Earth's natural systems that define the safe environmental limits within which humanity can flourish. Put simply, planetary health is the health of human civilisation and the state of the natural systems on which it depends.[51]

Progress toward planetary health implies the development of an improved understanding of the connections between natural systems and health, including the potential for destabilising changes in crucial ecological pathways. Progress also requires recognition of the benefits to health arising from the conservation and rehabilitation of natural systems and the mitigation of greenhouse gases and other damaging emissions that result from human activities. For humanity to achieve planetary health in the face of increasing demands for resources, while addressing unacceptable inequities, will necessitate the development, implementation, and assessment of ambitious, integrated policies to address the social, economic, and environmental determinants of health.[51]

as population and consumption levels increase.[44] A danger also exists that wealthy nations and populations will meet their demands at the expense of poorer nations and populations, thus widening health inequities.

Humanity has undoubtedly benefited greatly, if inequitably, from the harnessing of the environment to human needs and demands, but the pace and extent of recent changes suggest that we cannot continue to exploit nature in the same way to provide for a world population that might continue to grow to the end of the century or beyond.[46]

Reasons for hope

The interconnected nature of people and the planet mean that solutions that benefit both the planet and human health lie within reach.[47] Unparalleled opportunities now exist to improve governance, harness new knowledge, and exploit a range of technologies that can improve health and reduce environmental damage. Increasing demands from investors, shareholders, and civil society can also potentially be capitalised on to develop sustainable business models that address social, environmental, and commercial goals. The advent of the Sustainable Development Goals (SDGs) and the post-2015 development agenda provide an important opportunity to address these trends and to tackle health, social, and environmental challenges in an integrated way.[48] Wise policies to make the best use of resources within environmental limits can help to safeguard humanity through the 21st century. Panel 2 outlines the concept of planetary health, which integrates human health and environmental sustainability.

The scope of the Commission

This Commission assesses the threats to health and to the prospects for development posed by the many environmental changes happening in the Anthropocene epoch. The Commission also identifies major gaps in evidence in the understanding of links between environmental change and health and the effects of interventions and policies to reduce environmental change and protect and promote health. The Commission also outlines research needs and implementation efforts to help humanity to address these threats successfully. A call for accompanying papers and case studies was issued by *The Lancet* in August, 2014.[52]

The Commission builds on previous work, including that of the Brundtland Commission (formerly known as the World Commission on Environment and Development), the IPCC, the MEA, the Convention on Biological Diversity (CBD), and Tony McMichael whose visionary book *Planetary Overload*, published more than 20 years ago, presciently addressed many of the issues that confront the world at present (see appendix for an abridged overview of past studies).[3,39,42,53,54] The work of this Commission is complementary to that of the *Lancet* Commission on climate change,[55] which focuses particularly on the opportunities for health and development that arise from policies to address the challenge of climate change. An assessment of systematic reviews on the relation between environmental change and human health was undertaken (see Acknowledgments), which included studies detailing potential policy options to improve health and environmental outcomes. A full description of search methods and findings are provided in the appendix. Systematic reviews were assessed by use of the AMSTAR measurement tool[56] and relevant reviews rated as good or excellent are referred to in this Commission report.

How are the Earth's global systems changing?

Pressures on the Earth's biophysical systems

The planetary boundaries framework identifies those biological and physical processes and systems important to the maintenance of the Earth's functions that human beings rely on to grow and flourish—the "safe operating space" (figure 4).[57,58] Changes in these systems either manifest at the global or regional scale (eg, climate change) or at the local scale (eg, biodiversity loss) but show such similar trends, effects, or interactions that they can add up to a global issue. Substantial changes in these systems could produce rapid, non-linear, and potentially

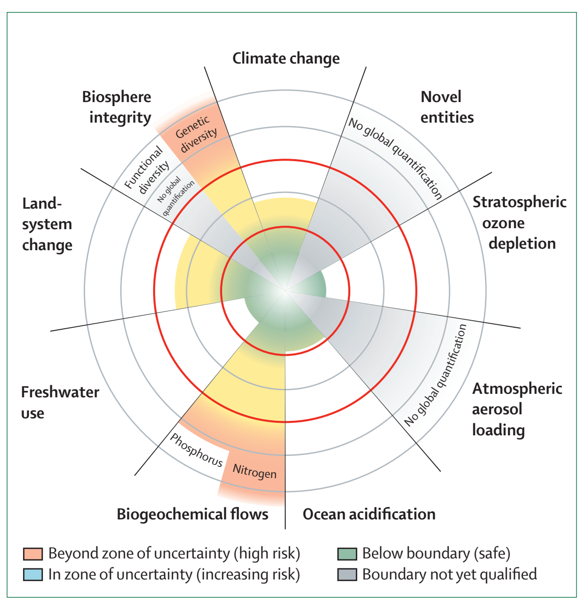

***Figure 4:* The present status of the control variables for seven of the nine planetary boundaries**

The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner red circle. The control variables have been normalised for the zone of uncertainty (between the two red circles); the centre of the figure therefore does not represent values of zero for the control variables. The control variable shown for climate change is atmospheric carbon dioxide concentration. The term novel entities represents the growing awareness that, in addition to toxic synthetic substances, other potentially systemic global risks exist, such as the release of radioactive materials or nanomaterials. Processes for which global-level boundaries cannot yet be quantified are represented by grey wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity. Reproduced from Steffen and colleagues,[57] by permission of The American Association for the Advancement of Science.

See Online for appendix

irreversible changes in the Earth's environment that would be disadvantageous to human development and health. The framework relates to nine global or regional pressures facing the Earth's biophysical systems.

The boundaries associated with climate change—biosphere integrity (measured at present by use of extinction rates), biogeochemical flows (measured by flows of nitrogen and phosphorus), and land-system change (measured through amount of remaining forest)—are estimated to already be outside of the identified safe operating space. Additionally, the boundary associated with ocean acidification is estimated to be nearing the identified threshold value and freshwater use shows high spatial variation, breaching regional thresholds in areas of low water availability or high consumption.[57]

Trends in global environmental change

Climate change

Clear evidence now exists that climate change has occurred because of human activity.[7] Climate change is caused by increases in the atmospheric concentrations of the greenhouse gases, particularly carbon dioxide, methane, and nitrous oxide,[7] together with black carbon. The burning of fossil fuels to provide power for transport, domestic use, agriculture, and industry, and the conversion of areas of natural habitat to land used for agriculture and human settlement cause most of these emissions. At present, the world's emissions trajectory is greater than the highest Representative Concentration Pathway (RCP 8·5; panel 1) used by the IPCC.[59]

The present and future effects of climate change include increased melting of ice sheets in Greenland and the Antarctic; a rise of mean sea level of about 0·19 m since 1900, and a projected rise of 0·52 m to 0·98 m by the year 2100 (relative to 1986–2005 levels) under RCP 8·5; an increase in global mean surface temperature of 0·85°C since 1880, and a projected further rise of between 2·6–4·8°C by the end of the 21st century (relative to 1986–2005; RCP 8·5), with greater warming over the land than the sea; an increase in the frequency and duration of both heatwaves and extreme rainfall events[7,42]—although in many mid-latitude and subtropical dry regions, mean precipitation will probably decrease; and changes in the abundance, distribution, and composition of plants and animals, with a cascading effect for whole ecosystems.[42]

Ocean acidification

Increased absorption of atmospheric carbon dioxide has resulted in changes to the chemical balance of the oceans (which are naturally slightly alkaline), causing their acidity to increase. The pH of the oceans has, on average, decreased by 0·1 pH since the beginning of the Industrial Revolution 250 years ago—equivalent to an increase in ocean acidity of about 26%.[7] Ocean acidity is predicted to increase by up to 170% by 2100.[60] Ocean acidification also causes a reduction in the saturation of some forms of oceanic calcium carbonate that are used by marine species—such as mussels, clams, and corals—to grow shells and create skeletons.[60] The key predicted effects of ocean acidification include reduced survival rates and abundance and impaired growth and larval development of marine animals;[61] rapid, global-scale losses of coral reefs;[61] and a reduction in the ability of shelled animals such as molluscs (eg, mussels, oysters, and clams) to form and maintain shells.[60]

Cascading disturbances from individual affected species will also affect other parts of the food chain.[60] A study[62] published in 2013 predicted that the entire population of southern ocean Antarctic krill (*Euphausia superba*) could collapse within 300 years if carbon dioxide emissions keep increasing because of the effects of acidity levels on hatching success. Antarctic krill are not only the region's largest fishery resource, but are also a primary source of food for top predators such as whales, seals, and penguins.[62] Some organisms, however, can tolerate ocean acidification and others, such as some seagrasses and fleshy algae, might even benefit from an increase in carbon availability, but such disruptions could also have knock-on effects for ecosystems, affecting food webs and system dynamics.[60]

Freshwater

Freshwater resources can be defined as renewable (rivers, surface water, and groundwater) and non-renewable (eg, deep aquifers, which have a negligible rate of replenishment on human timescales).[63] At present, groundwater supplies about 50% of the freshwater globally withdrawn for domestic use, 40% of the non-piped water for industry, and 20% of the water used for irrigation. In many parts of the world groundwater is being extracted faster than it can be recharged and the rate of extraction doubled between 1960 and 2000.[64]

The highest rates of groundwater depletion are in regions of high agricultural production such as northwest India, northeast China, northeast Pakistan, California's central valley, and the Midwest of the USA.[64] The Arab world, is particularly susceptible to freshwater shortages, with a reduction in freshwater availability from 3035 m^3 per person in 1962, to 743 m^3 per person in 2011—far below the water poverty level of 1000 m^3 per person per year.[65] By 2050, 3·9 billion people (more than 40% of the world's population) are projected to be living in river basins under severe water stress.

Water demand is projected to increase by 55% worldwide between 2000 and 2050 (excluding rain-fed agriculture). The increase in demand will arise mainly from manufacturing (400% increase in water demand), electricity (140% increase in water demand), and domestic use (130% increase in water demand), suggesting that in many countries irrigation (which accounts for about 70% of all water used globally at present) cannot expand and will need to become more efficient than it is at present.[64] Water scarcity will have important indirect implications for health through decreases in food production and economic growth.[66]

The most recent IPCC assessment,[42] published in 2014, concluded that "climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions", and it is therefore likely to exacerbate water stress due to unsustainable extraction of groundwater. Climate change is also projected to affect water availability by speeding glacial melt, intensifying both precipitation events and drought in some regions, with major effects on availability projected, particularly after 2050.[42] Habitat loss and pollution (especially from agricultural run-off) also affect many water sources globally. Wetlands are highly sensitive habitats, which are crucial in maintaining the water cycle, which, in turn, underpins all ecosystem services. About 70% of the world's wetlands existing in 1900 were lost by the end of that century, with even higher losses in Asia.[67]

Changes in land use and soil erosion

The conversion of areas of natural habitat to areas used for agriculture and industry has affected most parts of the world. In all realms, except Oceania and Antarctica, at least a quarter of natural habitats have been converted to other land uses.[5] In southeast Asia, almost 50% of the natural habitat has been converted. The temperate northern realms of North America and Europe are widely cultivated and urbanised at present; however, after large reductions in natural habitat extent throughout the history of human occupation, the expansion of agricultural lands in these areas seems to have stabilised, with only small increases in the past 40 years.

Habitat conversion continues at a rapid pace in many places however, especially in tropical and subtropical regions, driven by a growing demand for animal products as populations increase in wealth[68] and the conversion of natural habitats to grow non-food crops (eg, maize, sugar cane, and oil palm) for biofuel and cosmetics. Oil palm (*Elaeis guineensis)* cultivation is increasing by 9% annually, driven by demand for biofuels in Europe and food demand in India, Indonesia, and China.[39] Oil palm plantations consistently hold half as many vertebrate species as primary forests and show reduced species richness compared with secondary forests.[69] Changes in land use (particularly tropical deforestation) are contributing to substantial losses of native species.[70] Conversion of natural habitats to agricultural land is linked to increased nitrogen and phosphorus deposition through agricultural run-off. Burning of forests through land clearing activities increases local levels of air pollution and contributes to global greenhouse gas emissions—driving climate change.

Land clearance and intensive farming techniques are accelerating natural soil degradation processes,[71] which are exacerbated by urban development (which paves over the top soil) and unsustainable use of the land by industry.[72] New soil is slow to form; tillage agriculture is causing erosion rates that exceed soil formation by one to two orders of magnitude.[73] Soil degradation has resulted in about 1–2·9 million hectares (10 000–29 000 km²) per year of agricultural land becoming unsuitable for cultivation,[74] often turning to desert. Globally, about 55% of land desertification is caused by soil degradation due to human activity.[75,76] The effects of soil degradation include threats to food security, flooding due to decreased freshwater retention, and microbial biodiversity loss from soil.[72] Soil also acts as a carbon sink and its erosion (especially when leading to a loss of peatlands or permafrost) contributes to increased greenhouse gases in the atmosphere due to a reduction in their removal by carbon fixing. Agricultural soils contain 25–75% less carbon than those in comparable natural ecosystems.[76] In turn, future climate change is expected to affect the extent, frequency, and magnitude of soil erosion, mostly because of changes in rainfall and temperature driven changes in plant biomass.[77]

Nitrogen and phosphorus pollution

Increases in the amounts of nitrogen and phosphorus entering the environment through agricultural fertiliser run-off and soil erosion have become key drivers of ecosystem change in the past 60 years.[58] Levels of biologically available nitrogen and phosphorus in the environment are projected to increase substantially in the future.[3] Human beings now produce more biologically available nitrogen than all the natural pathways for their production combined.[3] This is a result of the synthetic production of nitrogen fertiliser, which has been pivotal for the substantial increase in food production that has sustained population growth during the past 50 years.[78] Present flow of phosphorus into the oceans is also about three times the preindustrial level, stemming mainly from the application of phosphorus as a fertiliser sourced from mined reserves and from livestock slurry and manure.[79] Excess nitrogen running into terrestrial ecosystems, especially temperate grasslands, shrublands, and forests, leads to decreased plant diversity, whereas excessive amounts of nitrogen and phosphorus in water bodies, such as rivers and other wetlands, lead to algal blooms and eutrophication (the process whereby excessive plant growth depletes oxygen in the water) in inland waters and coastal areas.[3]

Toxic chemical pollution and exposure

Many chemicals have an essential role in modern life, in fields such as medicine, agriculture, and the production of consumer goods. Production and consumption of most types of chemicals have expanded greatly worldwide since 1950.[80] For example, more than 140 000 chemicals are estimated to be on the EU market.[80] Global chemical sales are predicted to increase at about 3% per year until 2050 and most of their production will shift from established high-income economies to low-income and middle-income

Panel 3: Convention on Biological Diversity and WHO State of Knowledge Review

Through an interdisciplinary panel of experts, the Secretariat for the Convention on Biological Diversity and WHO collaborated to create a comprehensive State of Knowledge Review examining the state of scientific knowledge on the links between human health and biodiversity, ecosystems, and the life supporting services they provide.[39] The evidence gathered shows how anthropogenic drivers of biodiversity loss are hindering the capacity of ecosystems to provide essential services, from provision of clean air and freshwater, to discovery and production of medicines, to support for spiritual and cultural values. The most pronounced risks often affect populations with insufficient social protection mechanisms, including women, children, Indigenous peoples, the poor, and those most reliant on natural resources for their health, wellbeing, livelihoods, and survival. Several key risks have been identified.

- The loss of agrobiodiversity, which supports the production, pollination, and pest control services needed for food and nutrition security.
- Complex effects on the regulation of infectious diseases, including the transfer of pathogens from wildlife to human populations.
- Emerging evidence that biodiversity loss in the wider environment might lead to reduced diversity in human microbiota, contributing to immune dysfunction and disease.

The review identifies key gaps in the state of present knowledge and calls for the creation of coherent cross-sectoral strategies to ensure that biodiversity and health linkages are recognised, valued, and represented in national public health and biodiversity conservation policies and implemented with the involvement of local communities. A concerted effort should also be made to unite work across research disciplines—in social and natural sciences—by use of approaches such as EcoHealth[84] and the One Health framework[85] to produce knowledge and recommendations that can be used by policy makers and practitioners.

countries.[80] Major sources of chemical contamination and waste include pesticides from agricultural run-off; heavy metals associated with cement production; dioxins associated with electronics recycling; mercury and other heavy metals associated with mining and coal combustion; butyl tins, heavy metals, and asbestos released during ship breaking; mutagenic dyes, heavy metals, and other pollutants associated with textile production; toxic metals, solvents, polymers, and flame retardants used in electronics manufacturing; and drug or pharmaceutical pollution through excretion in urine and improper disposal.[80,81]

The total quantity of chemicals released into the environment as waste globally is unknown,[80] but as an example of the scale of the issue in North America (USA, Canada, and Mexico) alone, 4·9 million tonnes of chemicals were released into the environment in 2009, including about 1·5 million tonnes of chemicals that are persistent, bioaccumulative, and toxic; of this more than 756 000 tonnes were known or suspected carcinogens, and nearly 667 000 tonnes were chemicals that are known to be reproductive or developmental toxicants.[80] In the USA, releases fell until 2009, and have subsequently increased with, for example, a 15% increase in total releases between 2012 and 2013, due largely to increases in on-site land disposal from metal mining.[82]

Toxic chemicals also cause reduced ecosystem function and thus can indirectly affect human health. For example, chemical pollution can increase the susceptibility of ecosystems to species loss and land-use change.[83] Many man-made pollutants accumulate in deep oceans where they are consumed by small marine organisms and enter the food chain.[41] Others are dispersed in the atmosphere and accumulate in the polar regions and their food chains (which include human beings). Detailed evidence exists for the ecotoxic effects of some chemicals on both aquatic and terrestrial ecosystems.[80] Examples include feminisation of fish and developmental delays and malformations in amphibians.[80] As levels of some pollutants such as polychlorinated biphenyl and dioxins in wildlife have decreased, others, such as brominated fire retardants and perfluorinated compounds, have increased.[80]

Climate change can cause increased mobilisation of persistent organic pollutants from environmental sources and increase airborne transport.[41] The impact on the environment and human health of complex mixtures of chemicals is also important to assess because together they might cause substantial toxic effects, even if all individual chemicals are only present at individually non-toxic concentrations.[83] Such assessments are difficult to implement however because of the large numbers of chemicals that are emitted.

Biodiversity loss

Biological diversity (biodiversity) underpins many of the benefits that humanity derives from the Earth (panel 1). A loss of biodiversity has potentially serious consequences for human health and wellbeing (panel 3).[5,39,86] Much of nature is uncatalogued however, and only 10–20% of species are described at present,[5] with pronounced gaps in groups such as fungi, insects, and marine invertebrates. Most measures for which we have indicators show that biodiversity is decreasing.[86,87] At the species level, biodiversity is being lost at a rate unprecedented in human history.[5] The 2010 Global Biodiversity Outlook[86] reported that all major types of pressure were increasing. Key threats to biodiversity include the loss, degradation, and fragmentation of natural habitats; overexploitation of biological resources (eg, overfishing); pollution, particularly the build-up of nutrients such as nitrogen and phosphorus in the environment; the introduction of invasive alien species; and climate change and the acidification of the oceans.

The loss of biodiversity can affect the ways that ecosystems are structured and function, with local consequences especially for ecosystem services.[39] At a planetary scale, biodiversity also has a major role in limiting the impacts caused by changes to other Earth systems. For example, biodiversity has a key role in regulating the climate and removing harmful pollutants from the environment.[88]

Non-linear changes and interactions between multiple environmental threats

In addition to the effect of a single environmental threat, multiple threats might also negatively interact and exacerbate each other, creating a total effect that is worse for the environment than the sum of its parts.[89] Rather than a steady decrease in ecosystem services as human pressure increases, ecosystems might suddenly change, affecting the services that they provide. These shifts in social–ecological systems (panel 1) are based on well documented past observations, wherein ecosystems have transitioned rapidly to radically different states after threshold or tipping point effects were reached or breached.[90] An overview of recent social–ecological system shifts and their consequences is given in the Regime Shifts Database. Such effects are difficult to predict because a critical threshold might only become apparent in retrospect and changes can be rapid as thresholds are approached. An analysis of the causes and ecosystem consequences of 13 shifts in marine ecosystems reported that they were driven by combinations of factors acting across different scales. Factors included nutrient inputs, fishing, climate change, climate variability, urbanisation, deforestation, sewage, agriculture, and demand for food and fibre.[91] An example of how multiple interacting environmental changes contributed to an increase in the risk of adverse pregnancy outcomes in coastal populations in Bangladesh is given in the appendix.

Population growth, consumption, and technology—drivers of environmental change

Key factors mediating human induced environmental changes

The scale and pace of the human induced environmental changes are ultimately driven by the context of human civilisation in the Anthropocene. Three key factors in mediating these changes are unsustainable consumption or overuse of resources (that in turn is closely linked to affluence); population numbers; and available technologies that determine the effect of a given level of economic activity on the environment. Moreover, these factors interact, usually to multiply each other's impact on the environment, although appropriate technology (efficient, sustainable) can reduce these effects.

Consumption

A study[92] ranking nations, for which relatively complete data was available on their past and present effects on the environment, reported that overall, increasing absolute wealth was the main factor for increased absolute environmental impact (figure 5). Population size made an additional contribution to absolute environmental impact and poor governance made a smaller but significant contribution. The investigators found no evidence for an environmental Kuznets curve (ie, at the early stages of economic development, environmental degradation increases until a specific level of income is reached and then environmental improvement occurs), although they did identify a small reduction in environmental impact for countries with increasing per-person wealth. This reduction could be due to some degree of environmental recovery after widespread habitat loss in the past (eg, European deforestation). A limitation of the analysis is that so-called leakage cannot as yet be accounted for (ie, outsourcing of production processes that have high environmental impacts through international trade). Overall this analysis corroborates the damaging effects of an array of environmental challenges that are unprecedented in human history, which have mostly resulted from a profoundly unequal, resource intensive global economy. Most recent economic growth has been in countries that are not members of the Organisation for Economic Co-operation and Development (OECD), but profound global inequities in development still exist, with the OECD economies still dominating consumption patterns.[22]

For the **Regime Shifts Database** see http://www.regimeshifts.org

Present patterns of production and consumption are often inefficient—one key example is that, at present, 30–50% of all food produced is wasted because of poor practices in harvesting, storage, transportation, marketing, and consumption.[93] Gross inefficiencies also exist in the use of energy and water to drive development; for example, about a third of global energy use is dissipated as waste heat.[94] Although historically energy intensity (expressed as units of energy per unit of gross domestic product [GDP]) has improved, the rate of improvement has been more than offset by GDP growth, resulting in increased energy use over time. Therefore, a priority for research and innovation is to achieve accelerated progress in human development by use of much lower amounts of resources and energy from non-renewable sources than are used at present.

In 2011, world biofuel production was five times that of in 2001.[95] First generation biofuels compete for land with food crops (figure 6) and could increase food prices. A 2013 review[95] of this complex and sometimes contested topic concluded that "Everything else being equal, the introduction of a rigid biofuel demand does affect food commodity prices".[95] The cultivation of different crops (eg, corn alcohol *vs* sugar cane alcohol) and types of fuel (ethanol *vs* biodiesel) are associated with different land-use changes and agricultural practices and therefore might have different impacts on the environment. In some low-income countries, farming of biofuel crops might have beneficial economic effects if they compete with food exports but not domestic food production. The dietary shift towards high consumption of fats and oils, meats (particularly from ruminants), processed foods, and refined carbohydrates—including so-called empty calories—is a major contributor to the non-communicable disease burden, and to greenhouse gas emissions, land-use change, and agrochemical pollution.[68]

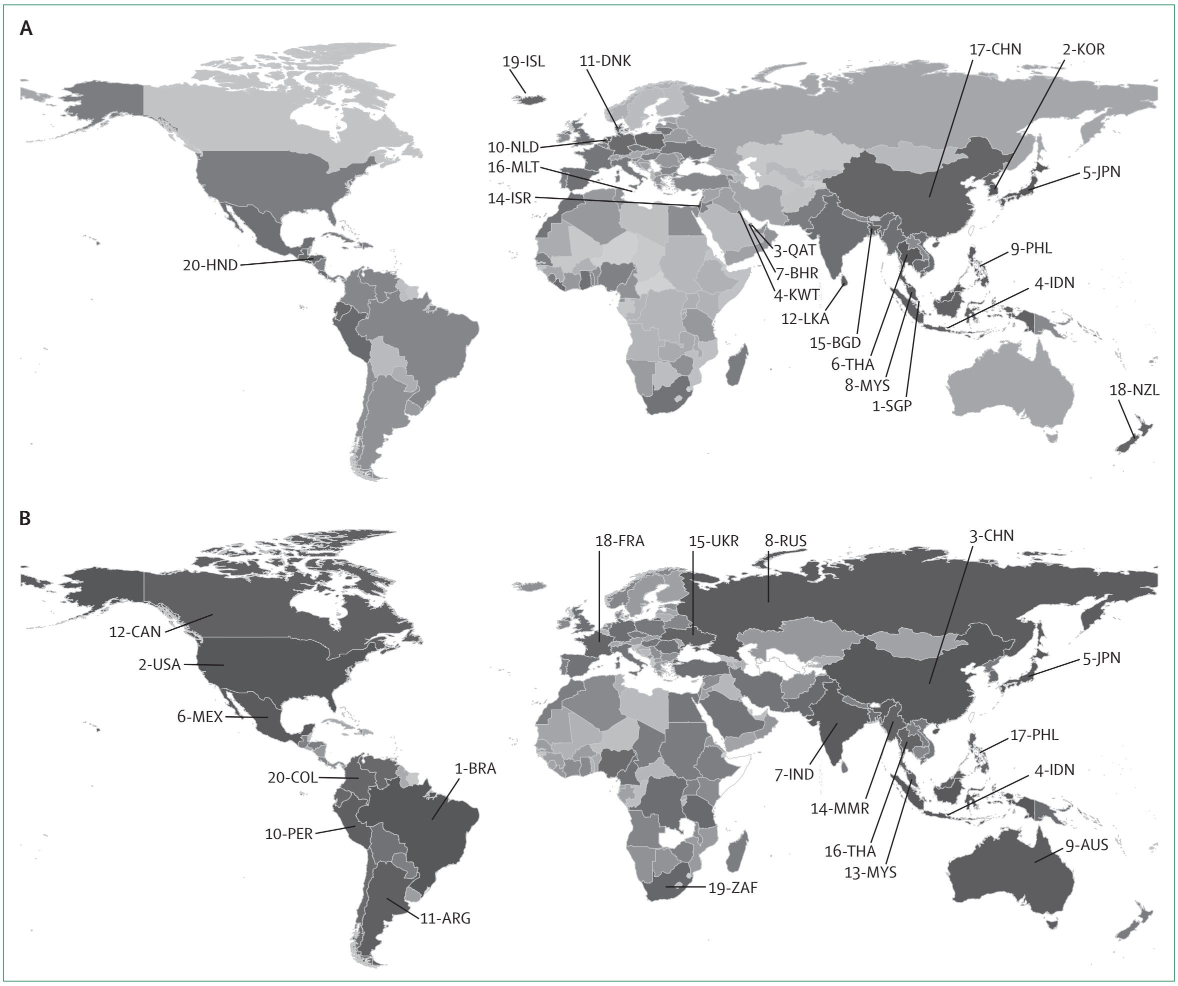

***Figure 5:* Relative rank of countries by proportional and absolute impact on the environment**
Proportional impact rank (A; 179 countries assessed) and absolute environmental impact rank (B; 171 countries assessed) are shown; the darker the grey the higher the impact. The proportional and absolute rank of each country's impact on the environment was a combination of their ranks for natural forest lost, habitat conversion, marine captures, fertiliser use, water pollution, carbon emissions, and proportion of threatened species. Proportional ranks are relative to total resource availability per country. Reproduced from Bradshaw and colleagues,[92] by permission of *PLoS One* under the terms of the Creative Commons Attribution License.

Population growth

Recent projections (revised in 2012) by the UN suggest that the world population could reach 9·6 billion by 2050 (figures 2, 7).[15] A study[46] published in 2014, based on revised UN Population Division estimates, used a probabilistic model to address the limitations of previous population projections and concluded that there is a 95% probability that world population in 2100 will be between 9·0–13·2 billion. Gerland and colleagues[46] concluded that population growth is unlikely to end this century without unprecedented reductions in fertility in sub-Saharan Africa. Between 1990 and 2012, unmet need for family planning decreased from 17% to 12% in developing regions. However, in 2012, in sub-Saharan Africa, 25% of women aged 15–49 years, married or in union, reported the desire to delay or avoid pregnancy, but had not used any form of contraception. Large differences in contraceptive use existed between urban and rural residents, rich and poor households, and the educated and uneducated.[66]

If worldwide mean fertility could be reduced to two children per woman by 2020 (compared with 2·37 at present), the world's population would have 777 million fewer people by 2050 than if present fertility rates continued.[99]

Empirical analyses of historical trends suggest that carbon dioxide emissions from energy use respond almost proportionally to changes in population size.[100] Comparison of UN low (7·4 billion) and high (10·6 billion) population growth scenarios for 2050, suggests a 32% difference in global carbon dioxide emissions between the two population projections by 2050. At present, large differences in per-person greenhouse gas emissions exist between high-income and low-income countries, but limited attention has been given to the links between rapid population growth and carbon emissions in the least-developed countries.[101] To merely consider change in population size however, does not take into account other factors.[102] For example, population ageing can reduce emissions substantially over time, especially in industrialised nations, through the effect on labour supply and economic activity.[100]

In the case of tropical deforestation, population growth operates in concert with political, economic, and other factors, such as the transition from subsistence farming to market-oriented crops, with migration often constituting a major driver of forest loss.[103] Population growth also places pressure on biodiversity hotspots and stresses on 35 world biodiversity hotspots are projected to be greatest in Africa and south Asia.[99] Reduction of population growth is essential to move humanity towards a more sustainable trajectory of development, but it will not be sufficient to avoid severe environmental damage unless it is combined with policies to reduce consumption of material resources and greenhouse gas emissions in high-income and emerging economies.[102]

Technology

Technologies define the magnitude of environmental impact resulting from the pursuit of a particular level of affluence for a given population size. Technological development has underpinned humanity's exploitation of the environment and has made possible human progress across all key sectors of the economy. Many technological advances increase resource use efficiency, but frequently this does not result in an overall reduction in the environmental footprint because these efficiency gains stimulate consumption either directly or indirectly through increasing disposable income, which can fuel the purchasing of additional goods. This situation is often known as the rebound effect (or Jevons paradox).[104] In developed economies, rebound effects, for example, for household energy efficiency measures, are between 20–45% and are probably higher in low-income countries.[105] Thus, technologies that improve efficiency might only reduce the overall environmental footprint of the economy if they are accompanied by policies to cap emissions or the use of a given resource.

Urbanisation

Most of the world's population now live in towns and cities and, for the foreseeable future, most population growth will be in urban areas (figure 7).[98] By the middle of the 21st century, another 2–3 billion people will need to be housed in the cities of the world—more than 1 million people every week. Most urban population growth is projected to take place in small and medium sized cities in low-income and middle-income countries.[106]

Rapid economic development and urbanisation is making cities in developing countries both susceptible to health hazards from environmental changes and, simultaneously, an increasing contributor to them,[107] but the relationships are complex.[108] By 2050, urban population growth will increase the number of people living in cities with perennial water shortage (less than 100 L per person per day of sustainable groundwater and surface flow within urban boundaries) from 150 million to almost 1 billion people.[109] Urbanisation can lead to an increase in greenhouse gas emissions in developing regions through effects on labour supply, but, after controlling for income, urban living can be more energy efficient than living in rural areas.[110] At the same time, research undertaken in India suggests that urban living can accelerate the transition away from highly polluting biomass and coal combustion to clean household energy, with major population health benefits.[111]

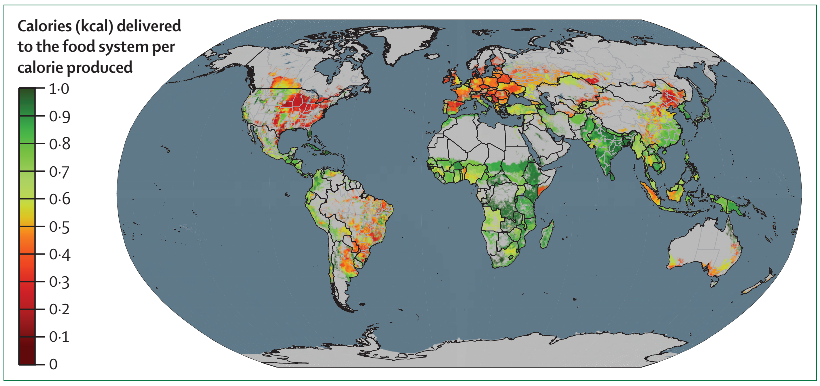

***Figure 6:* Calorie delivery fraction per hectare**
The proportions of produced calories that are delivered as food are shown. Crop use statistics were used to determine the number of calories delivered to the food system, which include food calories (calories used for direct human consumption), and feed calories after they were converted to meat, egg, and dairy calories. Crops that were used for other non-food uses (biofuels and other industrial uses) were not delivered to the food system. Reproduced from Cassidy and colleagues,[96] by permission of IOP Publishing under the CC-BY license.

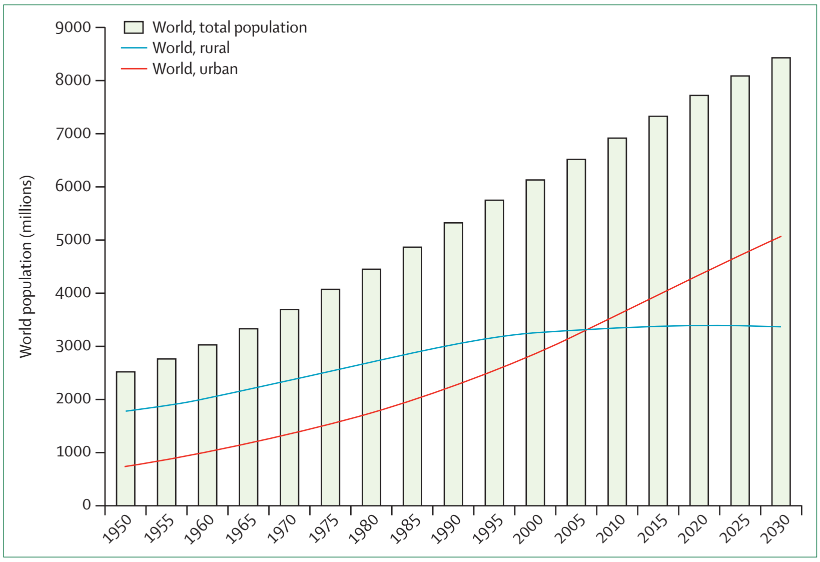

***Figure 7:* The urban and rural population of the world, 1950–2030**
Estimated and projected values of the proportion of urban and rural populations from 1950 to 2030 based on a model of medium variant population growth. Data are taken from the UN DESA World Urbanization Prospects, the 2014 revision.[97] Reproduced from Capon and colleagues,[98] with permission from *The Medical Journal of Australia*.

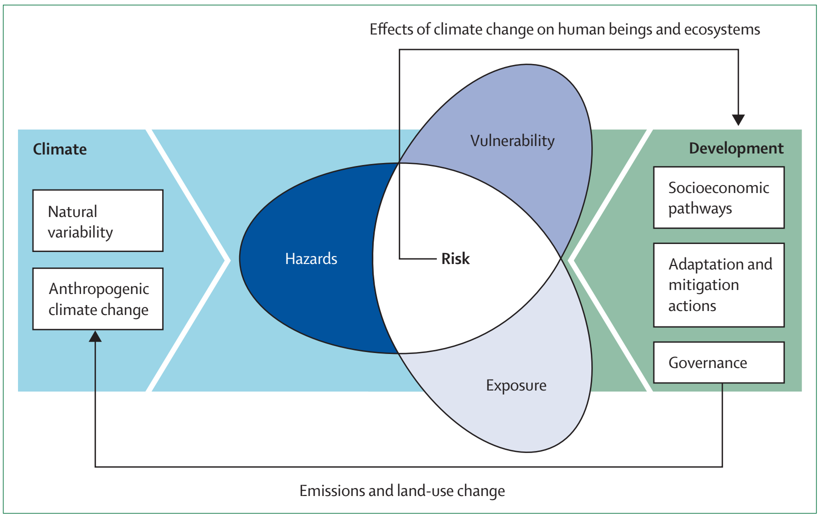

***Figure 8:* Example schematic of how hazard, exposure, and vulnerability interact to determine risk from environmental change**

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes, including adaptation and mitigation (right), are drivers of hazards, exposure, and vulnerability. Reproduced from the Intergovernmental Panel on Climate Change, Working Group II, Summary for Policy Makers,[118] by permission of the Intergovernmental Panel on Climate Change.

Low elevation coastal zones occupy 2% of the world's land area but contain 13% of its urban population.[112] The coastal location of many cities predisposes them to flooding and, in some areas, exposure to extreme events.[113] Exposure to dangerously high temperatures in urban centres is also increasing because of global climate change and the urban heat island effect,[114] and is exacerbated by urban sprawl.[115] The urban transition provides an unparalleled opportunity to improve population health, increase resilience to environmental change (eg, the 100 Resilient Cities—Pioneered by The Rockefeller Foundation[116]), and reduce the environmental impacts of cities through improved urban planning, design, housing, development, and management.[117]

Key health effects of environmental change

The unfinished agenda of environmental health

The 2006 study,[32] published by WHO on the burden of disease from direct environmental causes, identified the largest disease burdens related to environmental exposures as including diarrhoeal disease, undernutrition, acute respiratory infections (particularly from household air pollution), malaria, and some categories of unintentional injuries. The total number of healthy life years lost per person from environmental exposures was 15 times higher in developing countries than in developed countries. The public health impacts of these environmental exposures are important in their own right and populations exposed to some of these risks might have increased susceptibility to the effects of global environmental change on health. The 2006 WHO assessment[32] did not include the effects of global environmental change, which are the focus of this Commission report.

Exposure and vulnerability increase the risk of negative health effects due to global environmental change

The risks to human beings from global environmental change arise from the interaction between specific hazards, exposure, and vulnerability; figure 8 shows an example of this interplay in risk due to climate change.[118] Vulnerability is related to sensitivity, one or more factors that increase the likelihood that individuals will have negative health effects due to environmental change. The level of exposure of individuals or populations is related to the likelihood that they will experience hazards resulting from environmental change from living in a particular place. For example, those living at high latitudes might experience greater magnitudes of change of temperature than those living at lower latitudes, whereas those in the tropics are at more risk from droughts and floods.[113]

Important factors that make people more sensitive to environmental change include undernutrition, age (both the very young and old are often at increased risk), and the presence of a pre-existing disease burden. Elderly people are particularly susceptible to thermal stress and are disproportionately at risk of death in heatwaves. An ageing world population means that the number of people potentially at risk from heatwaves is growing rapidly in many countries.[55,113] Children are particularly susceptible to the effects of toxic chemicals because of their disproportionately large exposure, the sensitivity of their developmental processes to disruption, and because they are less able to detoxify and excrete many environmental chemicals compared with adults.[119]

Interactions between existing health burdens and environmental change might negatively affect the present rates of progress in many diseases in a population. For example, the number of new HIV infections per 100 adults (aged 15 to 49 years) reduced by 44% between 2001 and 2012, but an estimated 2·3 million people of all ages still became newly infected in 2012.[66] Many people living with HIV/AIDS might also be susceptible to inadequate nutrition due to environmental change (panel 4) and to other infections. During symptomatic HIV, and subsequently during AIDS, energy requirements increase by about 20–30% to maintain adult bodyweight,[127] therefore without a secure supply of food, bodyweight can quickly decrease. Food insecurity (which can be exacerbated by environmental change) can also negatively affect the ability of patients with HIV to adhere to antiretroviral therapy, a primary determinant of HIV clinical outcome.[128]

Poverty increases risk from environmental change through both increased sensitivity and exposure. Despite progress, 1·2 billion people still live on less than US$1·25 per day.[66] Those living in poverty are at increased likelihood of living in hazardous locations prone to flooding or landslides, or close to waste sites, with inadequate housing and inadequate access to health care, clean water, sanitation, and other essential services. People living in poverty are also more likely to be living with an existing infectious disease burden and are more

Panel 4: Case study—green safety nets of natural resources buffer households affected by HIV from hunger in rural South Africa

In sub-Saharan Africa high rates of HIV infection are causing substantial strain on households, with infection rates in a South African research site peaking at 45·3% in men aged 35–39 years.[120] In some cases, these high HIV rates are occurring in settings where rural households rely greatly on the local natural environment for a range of resources to meet daily needs—eg, food, medicine, and cooking fuel.[121] Thus, households at the intersection of the HIV/AIDS pandemic and environmental degradation face two crucial challenges simultaneously. This case study examines the role of local natural resources in the coping strategies of households affected by a prime-age death—between 18 and 49 years of age—and HIV/AIDS particularly, with a specific focus on food security.

Two cross-sectional household surveys were done in 2004 (n=240) and 2006 (n=290) at the Agincourt Health and Socio-Demographic Surveillance System[122] site (part of the INDEPTH network), which collected data on about 90 000 people in rural South Africa. The study area is characterised by large rural villages embedded in a matrix of savannah woodland used for agriculture and to harvest natural resources. Adult mortality negatively affects household food and nutrition security by reducing the capacity of the household to purchase food if the deceased was an income earner (usually male), or produce food if the deceased had an important role in food cultivation (usually female).[123] The local environment offers a means for mortality-affected households to cope with these negative effects in several ways.

First, local ecosystems provide a source of readily available wild foods, such as fruit, herbs, and insects, which substitute for previously purchased food. In the words of one respondent from a mortality-affected household, "Locusts are now our beef".[123] Wild foods buffer households from severe food shortages and increase dietary diversity.[124] They are most often consumed by households that have lost an adult male, irrespective of socioeconomic status, usually in response to a loss of income.[122] Reliance on wild foods often persists for up to 3 years after the death of the income provider, suggesting that such substitution is not a short-term coping strategy, but a longer-term adaptation by the household.[39,123]

Second, local natural resources provide other materials that enable households to save money—eg, fuel wood and medicinal plants. Mortality-affected households are far more likely to use wood as their main source of cooking fuel,[125] and to note cost savings as the prime reason for using a range of natural resources and products compared with households not affected by a death.[124]

Third, the local natural environment provides opportunities for the generation of supplementary income in times of crisis. Although only 5% of survey households had been selling natural products, most of these (86%) had been affected by an adult death in the past 2 years.[126] Taken together, these findings point to the underappreciated contribution of the local environment to the resilience of rural households faced with livelihood shocks related to health. Environmental degradation weakens this green safety net, emphasising the importance of action to promote the use of sustainable resources and improve environmental governance and ecosystem management at the local level.

susceptible to undernutrition due to increases in food prices than people who are not in poverty.[129] The "ecological transition" from a society or population with direct dependence on local ecosystems for essential services to one with the ability to purchase these services is associated with health benefits for most people who are able to make the transition successfully, but leaves poor populations increasingly susceptible to negative health effects if their natural infrastructure is degraded while their poverty prevents them from accessing the benefits of engineered infrastructure or markets.[43]

Recent reports on links between environmental change and health

The findings of two reports[39,42] on biodiversity and health published in 2015 (panel 3) and climate change and health published in 2014 (panel 5) have provided insights into the links between global environmental change and health.

Effects of global environmental change on food security and undernutrition

Overview

Undernutrition contributes to the deaths of about 3 million children each year, about 45% of the total deaths in this age group.[130] Despite reductions in rates of undernutrition in most regions, one in four children younger than 5 years worldwide are stunted, with attendant risks of impaired cognitive and physical development. Some areas of the world are still showing absolute increases in stunting; between 1990 and 2012, the number of stunted children in sub-Saharan Africa increased from 44 million to 58 million, although the proportion fell from 50% to 30% (appendix).[66]

Global environmental change has the potential to increase undernutrition and stunting, and to adversely affect four dimensions of food security: food availability, food accessibility, food utilisation, and food system stability.[131] Additionally, growing evidence suggests that environmental changes can affect the nutritional content of foods. Changes in land use and ownership, together with failure to reduce food waste and spoilage, amplify the effects of global environmental change on undernutrition. An overview of food price fluctuations and their effects is given in the appendix.

Land degradation and soil erosion: effects on agricultural yield

Degradation of arable land from a combination of erosion, desertification, salinisation, and conversion to

Panel 5: Health effects of climate change

The Intergovernmental Panel on Climate Change (IPCC) concluded that it is likely that climate change has contributed to global levels of ill health in recent decades. However, the present global burden of ill health from climate change is relatively small compared with other stressors on health, and substantial uncertainty on estimates still remains.[118] According to the IPCC it is likely that rising temperatures have increased the risk of heat-related death and illness and the IPCC has medium confidence that local changes in temperature and rainfall have already changed the distribution of some water-borne illnesses and disease vectors, and reduced food production for some susceptible populations; see IPPC (2014)[42] for the levels of confidence for each of these statements and how they were reached.

Under the assumption that climate change continues as projected, the IPCC predicts (with very high confidence) that, until the middle of the century, the global risk of adverse health outcomes will increase because of additional intense heatwaves and fires, and an increased risk of food and water-borne diseases.[42] They also predict that poor regions will face an increased risk of even greater undernutrition, compared with no climate change, resulting from diminished food production (with high confidence); that work capacity and labour productivity will be reduced in susceptible populations (with high confidence); that the risk of vector-borne diseases will increase (with moderate confidence); and that any possible positive effects on global health due to climate change (eg, from warmer winters) would be outweighed by negative effects. Under the high emission pathway (Representative Concentration Pathway 8·5, which humanity is exceeding at present), by 2100, the temperature of some of the world's land area is predicted to increase by 4–7°C. The IPCC concluded with high confidence that if this temperature increase occurs, normal human activities—including growing food or working outdoors—will be compromised.

developed land has led to substantial reductions in agricultural productivity in many regions of the world.[132] At present, 90% of food is grown in soil, a non-renewable (in human timescales) resource. Soil degradation leads to a loss of between 1 and 12 million hectares (120 000 km²) of agricultural land per year (see appendix of reference 74 for an explanation of variation in soil degradation estimates), therefore a potential loss of up to 20 million tonnes of grain per year.[74,133] In many parts of the world, a substantial amount of land has lost its soil nutrients. In 37 African countries, severe soil nutrient depletion over the past 30 years has led to substantial soil impoverishment and reduced agricultural output.[134]

Loss of pollinators

Good evidence exists that concerns about reductions in both wild and domesticated pollinators are well founded, but multiple factors are implicated.[135] For example, widespread population decreases in domesticated honey bees are probably due to a combination of increased exposure to pests and parasites, environmental stressors (including agrochemicals), and reduced genetic diversity.[135] Pollination by insects is an important form of reproduction for at least 87 types of leading global food crops, comprising more than 35% of the annual global food production by volume.[136] As such, reductions in the distribution and abundance of pollinators has substantial implications for agricultural productivity and nutrition.[137] Depending on dietary composition, up to 50% of the cultivation of plant-derived sources of vitamin A requires pollination throughout much of southeast Asia.[138] Iron and folate have lower, but still significant pollinator dependence, reaching 12–15% in some parts of the world.[138] Smith and colleagues[139] report that losses of pollinators could leave hundreds of millions of people at risk of vitamin A and folate deficiencies, and reduce the amount of fruits, vegetables, and nuts and seeds in the diet. The consequences for global health of such dietary changes would be severe; a 50% loss of pollination is estimated to increase deaths by around 0·7 million annually.

Unsustainable fisheries

Human health and the health of fisheries are tightly linked. Fish are an important source of protein, with about 2·9 billion people getting 20% of their annual protein from fish.[27] Fish also provide a valuable source of vitamins and important micronutrients such as iron, zinc, and omega-3 fatty acids.[140] Overfishing, warming, and acidification associated with climate change and marine habitat degradation all threaten to disrupt fish supplies,[141] leading to food insecurity and poverty. According to the latest Food and Agriculture Organization assessment,[27] at present, nearly 90% of assessed stocks are overfished or fished at maximum yield. Overharvesting ultimately leads to fish population reductions, species extinctions, and the collapse of marine ecosystems.[142] Some evidence exists for stabilisation of fishing rates in North America, Europe, and Oceania, but many fish stocks remain unassessed[143] and the Food and Agriculture Organization catch data are often under-reported and therefore might underestimate what is truly being caught.[144] The true health of global fisheries is mostly unknown, but continuing reductions in fish catch, even under increased fishing effort, suggest that populations of fish species continue to be depleted.[145] Some kinds of fishing activity are more environmentally damaging than others. For example, bottom trawling causes massive habitat destruction and increases greenhouse gas emissions because of the additional energy required to drag the net across the sea floor.[68]

In addition to overharvesting, large-scale distribution shifts and local extinctions in commercially important species of fish and invertebrates are projected as the climate changes, which will negatively affect fish catch, especially at low latitudes (figure 9).[42] Climate change combined with ocean acidification, overfishing, and pollution also threatens the health of coral reefs. A third of reef-building corals are threatened with extinction because of human activities,[146] with implications for the livelihoods of millions of people living in coastal communities (through loss of income and food)[147] and for fish stocks because reefs provide vital habitats for many commercially fished species. In 2000, the US Coral Reef Taskforce estimated that 50% of all federally managed fisheries species depend on coral reefs for part of their lifecycle.[148] Shellfisheries in 16 of 23 bioregions around the USA are exposed to rapid ocean acidification.[149] The effects of ocean acidification have already cost the Pacific Northwest oyster industry nearly $110 million and jeopardised 3200 jobs.

Potential health benefits from consuming omega-3 fatty acids, mainly from oily fish on ischaemic heart disease risk,[150] are constrained by reductions in fish stocks. For example, the UK is unable to meet healthy diet guidelines for its population from its domestic landings, which fell to just 19% of the recommended intake in 2012.[151] Restricted stocks might also increase competition between different populations for fishing rights and marine resources. Reductions in fish stocks might also exacerbate terrestrial biodiversity loss. In Ghana, years of poor fish supply (partly caused by high fishing rates from European Union fisheries) coincided with increased hunting in nature reserves. The increased hunting led to sharp reductions in biomass of 41 wildlife species, showing that as fish supplies fell, bushmeat consumption in villages increased.[152]

Although aquaculture is keeping pace with increased demands for fish, it is often unsustainable, degrading, or destroying coastal habitats and polluting the marine environment with effluent organic and toxic waste.[153] About 70% of total aquaculture production in 2012 was dependent on supplemental feed inputs.[27] Poorly regulated aquaculture might also result in widespread use of antibiotics, leading to antibiotic resistance in bacteria such as *Vibrio cholerae* or *Escherichia coli*.

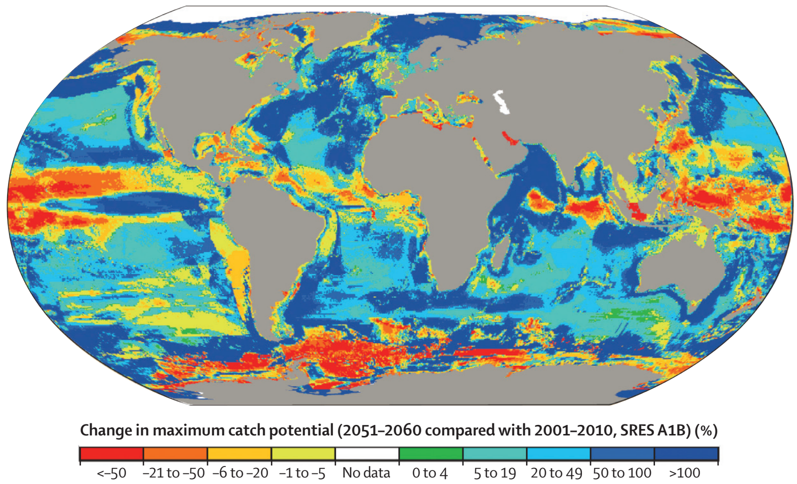

***Figure 9*: Climate change risks for fisheries**
Projected global redistribution of maximum catch potential of about 1000 exploited fish and invertebrate species. Projections compare the 10 year average of 2001–2010 and 2051–2060 by use of the Special Report on Emissions Scenario (SRES) A1B, without analysis of the potential effects of overfishing or ocean acidification. Reproduced from the Intergovernmental Panel on Climate Change, Working Group II, Summary for Policy Makers,[118] by permission of the Intergovernmental Panel on Climate Change, Working Group II.

Climate change

Climate change is expected to affect the quality and quantity of food produced in a range of ways. The IPCC also concluded with medium confidence that, based on models of present agricultural systems, "large negative impacts on agricultural productivity and substantial risks to global food production and security" would arise from mean local warming of 3–4°C, with particular risks to tropical countries.[42] The IPCC concluded with high confidence that although positive trends on crop and food production have been recorded in some high latitude regions, overall negative trends have been more common.[42]

Many studies have documented high levels of sensitivity of agricultural crops to increased temperature (see appendix for study references). This is important because growing season temperatures in the tropics and subtropics by the end of the 21st century are predicted to exceed the most extreme seasonal temperatures recorded between 1900 and 2006.[154] The IPCC concluded, on the basis of a meta-analysis of studies, that median crop yields would decrease by 0–2% per decade for the remainder of the century as a result of climate change alone, with or without adaptation, whereas demands for crops are projected to increase by 14% per decade up to 2050.[42] Such decreases in crop yields are projected to increase stunting in children due to malnutrition compared with a future without climate change. The effects of climate change are predicted to be worst in sub-Saharan Africa, increasing stunting by about 23%, and south Asia, where stunting rates might increase by as much as 63%.[155]

Changes in temperature variability might be an even greater concern than a rise in temperature for agricultural yield.[156] Although farmers have some capacity to adapt to increased mean temperatures by developing new cultivars or changing the timing or location of their planting, increased temperature variability is much more difficult to adapt to.

The potentially beneficial effect of carbon dioxide fertilisation on crop yield is not as evident as once thought.[157] Several studies suggest that crop productivity improvements reported in the field are lower than those shown by laboratory results.[158] Carbon dioxide fertilisation is expected in the long run to favour C_3 plants such as wheat, sugar, barley, potatoes, or rice over C_4 plants such as maize, sorghum, and millet.[157] Field trials show that rising concentrations of carbon dioxide in the atmosphere will lead to substantial reductions in zinc, iron, and protein in grain crops such as rice and wheat, and similar reductions in zinc and iron in legumes such as soybeans and field peas.[159] Myers and colleagues[160] estimate that these reductions in the zinc content of food crops could put about an additional 150 million people, mostly in Africa and south Asia, at risk for zinc deficiency.

Methane, a potent greenhouse gas, is a precursor of tropospheric ozone. If methane emissions rise—for example, as a result of leaks from gas wells or increased emissions from melting tundra—this will lead to increasing concentrations of ground-level ozone, which is a potent plant toxin. Increased ozone concentrations reduce the yields of important food crops[161] and could substantially exacerbate the effects of rising temperatures on crop yields.[162] Climate change will also change rainfall patterns globally and increase the likelihood of extreme rainfall events,[163] representing conditions different from those to which global agriculture has become adapted.

Climate change also threatens food security indirectly by triggering an increase in plant diseases caused by fungi, bacteria, viruses, and oomycetes (water moulds), potentially decreasing crop yields by an estimated 16% globally. These losses due to plant pathogens are expected to increase with climate change. Heat-stressed plants are generally less able to defend against pathogen attacks because several immunological systems in plants are impaired.[164]

A combination of water stress, rising atmospheric carbon dioxide, and raised temperatures can increase aflatoxin production by *Aspergillus* sp infecting crops such as maize.[165] Aflatoxin exposure increases the risk of liver cancer, particularly in conjunction with hepatitis B, and can increase the risk of childhood stunting.[166] Studies using analyses of aflatoxin albumin adduct levels, which are a biomarker of exposure, in west Africa in people of all ages show that 95% of blood samples contained detectable adduct. High exposures have also been found in east Africa, China, and parts of southeast Asia.[167] *Aspergillus flavus* (a fungus) and *Aspergillus parasiticus* (a mould), which produce aflatoxins, grow on a wide range of food commodities, including maize, oilseeds, spices, groundnuts, tree nuts, milk, and dried fruit.[168]

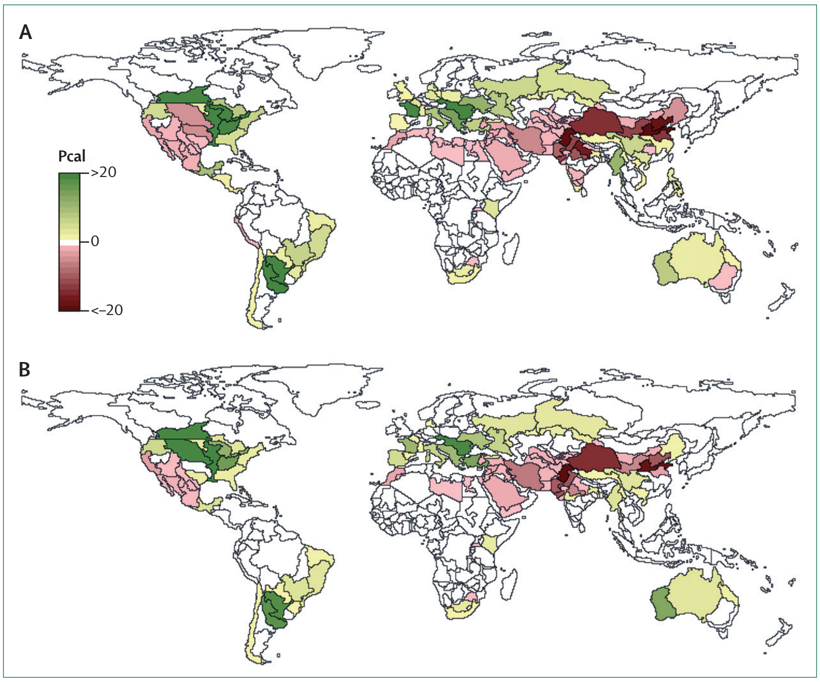

Figure 10: **Potential change in total crop production at end of century from maximal use of available water on rainfed or irrigated areas**

Figure shows areas with increased and decreased irrigation use in terms of total calories (Pcal) of food production of maize, soybean, wheat, and rice. (A) Median of 156 general circulation models (GCM), global hydrological models (GHM), and global gridded crop models (GGCM) combinations for scenarios created with GHM estimates of present irrigation demand. (B) Median of 202 GCM, GHM, and GGCM combinations for scenarios created with GGCM estimates of present irrigation demand. Figure reproduced from Elliott and colleagues,[171] by permission of National Academy of Sciences.

Diminishing freshwater availability—effects on food security and sanitation

Access to water for drinking, agriculture, and sanitation

Although major advances have been made during the Millennium Development Goal era, about 748 million people still relied on unsafe drinking water sources in 2012, of which 173 million used drinking water directly from rivers, streams, or ponds.[66] Many so-called improved water sources might not be bacteriologically safe. Despite advances in sanitation coverage, about 1 billion people are still defecating in the open.[66] Development of sewage treatment lags behind extension of sewerage connection, increasing risk of exposure to untreated sewage after floods and storms.[169] Conventional high volume flushing systems can be susceptible to failure after extended droughts.

Water tables in the world's three biggest grain producing nations are falling in response to unsustainable withdrawals for agriculture. In the North China Plain, where half of China's wheat is grown, water tables are decreasing by more than 1 m/year.[170] In India, 15% of grain production depends on water mined from fossil aquifers that are not being replenished. In the USA, the water table below parts of Texas, Oklahoma, and Kansas—three leading grain-producing states—has dropped more than 30 m. Climate change is predicted to cause freshwater limitations in some irrigated regions. This could mean that 20–60 Mha of cropland has to be reverted from irrigation back to rainfed watering by the end of the century, potentially causing a loss of 600–2900 × 10^{12} kcal of food production (depending on assumptions about water demand and the plants under consideration). Increases in freshwater availability in other regions might help lessen the impact of these losses, but a large investment in infrastructure would be required. These freshwater-related losses are projected to be in addition to direct adverse climate impacts on maize, soybean, wheat, and rice, resulting in yield losses of 400–1400×10¹² kcal, which is about 8% of the present-day total, even taking into account potential carbon dioxide fertilisation effects (figure 10).[171] These environmental challenges to maintaining the world's food supply are intensifying at a time when demands are expected to rise faster than at any time in human history[172] (see appendix for an overview of the Food–Water–Energy Nexus).

Growing populations and changing diets in emerging economies are also increasing freshwater consumption. To double the global production of meat and dairy products to address this increasing demand will need an estimated 2000–3000 km³ of additional water.[173] Beef requires about 11 times the amount of irrigation water per calorie consumed than poultry, eggs, and pork.[174] Biofuels can also require large amounts of water, ranging from 1400 L to 20 000 L of water per L of biofuel depending on the crop used.[175]

Water-rich and water-poor nations increasingly depend on the same finite water resources; for example, the importation of food is associated with a hidden transfer of freshwater resources (the water used to produce the foodstuff) from production to consumption areas, so-called virtual water trade. Climate change and over-consumption of water means that water-rich regions are soon likely to reduce the amount of virtual water they export, thus leaving import-dependent regions without enough water to sustain their populations. According to a recent analysis, declines in exports of foodstuffs dependent on large amounts of virtual water for their production could adversely affect the capacity of importing nations to sustain their populations by around 2030 in the absence of cooperative behaviour by water-rich nations.[176]

Effects of global environmental change on water-related diseases

Diarrhoeal disease

In 2012, inadequate drinking water and sanitation together accounted for 685 000 deaths from diarrhoeal disease.[177] For example, the Ganges river basin provides freshwater for 400 million residents of northern India, but also serves as a dumping ground for raw sewage from more than a hundred cities located along the river.[178] Despite prevention and treatment campaigns, by the 2040s the incidence of diarrhoeal disease is expected to increase by more than 13% in the Ganges basin and 8–11% globally due to changing environmental conditions.[179] Rising temperatures and humidity and increased variability of rainfall associated with climate change are likely to amplify the spread of water-borne pathogens, causing increased incidence of diarrhoeal disease.[180]

Schistosomiasis

Each year, schistosomiasis affects hundreds of millions of people, leading to malnutrition, stunting, anaemia, loss of worker productivity, and poor school performance.[181] River fragmentation and biodiversity loss has led to an increase in the number of freshwater snails that act as vectors of schistosomiasis, which in turn might lead to the widespread proliferation of the disease.[180] Eutrophication and overfishing can also contribute to an abundance of the snails that act as intermediate hosts of schistosomiasis.[180] Schistosomiasis has also been identified as a cofactor in the spread and progression of HIV/AIDS in places where both diseases are endemic[182] as a result of damage and inflammation in male and female genital tracts due to urogenital schistosomiasis.[183] The co-burden of the two diseases falls mainly on poor populations and countries with weak health systems.[183]

Effects of global environmental change on the occurrence and spread of zoonotic and vector-borne diseases

Overview

Nearly all of the most important human pathogens are either zoonotic or originated as zoonoses before adapting to human beings[184] and more than three-quarters of emerging infectious diseases are estimated to be directly transmitted.[185] Ecological changes have led to increased rates of emerging and re-emerging diseases, including malaria (in some locations), hantavirus pulmonary syndrome, Nipah virus, and Ebola virus disease (panel 6).[43,201] However, an improved understanding of the ecological mechanisms of human disease and how dependent the causal mechanisms are on local conditions is needed. At present, not enough predictive power exists to accurately model human disease outcomes resulting from environmental change (panel 7, appendix).[39]

Half of the global emerging infectious disease events of zoonotic origin between 1940 and 2005 are estimated to result from changes in land use, in agricultural practices, and in food production practices.[203] The highest risk areas for the emergence of infectious zoonotic diseases occur where human population growth is high, ecologically disruptive development is under way, and human and wildlife populations overlap substantially.[204] Only for a handful of infectious diseases do researchers have a detailed understanding of how causal mechanisms associated with ecosystem change contribute to new zoonotic risks. For a comprehensive overview of these mechanisms see Pongsiri and colleagues,[201] Myers and colleagues,[43] and the IPCC Working Group II Report 2014.[118]

Extreme weather events such as drought followed by rewetting can affect water table levels, vegetation, and aquatic predators and thus affect mosquito populations.[205] Several studies reported an association between a drought during the previous year and West Nile virus incidence. Urban mosquito vectors of dengue virus and chikungunya virus can exploit many aquatic habitats created in response to drought (eg, water storage containers).[205] Inadequate infrastructure can also exacerbate the risk of vector-borne diseases in times of drought—for example, water restrictions brought on by extreme drought in São Paulo have led to increased water hoarding, providing the ideal breeding ground for dengue carrying mosquitoes. The

Panel 6: Case study—the Ebola virus

The first documented outbreak of Ebola virus disease was in 1976. Since that time, human populations in Africa have increased substantially. Forest loss has accompanied this demographic explosion,[186] because new agricultural land was predominantly created by the cultivation of previously undisturbed forest.[187] Between 1990 and 2010, 10% of Africa's forest was lost.[188] Present evidence for causality between environmental change and Ebola virus disease outbreaks is still mostly circumstantial, but to conclude that these immense land cover and population changes have acted to increase the likelihood of contact between people and wildlife, and thus the likelihood of zoonotic disease emergence is not without reason.

Bats are the putative natural host of Ebola virus. The 2-year-old patient zero in the 2014 outbreak in Guinea possibly came into contact with bats or bat faeces,[189] as did a hunter in the Democratic Republic of the Congo connected to the 2007 outbreak in Luebo.[190] The 2007 Ebola virus disease outbreak was suspected to have links to an annual fruit bat migration and particularly a stopover site at a large abandoned palm oil plantation that was targeted by local hunters.[190] Further, surveillance of several species of fruit bats and a small number of other bat species shows that they can carry antibodies against Ebola virus or test positive for its viral RNA, or both.[191] Although fruit bats are probably the candidates, a definitive host has not been identified. Great apes, duikers, and pigs also seem to be susceptible to Ebola virus disease, with some outbreaks traced back to hunters consuming ape and duiker carcasses that were probably infected from other animals or fruit bats.[192]

Beyond the complex social, cultural, economic, and political settings that fuelled the spread of Ebola virus disease throughout west Africa, initial commentaries on the causes of the Guinea virus spillover event have pointed to the environmental context. "The region was systematically plundered and the forest decimated by clear-cut logging, leaving the 'Guinea Forest Region' largely deforested".[193] Wallace and colleagues[194] also argue that the region's "policy-driven phase change in agroecology," particularly to oil palm, is a disturbance that could be increasing human and fruit bat contact in the dry season, when Ebola virus disease outbreaks often happen. Fruit bats and land cover change after development have also been linked to human outbreaks of Nipah virus in Malaysia,[195] and to Hendra virus outbreaks in Australia.[196]

Fruit bats are social animals that often congregate in large groups. Shifting resource or habitat availability could substantially affect human disease risk by changing the bats' migratory patterns, group size, and connectivity,[196] along with other life history traits that are associated with zoonotic infections in bats.[197] Historically, little attention has been paid to steps that could prevent a patient zero from becoming infected with Ebola virus (eg, Kamins [2014]).[198] The overall cost to address the 2014 Ebola virus disease outbreak is staggering and its effects on food security, livelihoods, and national economies extend well beyond treatment and containment of Ebola virus disease.[199] Such outbreaks also set development activities back by decades. According to Margaret Chan, head of the WHO, the 2014 Ebola outbreak threatened the "very survival of societies and governments in already very poor countries".[200]

city had a substantial rise in dengue cases in the first 6 weeks of 2015, which have increased 163% compared with the same period in 2014.[206]

Malaria

Malaria is multifaceted and has many contributing factors, but ecological factors have a major role in driving transmission dynamics.[207] Forest loss, habitat fragmentation and modification, and the accompanying loss of plant diversity have been shown to affect the risk of malaria transmission through changes in mosquito abundance, survival, and distribution.[208] Deforestation and resulting development and human settlement can create breeding sites for malaria-transmitting mosquitoes, but regional differences exist (see appendix for an overview). Microclimates that are warmer than the surrounding environment often speed up mosquito reproduction rates and development times of the pathogen in the mosquito.[209] In the wake of deforestation, malaria increased as a result of an increased density of the mosquito species *Anopheles gambiae* and *Anopheles arabiensis* in the Sahara, and of *Anopheles funestus* and *A gambiae* in sub-Saharan regions.[208]

Changes in biodiversity due to deforestation have also been reported to have adverse effects on the risk of malaria (increasing numbers of *Anopheles darlingi* and increased biting rates) in the Brazilian and Peruvian Amazon.[210] Another probable reason for increased malaria transmission risk in the Amazon is an increase in the number of preferred breeding sites created by human settlement—specifically, settlement followed by deforestation to clear land for farming practices.[210] Human factors, such as immune status, migration patterns, and treatment of disease, also have important roles in malaria incidence and continued transmission.[211] Therefore prevention and control programmes have to consider both the effects on disease transmission of human behaviours that contribute to ecological change and the human behavioural responses to malaria risk.[212]

The IPCC have reviewed in detail the future role of climate change in mediating risk from diseases such as malaria. They cite evidence that despite socioeconomic development helping to reduce malaria risk, 200 million additional people would be at risk of malaria under climate change (the A1B scenario)[213] and that disease incidence will depend on the effectiveness of control measures. The effects of climate change on malaria incidence are generally hard to predict;[42] different mosquito species differ in their response to climate warming and precipitation changes and, as with many such multifactored relationships, human actions to reduce the burden of disease are difficult to separate from the environmental impacts. Interactions between climate change, land-use change, and biodiversity change can be reasonably expected to substantially increase the frequency of emerging infectious diseases in the future by changing where species live and the composition of biological communities. The kinds of species most capable of withstanding global environmental change might be those species most likely to promote new diseases.[214]

Panel 7: **Mechanisms by which large-scale environmental change can affect exposure to vector-borne diseases with examples**

Change to the natural habitat (and associated human settlements)
Example: increased transmission of Marburg virus, Chagas disease, yellow fever, and leishmaniasis have been associated with the loss of primary forests for mining and logging operations, plantation development, and oil and gas extraction. Agricultural intensification—the conversion of forest to pig farming operations—contributed to the spread of Nipah virus in Malaysia because it creates a pathway for the repeated transmission of Nipah virus from fruit bat reservoirs to pigs.

Change in the number or type of species in a system
Example: the rates of infection of ticks by the pathogen associated with Lyme disease increases as animal community composition is reduced. Increased richness of non-passerine birds, which are less competent reservoir hosts than passerines, was associated with decreased West Nile virus infection rates in mosquitoes and a decreased number of human cases. The loss or extinction of large predators due to hunting and land-use change can increase the population of a particular vector or host. These population increases can result in an increased transmission of infectious disease to human beings.

Invasion or introduction of disease vectors to new areas—caused by global trade, climate change, and accidental introduction
Example: a review of studies modelling the potential effects of climate change on dengue projected that the area of the planet climatically suitable for dengue transmission would increase under most scenarios.

Genetic changes in disease vectors or pathogens caused by human actions
Examples include mosquito resistance to pesticides or the emergence of antibiotic-resistant bacteria. The drivers of these changes include pesticide application and the overuse of antibiotics.

Adapted from Sustaining Environmental Capital: Protecting Society and the Economy, Working Group Report.[202] See appendix for references.

Air pollution—impacts on health and the environment

Combustion of fossil fuels

Combustion of fossil fuels, particularly coal and diesel, produces large amounts of fine particulates. The health implications of fossil fuel combustion are discussed in detail by both the IPCC[42,118] and the *Lancet* Commission on Climate Change,[55] so will not be discussed in this Commission report.

Household air pollution

Household air pollution caused an estimated 2·6 million to 4·4 million deaths in 2010, mainly in women and children,[33] and a WHO estimate in 2014 put the number of deaths at the higher end of the range, at about 4·3 million per year.[215] Household air pollution is generated by the incomplete combustion of solid fuels (wood, charcoal, crop residues, dung, and sometimes coal) in the home. Although the proportion of households burning mainly solid fuels has decreased in the past few decades, the numbers of people exposed has remained constant at about 2·8 billion because of population growth.[216] Household air pollution is a risk factor for acute respiratory infections in children, together with chronic obstructive pulmonary disease, stroke, and ischaemic heart disease in adults.[33] Combustion of biomass results in large emissions of complex mixtures of several pollutants including black and brown carbon, which have warming effects on the climate together with some cooling aerosols. Black carbon has been particularly studied and can affect the climate, contributing to the disruption of the monsoon in south and east Asia and the warming of the Himalayan–Tibetan region—potentially having substantial effects on the food and water security of the region (see appendix for a list of relevant studies). Black carbon is also emitted from other sources such as agricultural open burning and diesel vehicles. The use of wood for fuel might also have local effects on deforestation.[217] Charcoal is easier to transport and causes less household air pollution than wood but is sourced from trunks or large limbs and requires that trees be cut down. Compared with wood burning, widespread charcoal use will reduce deaths from household air pollution but increase greenhouse gas emissions, forest cover loss, and biodiversity loss in the absence of new technological approaches.[218]

Landscape fires

Landscape fires also have important effects on health and the environment through emissions of PM2·5 (particulate matter with a diameter of 2·5 μm or less) and ozone.[219] Smoke from landscape fires, mainly related to deforestation and land clearing, is estimated to cause more than 300 000 premature deaths worldwide per year (figure 11).[219] A small number of reports from southeast Asia and Brazil exist that link various exposure indicators to short-term respiratory outcomes (see references in appendix).

Ground level ozone

Ground level ozone is formed from chemical reactions between oxides of nitrogen, methane, and volatile organic compounds. Ozone air pollution is estimated to kill about 150 000 people per year worldwide and also reduces crop productivity, forest growth, and the ability of vegetation to take up carbon dioxide.[220]

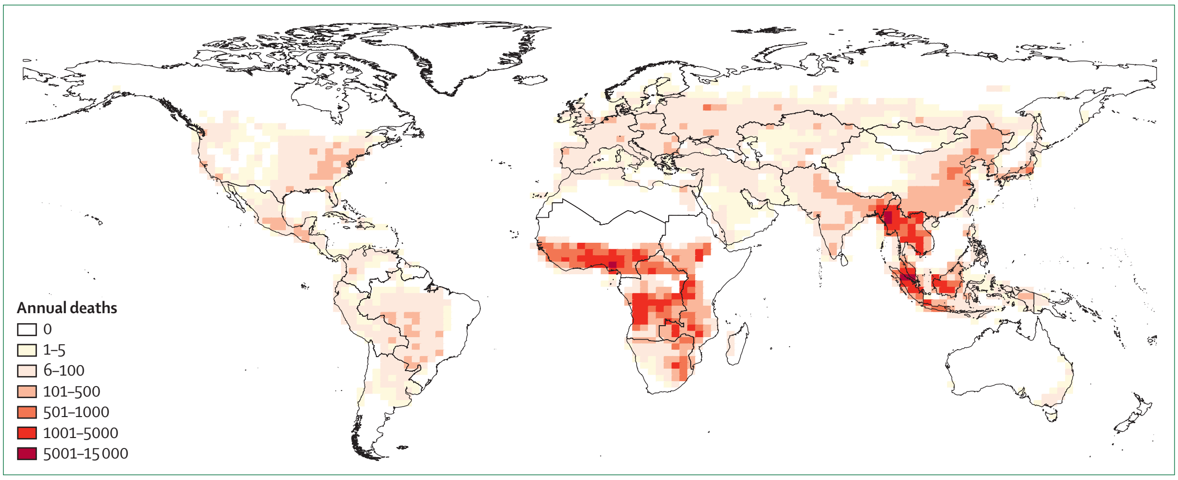

Figure 11: **Map showing the main estimates of the annual average (1997–2006) global mortality attributable to landscape fire smoke**
Reproduced from Johnston and colleagues,[219] by permission of Environmental Health Perspectives.

Toxic chemical exposure—implications for health and the environment

Toxic chemical exposure

Health risks from chemicals occur via several exposure pathways including the ingestion of contaminated water and food, inhalation of contaminated air or dust, dermal exposure, exposure of fetus during pregnancy, and the transfer of toxins through breastmilk. Some chemicals can travel vast distances by air or water, creating exposures far from the site of release.[221] Bioconcentration in food chains is of particular concern.[80] Key groups susceptible to the toxic effects of chemicals include individuals living in poverty because of their increased likelihood of being exposed to toxins and individuals who are undernourished, elderly, or very young (including those in utero) because of their sensitivity to toxins.[80]

Data on the release of pollutants relevant to human health are quite sparse. The International Agency for Research on Cancer has only assessed 941 chemicals and exposure circumstances for carcinogenicity, but has reported more than 400 of these to be carcinogenic, probably carcinogenic, or possibly carcinogenic—most of which are used in industry.[80]

Risks to children

Lead poisoning remains an issue in many low-income countries; an estimated 99% of all children exposed to excessive amounts of lead reside in low-income countries.[222] Methylmercury, which is known to have adverse effects on fetal brain development, bio-accumulates in aquatic food chains.[119] Although decreasing in high-income countries, mercury exposure through consumption of affected fish remains high in many low-income countries. The International Labour Organization estimated that about 215 million children aged 5–17 years are child labourers, of which 115 million work in hazardous conditions.[223] More than half of these child labourers work in agriculture where exposure to pesticides is common.

Of the 3000 chemicals classified as high production volume ("those chemicals produced or imported in the United States in quantities of 1 million pounds or more per year")[224] by the US Environmental Protection Agency, about half of them have insufficient information about their toxicity, whereas for about 80% of them, no information is available about their capacity to harm children or cause developmental toxicity.[119]

Endocrine disruption

About 800 chemicals are known or suspected to be endocrine disruptors and many more have not been tested.[225] A consensus statement on the state of the science relevant to human exposures to endocrine disruptors identified many reasons for concern, including a rising or persistently high incidence of genital malformations, such as undescended testes (cryptorchidism) and penile malformations (hypospadias) in baby boys, poor quality semen in up to 40% of men in some countries, increasing rates of endocrine-related cancers, and a high prevalence of neurobehavioural disorders associated with thyroid disruption in some countries, which has increased in past decades.[226] Compelling evidence is available about the effect endocrine disrupting chemicals have on wildlife, including feminisation of male freshwater fish exposed to treated sewage in parts of Europe, egg thinning and impaired reproductive success in birds exposed to dichlorodiphenyltrichloroethane, and the development of male genitalia in female marine molluscs due to exposure to some types of anti-fouling paint.[225] Overall, the evidence points to pervasive but so far mostly unquantified effects of chemical pollution on human health, both directly and indirectly, through damage to wildlife and a worrying failure to test many chemicals for adverse effects.

Extreme events—their relation to global environmental change and associated health implications

Extreme events result from the effect of unusual and severe natural hazards affecting people, property, and societies. They include floods, storms, cyclones, wild fires, landslides, droughts, and heatwaves. The severity of the effect on people is a combination of the hazard and the degree to which people are exposed to it, and to which they are vulnerable to its effects.[113] Progress has been made globally towards the reduction of the number of lives lost in extreme events since the 1980s, although mortality risk is still increasing in some countries with poor risk management. Evidence from past events suggests that societies are good at learning from disasters and taking steps to build resilience to them.[113] Conversely, however, the global economic cost of disasters has increased in recent decades, at a faster rate than population or economic growth.[227] The total costs of extreme weather events between 1980 and 2004 is estimated to be $1·4 trillion (of which just a quarter was insured).

Extreme events pose substantial risks to people and economies because of their potential to cause substantial damage, not only through immediate loss of lives and assets, but also through longer-term damage to health, livelihoods, and economies, which are often difficult to monitor. Documentation of the beginning and end of a specific event might also be difficult to do.[228] Climate, weather, and water-based disasters caused the loss of 1·94 million lives between 1970 and 2012.[227] For every person killed by natural disaster, another 1000 people are estimated to be affected physically, mentally, or through loss of property or livelihood.[229] For example, more than 50 million people globally were affected by drought alone in 2011 if all its effects are taken into account.[228] Furthermore, well documented evidence exists that after floods the risk of faecal–oral transmission of disease and of some vector-borne diseases increases, particularly in low-income settings, as does the risk of leptospirosis and adverse mental health effects in a range of settings.[230] A systematic review[231] of water-borne diseases after extreme water-related events showed that more than half (54%) were due to contamination of drinking water supply, particularly from floods and heavy rainfall.

Risk from extreme events can be compounded by increasing susceptibilities related to changing demographic profiles, population density, technological and socioeconomic conditions, unplanned urbanisation, development within high-risk zones, environmental degradation, climate change, competition for scarce resources, and the effect of epidemics such as HIV/AIDS.[232] See panel 8 for a case study from Pakistan exemplifying these complexities.

Conflict and displacement—environmental causes and health consequences

By the end of 2013 a record annual number of 51 million people were displaced forcibly worldwide as a result of persecution, violence, conflict, and human rights violations, with another 33 million displaced within the confines of their own countries. They constitute a growing pool of people susceptible to, and affected by, environmental and other threats.[66] The total amount of migration caused by environmental change is unknown. However, the increased frequency and severity of extreme events driven by climate change is probably already resulting in substantial population movements. In 2008, about 20 million people were displaced by extreme weather, compared with 4·6 million internally displaced by conflict and violence over the same period.[248] Gradual changes in the environment tend to have a greater effect on the movement of people than extreme events. For example, in the past 30 years, twice as many people have been affected by droughts (1·6 billion) as by storms (about 718 million). By 2050, between 50 million and 350 million people are predicted to relocate because of climatic reasons—a rise in sea level, increased water scarcity, desertification, insufficient food, and extreme poverty.[249] The growth of environmental refugees has been greatest in sub-Saharan Africa, but risk in other areas is likely to increase as multiple environmental stressors come into play.[250,251] See the appendix for a case study of displacement in Ethiopia.

The effects of climate change are already thought to increase the likelihood of conflict. A meta-analysis by Hsiang and colleagues[246] reported that for every SD of increased rainfall or temperatures, the likelihood of intergroup conflict increased, with a median increase of 14%. The CNA Military Advisory Board, composed of retired generals, warned that climate change could stimulate instability and conflict.[252] For example, the severe and long-lasting drought in Syria in 2007–2010, which is implicated in the present conflict, is estimated to have become more than twice as likely as a result of human induced climate change.[253]

Displacement, war, and conflict disproportionally affect the poor and have a range of health implications, especially on mental health (post-traumatic stress disorder and depression) and the health of women and children (especially after sexual violence during conflict).[254] In the so-called emergency phase, when crude mortality rates are greater than one death per 10 000 people in a single day, displacement also substantially affects the traditional disease burden—from undernutrition and infectious disease to diabetes.[254] At the same time, migration, particularly mass migration, can also have substantial environmental repercussions for the areas of origin, areas of destination, and the migratory routes in between, and contribute to further environmental degradation.[248]

Effects of global environmental change on mental health

Degradation of a familiar environment can cause solastalgia, a term that refers to distress associated with environmental change.[255] Research in Australia during

Panel 8: **Case study—environmental change: shocks and slow motion catastrophe in Pakistan**

Pakistan is facing threats to the health and development of millions of people from a combination of adverse environmental trends and a high population growth rate of nearly 2% per annum.[233] Surface water availability is diminishing rapidly in Pakistan and water demand is increasing,[234] putting many populations in Pakistan under conditions of water stress. About 5000 m³ of water was available per person per year in the early 1950s,[235] but by 2005 this number had reduced to 1400 m³ and, if preventive action is not taken and present trends continue, demand is projected to outstrip supply by 2025.[234,236] Most water in Pakistan is used for crop irrigation, in 2008, 96% of water used was for agriculture.[236] To support this demand, large volumes of water in the Indus river have been diverted for agriculture and cities, such that downstream, water flow has shrunk to a relative trickle, threatening the livelihoods of fishermen and destroying coastal ecosystems.[237] Widespread discharge of untreated effluents from cities and use of pesticides and nitrogenous fertilisers also affects water quality in many downstream areas.[234] This effect is compounded by salination and waterlogging of soils in some areas due to poor water management.[236]

Climate change is likely to increase water stress. The amount of water flowing into Indus river might decrease by as much as 30–40% in the next 20 years, due to a decreasing magnitude of run-off and a reduced contribution of glacier melt to the main stem of the Indus river.[234] Dwindling water flows, combined with a substantial increase in the frequency of heatwaves[238] have the potential to affect agricultural productivity through reduced yield and lost labour,[239] creating a serious threat to economic growth and food security as agriculture contributes 23% of the total gross domestic product and employs 45% of the workforce in the country.[234]

Although Pakistan is characterised by generally low rainfall for most of the year, heavy rainfall during the monsoon season between July and September is not uncommon.[236] In 2010, monsoon rains across Pakistan resulted in catastrophic flash floods and landslides,[240] submerging a fifth of Pakistan's total land, an area equal to the size of England. The floods killed more than 1900 people and affected an additional 18 million through displacement, disease, loss of income, and damage to infrastructure.[240] Short-term health consequences were widespread—10 million people were forced to drink unsafe water and 37 million infectious disease-related medical consultations were reported within 1 year of the floods.[241] A cross-sectional survey of more than 1700 households estimated that 6 months after the floods, 54% of homes destroyed by the initial flooding still stood wrecked, 50% of people affected were living in camps for the internally displaced, and an overwhelming 88% reported loss of income.[242] The following year, the highest ever recorded monsoon rains caused the 2011 Sindh floods; this time about 5·3 million people were affected. The Intergovernmental Panel on Climate Change predicts that extreme precipitation events are very likely to increase in frequency under climate change,[243] but a single extreme event such as the 2010 floods is difficult to attribute to climate change, particularly in view of natural variability.[244] Deforestation leading to soil erosion and landslides, encroachment onto flood plains by growing human settlements, and the diversion of river flow (often due to political influence) are also implicated in exacerbating the effects of the 2010 floods.[245]

As climate and other environmental changes become more manifest, the chances of conflict due to competition for scarce resources increases,[246] as does migration due to lost income from heat stress.[239] Pakistan's water stressed situation is already creating rifts between the country's ruling agriculturalist elite and the manufacturing sector over distribution of water for energy shortages. The situation is also creating rivalries between feudal families over timely and abundant availability of water for their crops.[247] In combination with pre-existing susceptibility and together with social and political issues, environmental changes could become a major destabilising factor in the country.

the recent decade-long drought, which officially ended in 2012, revealed an increase in anxiety, depression, and possibly suicidality in rural populations (see appendix for a list of studies). In these communities, concerns about financial and work-related issues were compounded by loss of hope for the future and by a sense of powerlessness or lack of control.[255] Similar effects have been reported in Alaskans whose villages were endangered by climate-related changes.[256] The extent and consequences of this disorder are not well documented, although an Environmental Distress Scale[257] has been proposed to support quantitative study. Place attachment refers to the psychological importance of bonds between individuals and their sociophysical environment. Disruption of these cherished bonds can cause grief, loss, and anxiety, which have to be addressed by the engagement of local communities to plan and implement adaptation to environmental change, which might involve managed retreat, for example, of threatened coastal communities.[258]

The mental health effects of environmental change-related displacement are caused by the trauma of leaving familiar surroundings and possessions, the breaking of social ties, the increased risk of violence, the difficulty of resettlement, and the absence of mental health services.[259] An important protective factor is to keep families, and even entire communities united.[260] Risk factors for depression in adults after natural disasters include being female; not being married; holding religious beliefs; having poor education; experiencing injury, or bereavement during the disaster; or losing employment or property.[261]

Challenges to achieving planetary health

The challenges for humanity from global environmental change can be broadly categorised into three categories (see appendix for a broader discussion of challenges).

Firstly, conceptual and empathy failures (imagination challenges), such as an over-reliance on GDP as a measure of human progress, the failure to account for future health and environmental harms alongside present day gains, and the disproportionate effect of those harms on the poor and people in developing nations—ironically the groups who often have least say about policy matters.

Secondly, knowledge failures (research and information challenges), such as an increasingly molecular approach to medicine, which ignores social and environmental context; a historical scarcity of transdisciplinary research and funding within the health community; and an unwillingness or inability to deal with uncertainty within decision making frameworks.

Thirdly, implementation failures (governance challenges), such as how governments and institutions recognise and respond to threats, especially when faced with uncertainties, pooled common resources, and time lags between action and effect.

In the second half of this Commission report we outline strategies and actions to address these challenges, identifying solutions that support both human health and the health of the planet. Our policy propositions provide a starting point to help move towards a conceptual planetary health framework that can guide humanity through the Anthropocene.

Charting a course for the future

Overview

Present trends have the potential to reverse health gains and to destabilise human civilisation unless collaborative and coordinated policies are put in place to reduce the risks. We believe that a course correction is required, which would be to address the unfinished agenda of ill health that is mainly related to poverty, to adapt to environmental change that cannot be prevented, and to achieve equitable human development within finite environmental limits. Just as the *Lancet* Commission on Climate Change[55] has articulated the opportunities for the improvement of health by tackling climate change, we outline the potential for policies to improve health and protect environmental sustainability across a range of sectors and drivers of change.

We start by outlining examples of specific strategies and interventions that can protect and promote human health while addressing environmental threats and the underlying drivers of change. We then discuss enabling policies and improvements in governance that can help achieve these ambitious goals.

Integrated strategies to address growing demands for food within environmental limits

Food and agriculture

Food and agricultural policies that can support 9–10 billion or more people in good health this century will need to address many challenges. The policies would have to reduce the environmental impact of agriculture and food production; develop resilience in the face of many environmental changes and increases in extreme events; ensure stability of food prices and protect the vulnerable from variability that does occur; and tackle malnutrition, both underconsumption of protein, calories, and micronutrients, and obesity and non-communicable diseases related to dietary risk factors.

Such policies will need to take into account the combined effect of trends in, and threats to, food production from both terrestrial and aquatic ecosystems (marine and freshwater; figure 12). They should also recognise the varying dependencies and capabilities of farmers, from poor subsistence farmers (who might use food and other products from public lands) to those working on highly mechanised farms with access to advanced technologies. The management of natural systems to protect biodiversity is an important cornerstone to the protection of global nutrition, particularly for resilience to shocks in the food production system. Interdisciplinary collaboration between public health, agriculture, environmental, and nutritional strategies will be needed to develop and implement appropriate policies.

Sustainable intensification

Although global crop yields grew by 115% between 1967 and 2007, the area of land in agriculture increased by only 8% and the total stands at about 4·6 billion hectares (46 million km^2) at present. With new land for agriculture becoming scarce sustainable agricultural intensification has been proposed as a strategy, which enables more food to be grown on the same land compared with under traditional agricultural practices while preserving

For the **Statistics Division of the Food and Agriculture Organization** see http://faostat.fao.org/

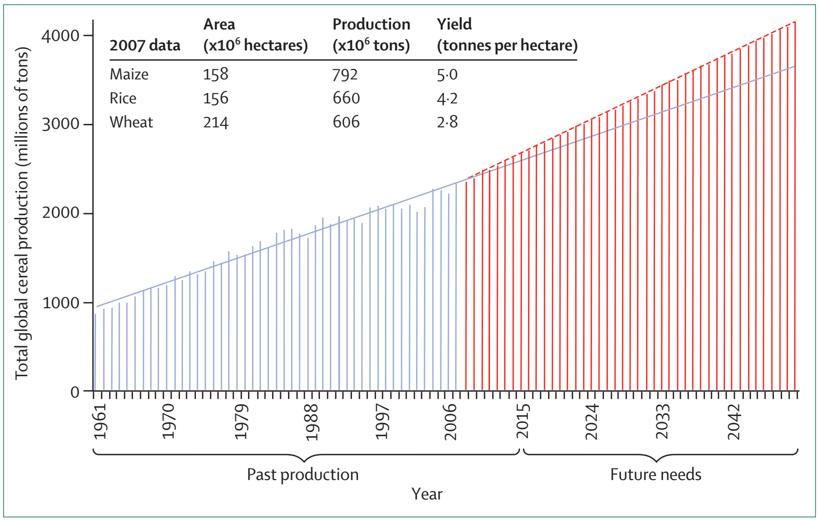

Figure 12: **Historical and projected grain production requirements to feed the world**
Global cereal production has risen from 877 million tonnes in 1961 to 2351 million tonnes in 2007 (blue). However, to meet predicted demands (red), production will need to rise to more than 4000 million tonnes by 2050. The rate of yield increase must move from the blue trend line (32 million tonnes per year) to the red dotted line (44 million tonnes per year) to meet this demand, an increase of 37%. The inset table shows the 2007 data for the three major cereals. Data are from the Statistics Division of the Food and Agriculture Organization website. Reproduced from Tester and Langridge,[172] by permission of The American Association for the Advancement of Science.

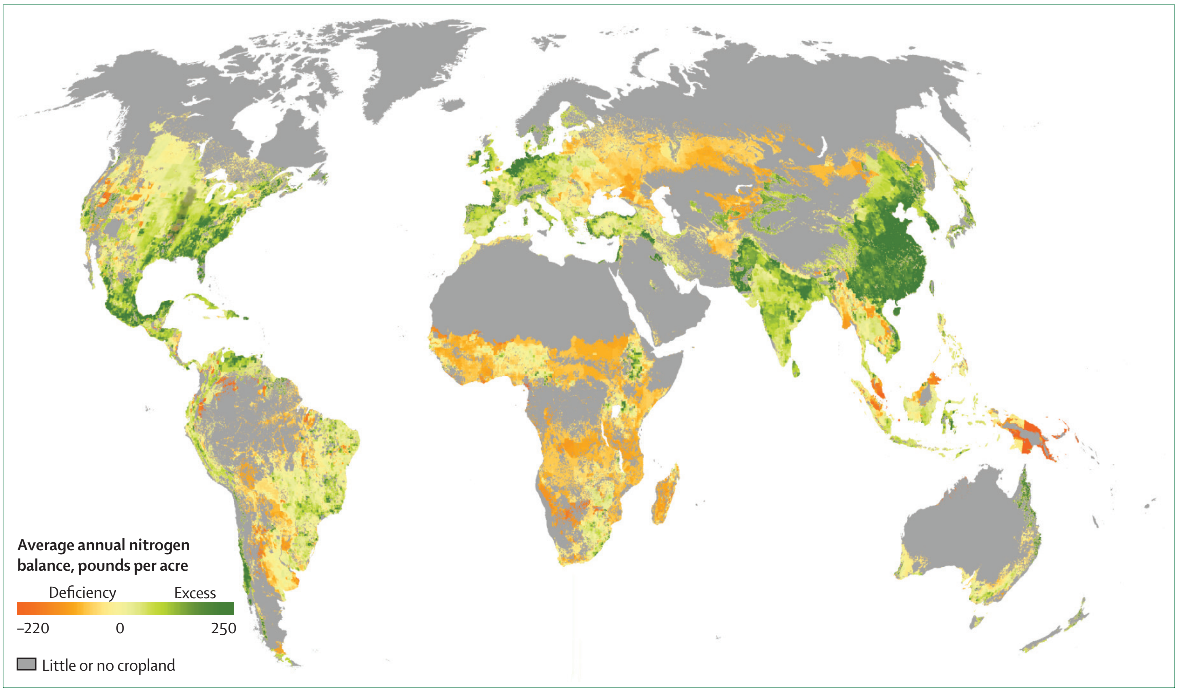

Figure 13: **Imbalance in global nitrogen consumption**
Redistribution of nitrogen could help reduce pollution in areas of excess and increase crop yield in areas of deficit. Original graphic created by Paul C West (Institute on the Environment, University of Minnesota, MN, USA; data from West and colleagues [2014], see appendix for citation). Reproduced from National Geographic,[267] by permission of Jerome Cookson/National Geographic Creative.

biodiversity and other environmental assets.[262] In a low-income country context, sustainable agricultural intensification might consist of three interlinked activities: ecological intensification (eg, conservation agriculture, agroforestry, and integrated pest management to minimise pesticide use), genetic intensification (plant and animal breeding), and market intensification, which provides an enabling environment for both producers and consumers to benefit.[263]

Innovation is an important component of each of these sustainable agricultural intensification strategies. For example, plant performance can be improved through molecular breeding, use of companion plants, and genetic modification. A report[264] published in 2014 suggests that no evidence exists that genetically modified crops are unsafe for human consumption but it was not a systematic review. If these technologies are to make a useful contribution to the reduction of global hunger they have to both protect the environment and be accessible to farmers in low-income settings, otherwise inequities will persist and increase.

Efficient use of water and fertiliser

Strategies to increase crop yields while reducing water losses include water harvesting and water conservation. Although drip or trickle irrigation methods are more expensive to install than conventional irrigation methods, they can be as much as 33% more efficient in water use and can carry fertilisers directly to the roots of crops.[93]

In China, integrated soil–crop system management practices based on present knowledge of crop ecophysiology and soil biogeochemistry have been shown to increase yields for rice, wheat, and maize substantially while reducing greenhouse gas emissions and not increasing demands for fertiliser.[265] This approach would enable China to meet its increased demand for crops for direct consumption and animal feed by 2030 with lower environmental impacts than at present. Most of the benefit from fertilisers comes with the first increments of added nitrogen, but higher use produces diminishing returns and increased adverse effects. Only 30–50% of applied nitrogen fertiliser and about 45% of phosphorus are taken up by crops.[266] Much greater efficiency of use is needed, including through increased public sector research, extension education of farmers, soil testing, and improved timing of fertiliser application. In parts of the world, such as sub-Saharan Africa, increased fertiliser use might be necessary (figure 13). Recycling of phosphorus in regions of excess to regions of deficiency is recommended to mitigate eutrophication, increase crop yield, and address potential global shortages of phosphorus.[268]

Reduction of food waste and spoilage

The estimated 1·2–2 billion tonnes (30–50%) of all food produced globally per year that is wasted[93] is split fairly evenly between preharvest and postharvest losses.[269] In low-income countries the wastage occurs mainly at the farmer–producer end of the supply chain and, as countries become more developed, the wastage moves further up the supply chain. Almost 1·4 billion hectares (14 million km²) of agricultural land (nearly 30% of the world's total agricultural land) is used to produce food that is never eaten.[269] Additionally, food waste contributes to biodiversity loss, consumes about 250 km³ of surface and groundwater, and generates 3·3 billion tonnes of carbon dioxide equivalent greenhouse gas emissions, the third largest source after the national greenhouse gas emissions of China and the USA.[269] To reduce food waste along the food supply chain by about 50% seems feasible[270] and would have major benefits to the environment and the world economy.

Reduction of spoilage due to fungal contamination can improve health and reduce waste. Several promising aflatoxin control strategies are being developed, including the use of a natural, non-toxic technology that uses the ability of native atoxigenic strains of *Aspergillus flavus* (the fungus that produces aflatoxin) to naturally outcompete aflatoxin-producing strains and has been adapted for use in Africa.[271]

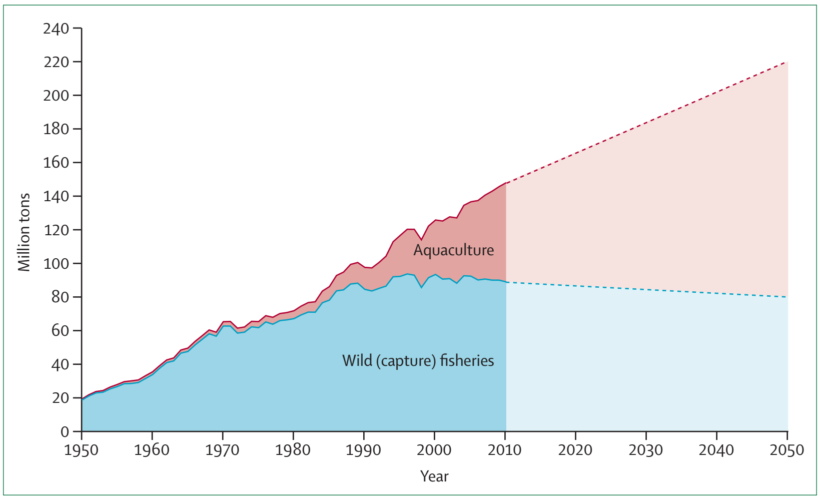

Figure 14: **Aquaculture production is expanding to meet world fish demand (million tons), 2011–2050**
Calculated at the World Resources Institute with historical data (1950–2010) sourced from the software FishStatJ published by the Food and Agriculture Organization of the United Nations. Graph assumes 10% reduction in wild fish catch between 2010 and 2050, and linear growth of aquaculture production at an additional 2 million tons (about 1·8 billion kg) per year between 2010 and 2050.[272] Although aquaculture is needed to meet world fish demand to reap co-benefits for nutrition and the environment, the aquaculture has to be sustainable. Reproduced from Waite and colleagues,[273] by permission of the World Resources Institute.

Sustainable aquaculture and fisheries

To address rising food demands, a major shift towards sustainable aquaculture is needed, which does not need major inputs of fish meal or large amounts of antibiotics (figure 14).[274] Aquaculture makes use of 600 freshwater and marine species from all trophic levels and this diversity might confer resilience to environmental change.[275] The Food and Agriculture Organization Code of Conduct for Responsible Fisheries contains principles and practices for sustainable aquaculture development.[276] The Global Ocean Commission aims to articulate strategies to protect coastal zones, control overfishing, reduce plastic pollution, and tackle harmful subsidies.[277]

Nutritional profiles of fish vary substantially. For example, the amount of omega-3 fatty acids is lower in fish at low trophic levels (eg, catfish or crawfish) compared with salmon and some other types of fish, particularly when they are farmed rather than wild, showing the importance of diversity of intake and the effect of feed composition of farmed fish.[278] Health and environmental policies should be harmonised—eg, to ensure that dietary recommendations to increase fish consumption because of the health benefits do not lead to further overexploitation of fisheries. Projected increases in aquaculture, which will add 15% to the total supply of seafood by 2021, could, if equitably distributed, provide sufficient fish globally to satisfy nutritional guidelines, depending on the type of fish farmed.[278] Aquaponics has potential to support both sustainable aquaculture and the reduction of fertiliser use in agriculture by integrating aquaculture and hydroponics (soil less plant farming). Fish waste water is used as a source of nutrients for plant farming by circulating it through hydroponic growing beds.[275]

Support of subsistence farmers

Experts debate about the balance between support of large-scale industrial and smallholder subsistence farming, which is of particular concern because subsistence farming overlaps with undernutrition and is often done by women. An indirect strategy is to rely on the spillover benefits of economic growth in agriculture. A direct strategy, particularly for forest communities, is to promote integrated agricultural development and forest conservation projects[279] or to support forest based enterprises[280] so that households can both protect and rely on forest products to cope with agricultural shocks. Other potential strategies include enhanced social protection, education, improved access to markets, infrastructure, credit, and information systems.[270] Furthermore, thermal stress because of climate change will prove to be a major threat to agricultural labour productivity.[281] Strategies such as clean water for hydration, changes in working practices, and mechanisation could help to sustain farmer productivity in the face of increased thermal stress from climate change.

For **FishStatJ** see http://www.fao.org/fishery/statistics/software/fishstatj/en

Innovative sources of nutrition

Insects are estimated to form part of the traditional diets of at least 2 billion people. More than 1900 species have reportedly been used as food.[282] Insects have high feed conversion efficiencies, lower greenhouse gas emissions than conventional livestock, and usually require less land. Insects are less likely to transmit zoonotic infections. Insects have substantial diversity in their nutritional value[282] but they can be a highly nutritious and a healthy food source with high fat, protein, vitamin, fibre, and mineral content. Novel sources of protein such as

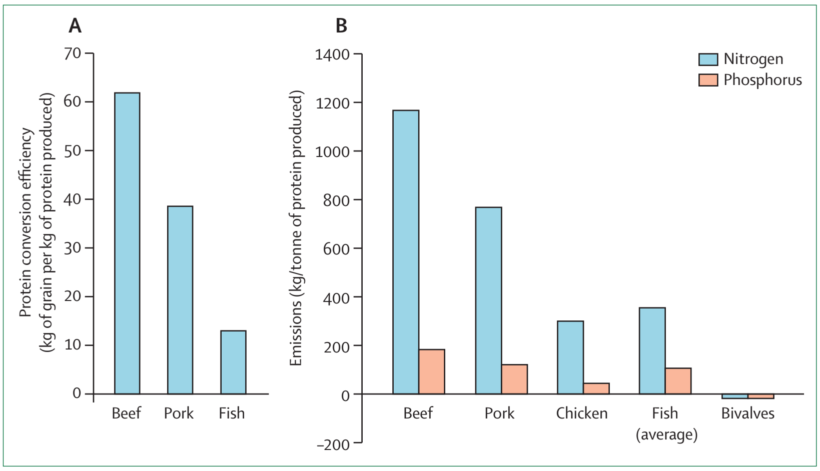

***Figure 15:* Protein conversion efficiency and emissions comparison for various livestock**
(A) Feed and protein conversion efficiency of beef, pork, and fish. (B) Nitrogen and phosphorus emissions for animal production systems. Data for fish sourced from Hall and colleagues, and data for beef, pork, and chicken sourced from Flachowsky and from Poštrk (references in appendix). Reproduced from Béné and colleagues,[290] by permission of Springer under the Creative Commons Attribution License.

seaweed or microalgae could also be exploitable if heavy metals and other possible hazards can be addressed.[283]

Diversification of diets and crops can both improve the prospects for adaptation and nutrition

The world's agricultural landscape has been dominated by 12 species of grain crops, 23 vegetable crop species, and about 35 fruit and nut crop species.[284] Dietary diversity is increasingly recognised as being good for health by improving dietary quality, including micronutrients.[285] Major variation in nutrient content can exist within a single type of food; for example, rice can vary in protein content from around 5–15%[286] and the provitamin A content of different species of bananas varies substantially.[287] To combat undernutrition, promotion of increased production of nutrient-rich foods for direct consumption by poor populations will be essential, as will income generation, particularly for women, through diversification and the use of technologies and practices that reduce food losses and conserve nutrients.[288]

Biofortification

In view of the existing burdens of micronutrient deficiency and future challenges to improve nutrition, several strategies can be used. These strategies include fortification of foods such as staple grain flours with vitamins or minerals and the pursuit of increased agricultural and dietary diversity. Biofortification is also being increasingly promoted to address micronutrient deficiencies in poor populations particularly. Crop varieties with particularly high concentrations of the desired nutrients are cross-bred with high yielding varieties, resulting in high levels, for example, of zinc or beta-carotene. The seedlings or cuttings can be made available through extension programmes, targeting of nutritionally vulnerable smallholders, or market mechanisms. Growing evidence exists that biofortified crops can improve micronutrient profiles in deficient populations. Examples include high iron staple foods in four countries; maize with high beta-carotene traits, which is as efficacious as supplements; and orange flesh sweet potato, which increases beta-carotene levels and vitamin A status in consumers (see appendix for references). However, regulatory hurdles will need to be addressed for biofortification to make a contribution to meeting nutritional requirements.[289]

Promotion of healthy, low environmental impact diets

Major proportions of the world's crops are being fed to animals (and are subject to conversion inefficiencies) or are used for biofuels, resulting in 41% of the calories available from global crop production being lost to the food system (figures 6, 15).[96] Without changing crop mix, if food was exclusively grown for direct human consumption enough extra calories would be available to feed an additional 4 billion people (more than the 2–3 billion people projected to be added to the world population in the coming decades).[96] The ratio of animal product calories to feed calories is, on average, still only about 10%.

Animal products have much higher greenhouse gas emissions per gram of protein than legumes. For example, beef and lamb have emissions per g of protein that are about 250 times those of legumes.[68] By 2050, if present dietary trends continue, the increase in demand for animal products will be a major contributor to the projected 80% increase in global agricultural greenhouse gas emissions from food production and to global land clearing.[68] Thus even small shifts in allocation of crops from animal feed and biofuels to direct human consumption could substantially increase global food availability. However, the different bioavailability and aminoacid content of vegetable and animal protein needs to be taken into account because this would probably necessitate that more legumes be grown than are grown at present.

Another consideration is affordability of food traded internationally, which is out of reach for many poor people. For some populations, livestock products provide both essential protein and a wide range of essential micronutrients and can help to prevent stunting. In pastoralist communities, for example, livestock represent a vital source of wealth and nutrition and can be grazed on marginal land that would not support food crops. However, in high consuming countries, animal product consumption could be reduced and fruit and vegetable consumption increased, benefiting health in terms of reduced non-communicable disease burden and reducing the impact on the environment (figure 16). At present, the global production of fruit and vegetables is insufficient to meet nutritional requirements, with a global shortfall of about 22% (34% if food waste is included), mostly as a result of supply gaps in low-income and middle-income countries.[292] This shortfall underscores the need for policies to incentivise fruit and vegetable production and remove subsidies on less healthy foodstuffs, which also generally

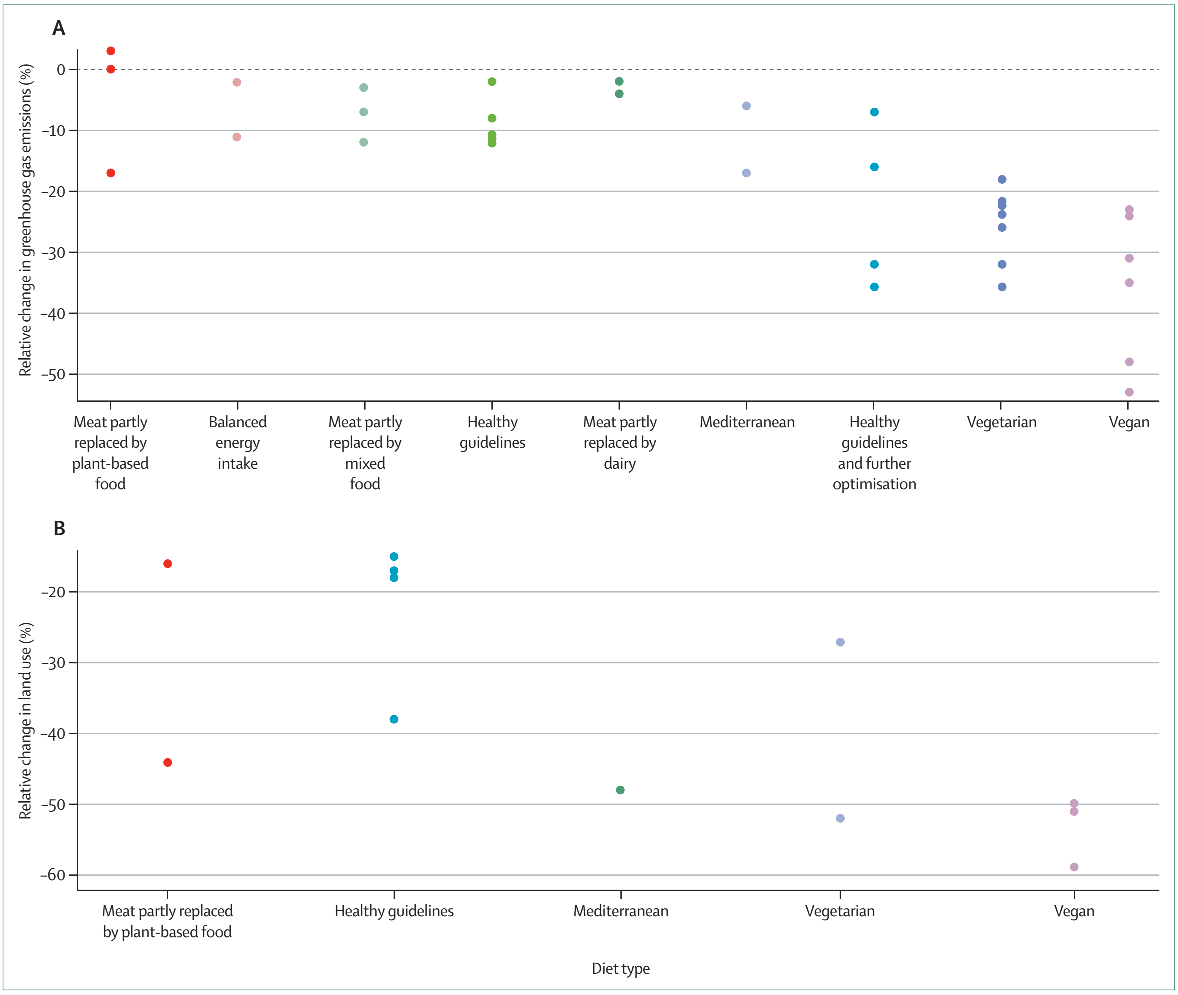

***Figure 16*:** **Relative change of greenhouse gas emissions and land use of alternative diets compared with baseline diets**
(A) Point estimates of relative changes in greenhouse gas emissions from studies comparing environmental impacts of present dietary patterns with healthy and sustainable alternatives, in carbon dioxide equivalents per person per year.[291] An alternative diet category of switching from ruminant to monogastric meat intake was omitted because it contained only one study (–18% relative difference in greenhouse gas emissions). (B) Point estimates of relative changes in agricultural land use from studies comparing environmental impacts of present dietary patterns with healthy and sustainable alternatives, in square metres per person per year.[291] The existing scientific literature has several limitations in the methods used, including the widespread use of a single absolute number for environmental impacts and emissions derived from lifecycle analysis. These limitations make the reliability of results difficult to assess. The scientific literature is dominated by studies of European populations. Additionally, varying assumptions existed about system boundaries (eg, greenhouse gas emissions up to the farm gate or including the retail sector) and the inclusion of greenhouse gas emissions from direct and indirect land use change.[291] However, the use of relative changes might counteract some of the variability in the methods across studies. Figure prepared by Lukasz Aleksandrowicz.

have higher greenhouse gas emissions. A report[45] from the Chicago Council on Global Affairs published in 2015 has made a compelling case for prioritising actions by the US Government and other stakeholders, both nationally and internationally, to make food systems more productive, nutritious, and sustainable than they are at present.

Dietary risk factors are among the most important contributors to the global burden of disease, with large numbers of premature deaths in particular being due to inadequate consumption of vegetables, fruit, and nuts (figure 17). Generally, diets with reduced animal product consumption, particularly from ruminants, are associated with reduced greenhouse gas emissions. More environmentally sustainable diets tend to be healthier than less sustainable diets, but not invariably so.[291] For example, a study[293] in France suggested that diets that scored higher in the author-defined nutritional quality class also had higher greenhouse gas emissions. This finding might have been due to the low greenhouse gas emissions associated with starches and sugar, which also scored low on the authors' measure of nutrient quality, and underscores the need to use approaches that optimise diets for low environmental impact, high nutrition quality, and affordability and minimise deviations from present patterns to enhance acceptability.

Using an optimisation modelling approach, researchers have shown that if the UK population were to adhere to WHO dietary recommendations, this would incidentally

2010 Risk factor	Mean rank (95% UI)	% change (95% UI)
1 High blood pressure	1·1 (1–2)	27% (19 to 34)
2 Smoking (including second-hand smoke)	1·9 (1–2)	3% (–5 to 11)
3 Household air pollution	4·6 (3–7)	–37% (–44 to –29)
4 Low dietary fruit	5·0 (4–8)	29% (25 to 34)
5 Alcohol use	5·1 (3–7)	32% (17 to 47)
6 High body-mass index	6·1 (4–8)	82% (71 to 95)
7 High fasting plasma glucose	6·6 (5–8)	58% (43 to 73)
8 Childhood underweight	8·5 (6–11)	–61% (–66 to –55)
9 Ambient particulate matter pollution	8·7 (7–12)	–7% (–13 to –1)
10 Physical inactivity	10·0 (8–12)	0% (0 to 0)
11 High dietary sodium	11·2 (8–15)	33% (27 to 39)
12 Low dietary nuts and seeds	12·9 (11–17)	27% (18 to 32)
13 Iron deficiency	13·5 (11–17)	–7% (–11 to –4)
14 Suboptimum breastfeeding	13·8 (10–18)	–57% (–63 to –51)
15 High total cholesterol	15·2 (12–17)	3% (–13 to 19)
16 Low dietary whole grains	15·3 (13–17)	39% (32 to 45)
17 Low dietary vegetables	15·8 (12–19)	22% (16 to 28)
18 Low dietary omega-3	18·7 (17–23)	30% (21 to 35)
19 Drug use	20·2 (18–23)	57% (42 to 72)
20 Occupational injury	20·4 (18–23)	12% (–22 to 58)
21 Occupational low back pain	21·2 (18–25)	22% (11 to 35)
22 High dietary processed meat	22·1 (17–32)	22% (2 to 44)
23 Intimate partner violence	23·8 (20–28)	0% (0 to 0)
24 Low dietary fibre	24·5 (19–32)	23% (13 to 33)
25 Lead exposure	25·5 (23–29)	160% (143 to 176)
26 Sanitation		
29 Vitamin A deficiency		
31 Zinc deficiency		
34 Unimproved water		

Figure 17: **Rank of risk factors for global burden of disease in 2010**
Dietary risk factors or those strongly associated with diet (highlighted in red) contribute substantially to the global burden of disease. The top 25 ranked factors in 2010 are listed alongside factors that were in the top 25 in 1990. Percentage change shows change in rank since 1990. Air pollution and physical inactivity are also major environment-related risk factors for ill health. UI=uncertainty interval. Reproduced with permission from Lim and colleagues.[33]

result in a 17% reduction in greenhouse gas emissions and increase life expectancy at birth by about 8 months, mainly from benefits to coronary heart disease.[294] Greenhouse gas emissions could also be reduced by about 40% in the UK through dietary change while adhering to WHO dietary recommendations, maintaining affordability, and without departing radically from existing diets.[294] Such diets would produce substantial improvements in health, particularly as a result of increased fruit and vegetable consumption and reduced consumption of red and processed meat. An outline of the implications of palm oil and organic food for health is given in the appendix.

Integrated land use solutions

The REDD+ mechanism (panel 1) has been created to reduce greenhouse gas emissions from deforestation and forest degradation, and also holds the promise of providing a host of regional and local co-benefits such as livelihoods and ecosystem services. Although the programmes are too recent to generate empirical evidence of benefits,[295] lessons can be learnt from Costa Rica, which is a pioneer in taking an integrated landscape perspective to conservation (appendix). Costa Rica has effectively combined protected areas, innovative payments for ecosystem services, and strict enforcement to achieve conservation targets related to biodiversity protection, hydrological services, and carbon sequestration, among others.[296] Evidence from Indonesia also suggests that forest protection can improve watershed functions, reducing cases of diarrhoea[297] and evidence from Brazil offers hope that forest protection can deliver health benefits (panel 9).[298]

Human disease risk can be reduced indirectly by management of the landscape, ecosystems, and the biodiversity they contain. For Lyme disease and West Nile virus, high risk of transmission is associated with the loss of vertebrate diversity, which in turn is associated with some types of habitat destruction and fragmentation.[299] For example, forest fragmentation and destruction in the USA have been shown to reduce mammalian species diversity and to increase populations of the white-footed mouse, the most efficient host of Lyme disease.[299] The maintenance of forested areas near or abutting to residential zones—which keeps the composition of ecological communities intact and mouse population sizes low—might help to reduce the risk of Lyme disease transmission.[201] Community zoning policies can protect contiguous forests while at the same time promoting the spatial aggregation of deforested areas. For example, housing developments can be designed in which lawns and cleared backyards are clustered—leaving neighbouring forests untouched. For infectious diseases, in which high species diversity has been shown to reduce disease risk, policies that maintain or enhance biodiversity could be implemented. Further evidence on the role of the environment in mediating risk from vector-borne and zoonotic disease and how policies can be developed to benefit both health and ecosystems is given in the appendix.

Landscape fires in southeast Asia are one of the greatest drivers of biodiversity loss and are also a major regional public health threat. A 2015 study[300] reported that protection of peatlands in Indonesia from degradation and burning would reduce smoke concentrations in Palembang and Singapore by more than 90%, and by 80% for equatorial Asia. The health effects of landscape fires can now be modelled and quantified at a very fine scale. Incorporation of the public health effects of land use can help create targeted policy solutions that can simultaneously reduce biodiversity loss and optimise the health of populations. A recent analysis[301] published in 2015 shows that PM2·5 air pollution levels are lower in

Panel 9: **The complex interrelations between health and land use change**

Protected areas and indigenous reserves reduce deforestation, whereas roads and mines increase (or at least are positively related to) deforestation. Generally, the process of deforestation benefits the mosquitoes that transmit malaria by creating new breeding sites, reducing biodiversity (including predator populations), and creating microclimates that are favourable to mosquitoes for survival and reproduction (eg, by increasing temperature and humidity). Deforestation is also associated with smoke and sedimentation, and more generally, with disruption of the hydrological cycle and loss of the water and air filtering functions of trees. However, protected area types, indigenous reserves, roads, and mines also have their own distinct effects on the environment and people's interaction with the environment, hence affecting both disease and exposure to disease. Several conclusions have emerged regarding the interactions between health and land-use change on the basis of research that focuses on Latin America.[298]

Forest conservation

Malaria

(–) Intact forests affect anopheline ecology and malaria epidemiology because they contain fewer breeding sites than fragmented forests.

(–) Intact forests contain larger vector predator populations and a greater diversity of mammalian species (promoting dilution effects) compared with fragmented forests.

(–) Intact forests generate microclimates that inhibit anopheline mosquitoes.

Acute respiratory infections

(–) Forests can filter air particulates.

(–) Conservation reduces the number of fires and amount of smoke emission.

(–) Intact forests are associated with a reduction in the collection and burning of biomass fuels, and an increased water supply (improving personal hygiene) compared with fragmented forests.

Diarrhoea

(–) Intact forest can reduce flooding and filter pathogens from surface water, thus maintaining water quality and stabilising the hydrological cycle.

Protected areas

Malaria, acute respiratory infections, and diarrhoea

(–) All protected areas generate disease regulation service through the ecosystem changes associated with forest conservation (already described).

(–) Strict protected areas reduce human exposure to forest habitat of anopheline mosquitoes, in addition to reducing forest disturbance.

(+/–) Sustainable use protected areas have people living and working in them and thus exposed to forest habitat of anopheline mosquitoes, in addition to allowing more forest disturbance than strict protected areas. Compared with strict protected areas and indigenous reserves, these protected areas are more likely to promote the mixing of infected and susceptible populations.

(–) Indigenous reserves are established where indigenous populations live, who are often highly susceptible to disease, but if regulations and borders are enforced, these reserves can reduce mixing of infected and susceptible populations.

Roads

Malaria

(+) Roads create a forest fringe, which is a favourable habitat for anopheles, thus creating so-called frontier malaria.

Acute respiratory infections

(+) Roads worsen air quality because of traffic, road construction, and economic activities.

Diarrhoea

(+) Roads worsen water quality because of traffic, road construction, and economic activities.

Malaria, acute respiratory infections, and diarrhoea

(–) Roads ease access to medical care and public health system.

(+) The construction of roads attracts susceptible labourers, who move too quickly and often to be helped by the public health system and who might not have developed any natural immunity.

Mining

Malaria

(+) Mining creates vector breeding sites such as borrow pits and dammed ponds used to process alluvial deposits.

Acute respiratory infections

(+) Mining worsens air quality (eg, through associated production of charcoal and increases in unplanned settlements).

Diarrhoea

(+) Mining worsens water quality and increases unplanned settlements.

Malaria, acute respiratory infections, and diarrhoea

(+) Mining draws in migrants who can be both susceptible and disease carriers, and who typically work long hours and live in precarious housing, which increase exposure to disease.

Each change in land use might either decrease (–) or increase (+) the likelihood of the spread of the given disease or diseases in the area. Reproduced from Bauch and colleagues.[298] References are given in the appendix.

communities with forest certification compared with communities without forest certification.

Ecosystem restoration can also contribute to poverty alleviation (panel 10). For example, the Shinyanga Soil Conservation Programme, better known by its Swahili acronym HASHI (Hifadhi Ardhi Shinyanga), ran between 1986 and 2004 in northwest Tanzania and combined forest restoration and traditional land management

Panel 10: **Case study—relieving poverty through ecosystem restoration in the Loess Plateau**

The Loess Plateau in China has had soil and water loss caused by grain production for more than two thousand years. Consequently, land productivity has diminished greatly and riverbed height has substantially increased in the lower reaches of the Yellow River.[302] In 1994, the Loess Plateau was also one of the poorest regions in China, with about half of the counties listed as poverty stricken as part of the Seven-Year Priority Poverty Alleviation Program.[303] With support from the World Bank and the Chinese Government between 1994 and 2005, two consecutive projects, which covered 22 counties in Shaanxi, Shanxi, Gansu, and Inner Mongolia, aimed to increase agricultural production and income, reduce sediment inflows to the Yellow River, and restore local ecosystem productivity. Eco-based adaptions were adopted to control soil and water loss, including afforestation, dune stabilisation, the banning of grazing, and the construction of sediment retention dams and terraces. Additionally, an ownership structure was established to encourage local engagement, giving participating farmers the right to acquire use of the land after completion of the project.[304] Consequently, the Loess Plateau is becoming greener,[305] with forest and grass coverage increasing from 11·4% to 27·3%.[306] These projects also resulted in an increase in mean annual per person income from ¥360 to ¥1624, an increased annual grain output from 427 000 tonnes to 1 265 000 tonnes, a reduction of annual sediment inflow to the Yellow River by 57 million tonnes, increased biodiversity, improved soil fertility, and increased carbon sequestration. Furthermore, high grain yields in good years, together with livestock and fruit trees, help to provide enough food to sustain local people through drought years of low crop yield and the increased income also helps buffer against food poverty.[304]

techniques to restore ecosystems and also increase household income.[307]

Policies for planetary health: co-benefits to health and the environment

Greenhouse gas emissions

Many measures to reduce greenhouse gas emissions in the housing, transport, food and agriculture, and electricity generation sectors have ancillary health benefits (co-benefits), which are often substantial.[114] An important mechanism is by the reduction of fine particulate air pollution. Ambient air pollution from fine particulates causes between 2·8 million and 3·6 million deaths per year, mostly as a result of fossil fuel combustion, particularly coal and diesel fuel.[33] WHO estimates of mortality for 2012 are even higher at 3·7 million deaths.[215] The health co-benefits from reduced fine particulate air pollution as a result of reduced fossil fuel combustion have been studied in detail and the evidence has been synthesised by the IPCC and the *Lancet* Commission on Climate Change[42,55] and are not discussed in detail in this Commission report.

Short-lived climate pollutants

Measures to reduce short-lived climate pollutants could yield major health benefits; an estimated 2·4 million premature deaths worldwide could be prevented annually, mainly as a result of some measures to reduce black carbon exposure. Some measures to reduce short-lived climate pollutants also reduce carbon dioxide emissions and thus additionally contribute to efforts to combat climate change.[308] Access to clean household energy has the potential to greatly reduce household exposure to air pollution, the risk of burns, and the emissions of black carbon and a range of other pollutants.[309] Solar lamps, for example, reduce black carbon emissions, burns, and dependence on costly kerosene.[310]

Policies to reduce ground level ozone, which is formed from chemical reactions between oxides of nitrogen, methane, and volatile organic compounds, can also yield co-benefits. Ozone air pollution directly affects health and also reduces crop productivity, forest growth, and the ability of vegetation to take up carbon dioxide.[220] As such, policies to reduce methane emissions yield health and agricultural co-benefits through increased crop productivity as a result of reduced tropospheric ozone levels.[212]

Increased physical activity

Increased active travel (walking and cycling) in cities can reduce greenhouse gas and fine particulate emissions and address physical inactivity, which contributes to more than 3 million deaths a year[33] and is a risk factor for major non-communicable diseases such as ischaemic heart disease, stroke, diabetes, colon and breast cancer, Alzheimer's disease, and depression.[311] The health benefits generally outweigh increased risks of road injury. New technologies, such as electric vehicles, will reduce tailpipe emissions of hazardous pollutants but will not address other health problems of physical inactivity or road injuries. Furthermore, physical activity related to transport and changes in dietary patterns are associated with obesity.[68] Obesity could potentially be addressed through strategies to reduce private car use in cities by providing improved public transport and encouraging active travel.[312] See the appendix for a case study on the co-benefits of addressing health and the environment in cities.

Sound management of chemicals

The need for accelerated progress to achieve sound management of chemicals has been documented in the Global Chemicals Outlook,[80] which argues for "a revitalised commitment to the sound management of chemicals". The Global Chemical Outlook report concludes with a call for "an investment in capacity for sound management of chemicals that has widely been acknowledged as lacking".[80] Moral arguments have little effect on how chemicals are managed and evidence that permits quantification of externalities and costs is still fragmentary. Nevertheless, in their report[313] on the costs of inaction, the UN Environment Programme estimated a very high rate of return from investments to improve the management of chemicals. Unregulated pesticide use poses substantial risk to human health and ecosystems as shown by studies in west Africa[314] and Costa Rica.[315] According to a conservative estimate, the costs of inaction in Africa in 2009, related to pesticide use alone, were greater than the total overseas development assistance to health care (excluding HIV/AIDS) in Africa.

The estimated health costs of pesticides vastly outweighed the low costs of sound chemical management in a country such as Uganda. Sound chemical management in the agricultural sector would also result in improved crop yields (by about 20%).[313]

Barriers to progress include the erroneous perception that exposure to chemicals is mainly an environmental issue rather than a health issue, the absence of legally binding instruments linking chemical safety to development policies, poor communication between environment and health authorities, and fragmented regulatory approaches combined with inadequate implementation of regulations. Expertise on safe chemical management is not sufficiently transferred from high-income to low-income countries, although increasingly production is moving from high-income countries to emerging economies and low-income countries. Only about 45 countries have National Cleaner Production Centres that provide training and technical advice for sound chemical management to small and medium sized enterprises.

The total insurance capacity to support chemical liability risks (including pharmaceuticals) is only $2·5 billion worldwide annually and the actual purchase much lower, a tiny amount compared with the $4 trillion worldwide annual sales of the chemical industry. The costs incurred by the financial sector for mismanagement of chemicals can be high: more than $100 billion and rising fast for asbestos; $3·5 billion for the Bhopal chemical disaster; and $25 billion for Chinese drywall (the sale of imported synthetic gypsum panels in the USA, which cause corrosion and possible health effects). Banks have often tended to ignore such risks when providing financing. The financial and insurance sectors could also prove instrumental in promoting the implementation of policies to reduce risk. Liabilities arising from emerging risks such as nanotechnologies, endocrine disruptors, and mixtures between different chemical compounds are likely to particularly concern the insurance industry and this realisation could spur action.

Much of the flow of hazardous waste from rich to poor countries is in contravention of the Basel Convention on Transboundary Movements of Hazardous Waste, but the Protocol of the Convention on Liability and Compensation has so far been ratified by only half of the 20 countries needed to enter it into force. Consequently international mechanisms for the implementation of the "polluters pay principle" for hazardous waste are inadequate.

A range of approaches for sound management of chemicals are needed, including promotion of safer alternatives and guidance to accelerate the achievement of the Strategic Approach to International Chemicals Management (SAICM) goals by 2020.[316] To develop a comprehensive approach to chemical safety, all five themes encompassed in the SAICM—risk reduction, knowledge and information, governance, capacity building and technical cooperation, and illegal international traffic in chemicals—have to be addressed, backed by effective and enforced legal instruments.[316] Potential solutions include movement towards a circular economy, which minimises waste through recycling and reuse, procurement policies for public institutions that promote safe substitutes for chemicals of concern, the use of lifecycle assessment to assess health and environmental impacts, innovative technologies permitting rapid chemical screening, and assessment of alternatives.

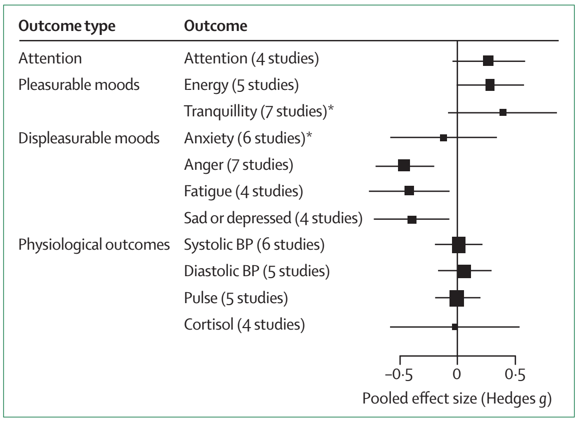

Figure 18: **Psychological and emotional outcomes from exposure to natural versus synthetic environments**
A systematic review[322] of benefits to health from exposure to natural environments reported that significantly lower negative emotions, such as anger and sadness, were experienced after exposure to a natural environment in comparison with a more synthetic environment in a subset of studies where these were measured. The pooled effect sizes (Hedges *g*) and 95% CI for each outcome are based on aggregated data (one average effect size per study). In brackets are shown the number of studies that were used to calculate the effect size and an asterisk is used to denote a significant heterogeneity test ($p<0·05$) for a particular group. Reproduced from Bowler and colleagues,[322] by permission of the Collaboration for Environmental Evidence.

Sustainable cities

Healthy city design promotes active and healthy living.[317] Active travel (walking and cycling) can reduce the risk of ischaemic heart disease, obesity, diabetes, some types of cancer, and all-cause mortality, while also averting costs to health systems and reducing greenhouse gas emissions.[318] Importantly, sustainable practices are associated with mental health benefits.[319] In epidemiological studies,[319] an increase in physical activity is associated with a reduced risk of depression. The steps needed to adapt to climate change and to prepare for disasters require cohesive community action. Implementation of such action could increase social capital,[320] which, in turn, promotes health.[321] Exposure to natural environments might also improve mood but had no effect on physiological variables (figure 18).[322]

The rich biodiversity that urban areas can contain is being increasingly recognised and policies to preserve ecosystems and their services could provide many benefits.[323] Almost a third of the 100 largest cities have nearby natural areas that provide catchment for the supply of stable and affordable drinking water. Furthermore, green spaces in or near cities also deliver services such as reducing air pollution, temperature regulation, groundwater recharge, and cultural services including recreation—all contributing to the physical and mental health of the urban population. Urban biodiversity and ecosystems deliver myriad other benefits including climate change adaptation and mitigation—eg, by absorbing run-off from heavy rainfall events and carbon sequestration. Urban parks are around 1°C cooler than built-up areas during the day and help reduce the effects of urban heat islands.[324]

More than 370 cities worldwide, mainly but not exclusively in industrialised countries, are experiencing population loss, and this process of urban shrinkage provides opportunities to create additional green space, enhance biodiversity, and promote urban food production with a range of social and health benefits, including the halting and reversal of population loss.[325] Allotment gardens can provide a range of ecosystem services, including habitats for pollinators (which can be better than formal parks) and benefits from physical activity and locally produced foods.[326]

Urban centres are susceptible to water supply difficulties—such as the case of São Paulo, which is experiencing its worst drought for 80 years. Policies to protect watersheds are increasingly recognised to have the potential to save money, conserve water, and improve water quality.[327] In the case of São Paulo, the Cantareira watersheds, which supply nearly 50% of the city's water, have lost 70% of their original forest cover, increasing the sedimentation of rivers, dams, and reservoirs, thus decreasing their ability to supply water. In 2005, the municipality established the first water payments for ecosystem services scheme in Brazil, Conservador das Águas.[327]

The external costs of urban sprawl are about $400 billion per year in the USA alone due to the increased cost to provide public services such as water and waste, increased capital investment needed for infrastructure such as roads, and the costs of increased traffic congestion, collisions, and air pollution not borne directly by private individuals. The total costs amount to about 2·6% of US GDP at present prices. If the USA followed an alternative growth pattern without urban sprawl, the savings could cover the funding gap for infrastructure investment.[328] These lessons are also relevant for the development and expansion of cities in low-income settings where much of the growth will occur. Integration of health and environmental goals into the planning of such cities will result in reduced costs and environmental impacts and improved health.

Improvement of access to modern family planning

Globally, an estimated 225 million women who want to avoid a pregnancy are not using an effective contraceptive method.[329] Fulfilment of the unmet need for family planning alone could cut the number of maternal deaths by almost a third, especially in sub-Saharan Africa, and help to improve food security. Meeting the needs for modern contraception in low-income countries would cost only an additional $5·3 billion per year.[329] A reduction in fertility by 0·6–0·7 births per woman in developing countries, which is similar to the fertility reduction assumed between the high, medium, and low population growth scenarios used in the UN long-range population projection, would also help to achieve greenhouse gas emission reductions.[330] The reduction in births would also have substantial positive effects on many of the other environmental trends mentioned in this Commission report and help to reduce pressure on infrastructure.

Provision of modern contraception at the health facility level should be accompanied by culturally appropriate social marketing approaches to increase demand, including use of the mass media and community based distribution, especially through primary health care.[47] An increased support for rights-based family planning services, including family planning, reproductive health, and HIV service integration, is an important complementary measure.

The population growth forecast for some high-income countries such as the USA and Australia might have disproportionate effects on environmental sustainability because of their prevailing high consumption lifestyles and will therefore need to be addressed by effective policies to reduce their environmental impact.[24]

Integration of environmental care with health systems

The concept of planetary health calls for improved health systems, above and beyond the present discourse on universal health coverage that pays insufficient attention to the need for transformation of health systems to encompass environmental health, the integration of multisectoral actors, or the benefits of balancing investments between the health of present and future populations. Health systems that address the investment trade-off between subsectors, and between technology, prevention, and care need to be created and successfully implemented (panel 11).

Opportunities exist for the integration of health care and environmental care at the primary level.[334] Primary health care can strengthen response and preparedness to natural disasters by providing community-based responses to common health problems such as diarrhoeal disease, mental health problems, and chronic disease. Primary care and public health provision that foster multisectoral collaboration should be developed and the effect assessed in different contexts, taking advantage of new technologies and building on local knowledge and human resources capacity. Metrics relevant to planetary health can also be systematically included in facility and population-based health surveys. The creation of integrated systems that collect rigorous health, socioeconomic, and environmental data for defined populations over long time periods is needed to attribute changes in health to underlying environmental change while accounting for potential confounding factors. These systems could give early warning of breakdown in adaptation mechanisms presaging rapid reduction in a population's health status;[335] for example, the INDEPTH network.[336]

In particular, growing opportunities exist to integrate primary health care into areas that are vulnerable to environmental change or managed by local communities. Training of indigenous and other local community members as primary health-care workers, while respecting their local knowledge and culture, can help protect health and biodiversity.[39] These training programmes also allow the development of locally credible strategies that sustainably and safely harness local biological resources; for example, by avoiding consumption of species such as bats or primates that can harbour hazardous viruses causing zoonotic diseases, such as Ebola, and by providing early warning of any outbreaks that do occur.

Principles for transformative change

Solutions for the drivers of global environmental change

Ethics and values

The UN IPCC pointed to the ethical challenges posed by climate change and this Commission suggests the need to widen the perspective to consider the range of interacting environmental changes. Principle 21 of the Stockholm Declaration of 1972 (modified by Principle 2 of the Rio Declaration) recognises the right of countries to exploit their own resources, provided that their activities do not damage the environment of other states or the global commons.[337] Although, in many cases, national policies and consumption patterns are having adverse effects outside their own boundaries.

Protection of future generations

Several justice theorists have advanced the view that the present generation has a moral duty to protect the health and wellbeing of future generations on the grounds that the basic rights of people in the future include health, subsistence, and survival, which could be violated by major rises in temperature and other environmental changes (for discussion see Knox[338]). Arguably, the principles of compensatory justice imply that those who act in the knowledge that their actions can cause harm should compensate those on the receiving end of adverse effects of environmental change. This argument is also grounded in the predominant global legal practice to attribute liability for the effects of harmful emissions to the party who emitted them. This argument is implicitly accepted by those developed nations prepared to contribute to climate change adaptation and mitigation funds. Economic approaches used to shape environmental policies also have important ethical dimensions. For example, the ethical dimensions of the practice of discounting, which places a reduced value on consumption at some point in the future for such reasons as because consumption levels are presumed to increase in the future, or because technological changes will make climate change easier to deal with than it is now, or because people inherently prefer the present. High discount rates diminish the attractiveness of action to prevent environmental change and ultimately the choice is an ethical one. The bioethics community has shown little inclination to tackle these fundamental ethical challenges, although they are now beginning to give attention to these issues.[339]

Addressing inequities

Many environmental changes predominantly affect the poor (at least initially) who have contributed little to the issues and thus could widen inequalities—eg, by increasing poverty. The perspective of low-income countries on environmental justice can be considered as having three elements: first, a concern that the past patterns of emissions or other effects have to play a part in determining present entitlement; second, entitlements to emissions or other environmental impacts should be equal (distributive justice); and third, the mechanisms for reaching agreement on environmental justice should be fair and transparent (procedural justice).[340] High-income countries, however, tend to focus on the most economically efficient approach for minimising the effects of climate change and delivering global ecological

Panel 11: The implications of planetary health for health systems

WHO has proposed a Health Systems Framework consisting of six building blocks to analyse health systems. This panel reviews the implications of planetary health for just two of the building blocks, namely the health workforce and financing.

Health workforce

To address the challenge of planetary health, countries need to ensure a minimum threshold of health-worker density and capacity to prevent and respond to the health consequences of environmental change in line with the International Health Regulations.[331] Planetary health concepts should be integrated into the training of health professionals, particularly, but not exclusively, that of public health professionals and health-care leaders. For example, in Ethiopia more than 35 000 health extension workers have been trained and deployed over 3 years. They help to prevent and treat diseases that are sensitive to environmental change such as malaria, diarrhoea, and undernutrition,[332] and work in multisectoral teams to address hygiene, sanitation, and nutrition issues. Such innovative models of health-worker education and training should be emulated and scaled up.

Financing

Planetary health concerns need to be fully integrated into health budgeting and purchasing processes. For example, present epidemiological and expenditure trends show an increasingly rapid expansion of health spending to respond to the epidemic of non-communicable diseases.[333] Meanwhile little if any attention is given to funding the unfinished agenda of environmental health (sanitation, hygiene, and household air pollution), let alone to the emerging and expanding planetary health agenda. Environmental health should thus be raised to a high level of budget priority and the potential for health financing through recycling of harmful subsidies and taxes on externalities should be exploited.

health and stability, which often has a lower priority than short-term economic gains. At present trends, even with optimistic assumptions, the eradication of poverty (with a poverty line income of $5/day per person) will take 200 years, or 100 years for a poverty line of $1·25/day.[341] A fundamental principle for the improvement and maintenance of human health should address present inequities in health and protect the health of future generations as far as possible while preserving the integrity of the biophysical systems, on which humanity ultimately depends.

Safe and just operating systems—adding a social foundation to efforts to address global environmental change

The doughnut concept is a framework that attempts to identify a "safe and just operating space for humanity" by adding social boundaries to the planetary boundaries framework previously described.[342] The framework adds a social foundation of resource use, below which lies unacceptable levels of human deprivation, including undernutrition, ill-health, income poverty, and energy poverty.[342] Social boundaries were identified on the basis of the priorities from global development goals identified in the lead up to the UN Conference on Sustainable Development in 2012 and the High-Level Summit on the Millennium Development Goals in 2013.[342] The doughnut approach has been tested at the regional scale, identifying the regional safe and just operating space for two rural Chinese communities through analysis of local ecological, palaeoecological data and social survey statistical data.[343] Dearing and colleagues[343] conclude that agricultural intensification has led to poverty reduction but not poverty eradication, and that agriculture has caused environmental degradation, including degraded water quality and effects on soil and sediment quality. Standards for available piped water and sanitation are identified as falling behind many other social development gains. In this example, the doughnut approach identified both the social needs and environmental constraints around water access and quality in the study communities.[343]

Building resilience

The imperative to strengthen resilience is becoming an increasingly dominant theme in the policy arena, as emphasised by recent events such as the Ebola crisis in west Africa, Hurricane Katrina (panel 12), the 2003 French heatwave, and the 2010 and 2011 Pakistani floods (panel 8).[13] Sudden failures in essential systems such as health care and public health, flood defences, or emergency responses can have disastrous consequences for many people. The term adaptation is often used to focus on the capability of social actors to respond to specific environmental stimuli and to reduce vulnerabilities to environmental change. Nelson and colleagues[356] state that "the resilience approach is systems orientated, takes a more dynamic view, and sees adaptive capacity as a core feature of resilient social–ecological systems". The two approaches converge in identifying necessary components of adaptation.

As Superstorm Sandy showed, even wealthy and highly developed areas of New York might be unable to cope with extreme weather and could suffer economic losses as a result. Accumulating evidence from both New York and New Orleans about the effectiveness of different features of community based responses at protecting people from the worst outcomes clearly suggests that societally based support and resilience networks can buffer people from the worst extremes. A systematic review[357] examining the health implications of power outages as a result of extreme events in 2013 reported that although evidence was scarce, loss of power increased the difficulty to access to health care and maintain front-line services. These difficulties suggest the need for resilient power systems, including the use of renewables that do not require a functioning grid.

Building resilience requires planning and preparation based on assessments of risks; development of capacity to restore functions quickly and effectively in the face of disruptions; and the capacity to adapt and change after a shock. Resilient health systems need to internalise five elements: awareness, diversity, self-regulation, integration, and adaptability.[358] Effective surveillance and early warning systems give an indication of prevailing disease patterns and permit early detection of disease outbreaks or changes in food security. The vulnerability of specific subgroups to environmental change should be understood and plans put in place—eg, heatwave early warning systems—to permit rapid intervention, particularly for elderly people living alone or in high risk institutions.[359] Multifunctional teams, which can be redirected towards emerging threats in times of emergency, are necessary. For example, the contribution of Lady Health Workers (trained community health workers) in the aftermath of the Pakistan floods.[360] Integrated resilience strategies are needed that work closely with other sectors vital to human health, including transport, communications, water and sanitation, and food supplies.

Intact and restored ecosystems can contribute to resilience, such as the improvement of coastal protection through wave attenuation or the ability of floodplains and greening of river catchments to protect from river flooding events by diverting and holding excess water.[113] Although the effectiveness of ecosystem-based adaptation measures is deemed to be lower than comparable engineered solutions at present, ecosystem-based adaptation measures tend to be implemented at much lower cost and are also often so-called low-regret options because they provide other benefits beyond resilience. For example, in Vietnam, planting mangroves for storm surge protection incurs one-seventh the cost of the creation and maintenance of seawalls or dykes for this purpose[361] and the coastal ecosystem also preserves wetlands and marine food chains that support local fisheries. Care has to be taken with ecosystem approaches, however, to consider and address potential adverse health effects, such as the proliferation of mosquitoes (a potential carrier of vector borne diseases) in restored wetlands.[362]

National governments have an important role in strategic planning for resilience, but plans need to involve local initiatives, including providing advice and technical and financial resources. In the poorest countries, support is needed from international institutions and initiatives such as the UN Framework Convention on Climate Change, the UN International Strategy for Disaster Reduction, the Sendai Framework for Natural disaster reduction (see appendix for an overview of the Sendai framework), and the new SDG process. Increasingly, adaptation to a range of environmental stressors could be addressed by building on National Adaptation Programmes of Action, which provide a process for countries to identify priority activities that respond to their urgent and immediate needs to adapt to climate change.[363] The 100 Resilient Cities Challenge is showing how cities can strengthen resilience to a range of threats by addressing social, health, environmental, and governance concerns in an integrated way. Cities can catalyse effective policy and action at the national level.[116]

Monetisation of non-market benefits

Many planetary health outcomes cannot readily be expressed in monetary terms, but construction of alternative measures of progress often depends on reasonably robust estimates of all benefits and costs in monetary terms. For example, monetisation of

Panel 12: Case study—Hurricane Katrina

Hurricane Katrina caused severe destruction and permanently changed the landscape of the US Gulf Coast in 2005. This enormous storm caused 1833 deaths and was one of the deadliest in US history; it was also the costliest natural disaster in national history,[344] with $108 billion in property damage.[345] Fatalities were greatest in New Orleans and concentrated among elderly people, who represented 49% of total deaths, and African–American people, who had mortality rates 1·7–4·0 times higher than white people in some areas,[346] raising important social justice issues. Katrina exemplified risks faced by large metropolitan areas in disasters. High population density, infrastructure susceptible to damage by extreme events, reliance on transportation infrastructure that might be damaged or whose capacity might be exceeded by evacuation demands, and likely utility outages are among factors that can adversely affect public health in emergencies. Climate change is expected to exacerbate such risks in coming decades by increasing the frequency of high intensity storms like Katrina and by increasing storm surge magnitudes, making preparedness efforts even more crucial.[347]

Devastation from Katrina was greatest in coastal communities of Mississippi and the city of New Orleans, where levees were overtopped or breached and left 80% of the city flooded at depths up to 6m for several weeks.[345] New Orleans, which has been flooded by hurricanes six times within the past century, was at particular risk because the city is below sea level and surrounded by water. Flooding from hurricane Katrina, which resulted from catastrophic failure of the New Orleans hurricane protection system, was mostly avoidable and attributed to many engineering and engineering-related policy failures.[348] In response to forecasts, a state of emergency was declared by the Federal Government before Katrina made landfall.[349] Despite mandatory evacuation orders, an estimated 100 000 to 300 000 New Orleans residents were unable to evacuate, mainly because of ineffective communication and insufficient access to personal vehicles among the urban poor.[350] The Superdome, which sheltered many people that could not evacuate, sustained substantial damage, and looting and violence ensued as remaining city residents searched for food, water, and supplies not immediately available through relief efforts.

Criticism of the Katrina response was widespread, spanned all levels of government, and focused on delayed evacuations, inadequate preparation for the relief effort, and mismanagement. Many difficulties that arose resulted from inadequate planning and back-up communication systems at various levels.[351] The 2004 US National Response Plan delineated disaster response as mainly a local government responsibility; when local response capacity is exceeded additional resource requests are made, first to the county and then at state and federal levels as needs are identified. The National Response Plan was revised in response to organisational changes and experiences in the 2005 hurricane season and was later replaced by the National Response Framework.[352]

The destruction of coastal wetlands in Louisiana, mostly due to the spread of urban areas, has also been cited as a contributory factor in increasing the susceptibility of New Orleans to inundation by flooding because of reduced river input and canal dredging, which previously acted as a buffer against coastal storms.[353] Coastal wetlands act as natural horizontal levees;[354] forest covered wetlands can reduce the wind stress available to generate surface waves; and the vegetation and shallow water depths associated with intact wetlands provide wave attenuation, reducing the destructive effect of waves on levees.[355] Therefore the restoration and protection of such habitats and their integration into the defence strategies of coastal cities is an essential consideration for planners and policy makers.[113]

Hurricane Katrina, and more recently the hurricane Superstorm Sandy, have important implications for preparedness efforts and human welfare in natural disasters in an age of increased variability in climate systems. An emphasis on the development and implementation of nationally appropriate preparedness and response strategies, combined with ecosystem and ecosystem–engineering hybrid approaches to adaptation[113]—particularly in low-income and middle-income countries and in Asia where most of their effects occur—is crucial to protect the health and wellbeing of populations that will inevitably experience these events in future.

co-benefits to help policy makers offset the cost of action is discussed in the *Lancet* Commission on Climate Change.[55] A 2014 full lifecycle analysis based in the USA shows that monetised human health benefits stemming from air quality improvements can offset the cost of US carbon policies by 26–1050%.[364] For locations such as east Asia, air quality-related health benefits are 10–70 times the abatement costs in 2030.[365] A recent paper[366] shows how the monetisation of the health co-benefits of climate mitigation should encourage the top 20 emitting nations to cut carbon dioxide emissions by 13–15%, even without considering climate or other benefits.

The USA and Europe traditionally estimate economic benefits and costs related to environmental change and ecosystem services.[367] This economic approach is not only because federal policies have to use cost–benefit analysis to develop regulations and standards, but also because non-market benefits are used to settle lawsuits (eg, Exxon Valdez oil spill damage), to improve the accuracy of estimates of quality-adjusted-life expectancy, and to identify sustainable sources of financing.[297] For example, enough empirical evidence already exists on some environmental changes (eg, water quality) in some settings (eg, the USA) to learn from meta-regressions and synthetic reviews.[368] A set of credible methods and estimates for how to consider the values of human lives is now widely accepted.[369] More mundane and less controversial outcomes, such as time savings (eg, because piped water eliminates the need to fetch water from long distances), can be valued by examination of the behavioural choices of households.[370]

Incentivisation of behaviour change

Human behaviours have a pivotal role in both reducing damages from adverse environmental changes and reducing the magnitude of adverse environmental changes. By having a clear understanding of behavioural determinants, policy makers can harness an array of regulatory, fiscal, and tax policies; mass media campaigns; and incentive-based interventions to effect behaviour change.[370] The Vitality programme by Discovery, one of South Africa's largest health insurance providers, promotes healthy diets by offering cash incentives on healthy foods, which has increased fruit and vegetable purchases by 6–9% and decreased sugary and fatty food purchases by 6–7%. This change in diet of the participants led to estimated decreases of 8–13% in land requirements, 7–12% in water footprint, and 8–10% in greenhouse gas emissions.[371]

Similarly, information campaigns focused on showing households information about the quality of their drinking water[372] or combined social mobilisation and peer pressure to create a sense of public discomfort regarding open defecation[373] can lead to preventive behaviours that both improve personal health while reducing community contamination. A village-level intervention based on emotional drivers of behaviour, rather than knowledge, improved handwashing behaviour substantially in rural India.[374]

Mobile technologies (also known as m-health) have been used to promote behaviour change. For example, text messaging substantially reduced biochemically verified smoking.[375] The case study on technology developments for health in the appendix shows an example of a mobile phone application to change behaviour around the users personal environmental footprint. Low-income countries now tend to be thought of as having greater leeway for so-called technological leapfrogging (eg, use of telemedicine or going from biomass fuel for cooking straight to electric or other kinds of clean stoves) compared with in the past. However, behaviour change related to technology adoption in developing countries still faces many barriers, including financial constraints, cultural behaviours, and weak institution and infrastructure.[157] New technologies need to be assessed for their capacity to yield multiple benefits, including for health, and to avoid unintended adverse consequences. For example, diesel vehicles usually use less fuel than petrol engines but emit more fine particulates and although biofuels are (in theory) renewable, they might compete with food crops for land, helping to drive up food prices.[376] Examples of technologies that could fundamentally change the availability of resources at much lower levels of environmental impact than at present are given in the appendix.

Ultimately, many behaviour change interventions focus on encouraging individuals to reflect on their conscious decisions.[377] An alternative and probably more effective approach might be to change environments to constrain choices or target the automatic processes that underpin most decisions, or both.[370] For example, cafeterias, which increase the accessibility of food choices that are healthy and have a low impact on the environment increase the likelihood that those foods will be chosen. Restriction of marketing opportunities for unhealthy and unsustainable products could reduce opportunities for advertisers to prime the behaviour of potential customers—eg, as has been done with consumers of snacks and alcohol.

Movement towards a circular economy

Several essential steps need to be taken to transform the economy to support planetary health. These steps include the reduction of waste through the production of products that are more durable and require lower quantities of materials and less energy to manufacture than those that are being produced at present; the incentivisation of recycling, re-use, and repair; and the substitution of hazardous materials with safer alternatives. These changes will necessitate innovations in design and manufacture that capitalise on the potential restorative powers of natural systems combined with strategies to reduce overall demand for resources that greatly damage the environment during the course of their extraction, production, use, or disposal—leading ultimately to the circular economy (panel 1; figure 19).[11]

Importantly, such a transformation could also bring benefits to health and wellbeing if occupational health standards are adhered to, including through reduced amounts of air, water, and soil pollution; increased employment opportunities; and changes in diet and physical activity.

An example of how transformative economic change might affect health outcomes is given in the appendix case study using the PoleStar engineering–accounting integrated assessment model to assess four scenarios of future development that exemplify alternative worlds that might emerge from the present. Two scenarios represent an evolution of conventional world views and dominant forces; Market Forces exemplifies market-centred growth-oriented globalisation, whereas Policy Reform tells of a government-led redirection of growth toward sustainability goals.[378] The other two scenarios envision a fundamental restructuring of the global order: authoritarianism and fragmentation in Fortress World and positive transformation in Great Transition, in which material consumption is reduced but is more equitable than the present. Each scenario tells a different story of the 21st century, with varying patterns of resource use, environmental impacts, and social conditions. Both the Policy Reform and particularly the Great Transition scenarios result in substantially better health (greatly reduced stunting and improved nutrition) and less greenhouse gas emissions than the other two. The Great Transition brings added benefits for social (eg, reduced inequities and increased leisure time) and environmental outcomes (eg, reduced water stress and toxic chemical load).

Measures of human progress and wellbeing

The present focus on GDP as a global benchmark of societal success is a relatively recent occurrence, whose origins date back to the 1930s and 1940s.[379] Economists have long been aware that GDP was never intended as a broad measure for the state of national progress, moreover, Kuznets explicitly warned against the use of GDP as a measure of welfare.[380] In addition to missing non-market transactions, GDP fails to capture the cost of environmental degradation, ecosystem services beyond those traded commercially, and many other outcomes of relevance to human health and wellbeing.[381] Comprehensive wealth per person can reduce even when GDP per person increases or Human Development Index improves because these gains in manufactured and human capital might not offset the diminution of natural capital. In support of this point, compelling calculations by Arrow and colleagues[382] show that between 1970 and 2000, comprehensive wealth per person decreased in south Asia and sub-Saharan Africa, two of the poorest regions of the world, even though Human Development Index and GDP per person increased. This exercise by Arrow and colleagues[382] was a gross underestimate because it only considered three dimensions of natural capital—standing forests, oil and minerals, and carbon stocks—and omitted losses of several ecosystem services (eg, watershed protection, pollination, ecotourism, and non-timber forest products).[381]

In recognition of the limitations of GDP, in 2011, the UN General Assembly adopted Resolution 65/309, inviting member states to "pursue the elaboration of additional measures that better capture the importance of the pursuit of happiness and well-being in development with a view to guiding their public policies".[383]

Many measures and initiatives have been proposed to address the shortcomings of GDP. Adjusted economic measures such as the Natural Capital Initiative,[384] the Economics of Ecosystems and Biodiversity,[385] and genuine savings[386] attempt to capture the true financial worth of ecosystem goods and services, both in their provision and degradation. The Genuine Progress Indicator also uses an accounting framework to modify income inequality adjusted GDP with monetised economic, social, and environmental factors.[387] Alternative methods attempt to develop new measures by which to assess human progress and success that are entirely separate from GDP. The Social Progress Index measures three dimensions of society: basic survival needs (eg, food, water, and shelter), access to the building blocks for the improvement of life (eg, education and health), and the chance to pursue goals and dreams (eg, access to knowledge[388]) free from obstacles (eg, discrimination). Similarly, the Happy Planet Index measures the extent that countries deliver long, happy, sustainable lives for the people that live in them.[389] The Happy Planet Index uses global data on life expectancy and experienced wellbeing, weighted by ecological footprint, as a measure of environmental degradation. See the appendix for a case study describing

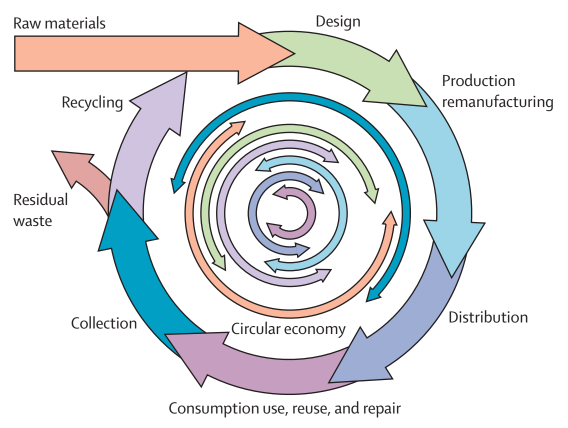

Figure 19: **Circular economy model**
A conceptual diagram showing in a simplified way the main phases of a circular economy model, with each phase presenting opportunities in terms of reducing costs and dependence on natural resources, boosting growth and jobs, and limiting waste and harmful emissions to the environment. The phases are interlinked, as materials can be used in a cascading way; for example, industry exchanges by-products, products are refurbished or remanufactured, or consumers choose product-service systems. The aim is to minimise the resources escaping from the circle so that the system functions in an optimum way. Reproduced from the European Commission,[11] by permission of the European Commission.

the efforts of Costa Rica to balance social, environmental, and economic concerns.

Subjective self-reported measures such as happiness need further development and scrutiny. Differences in culture and society norms mean such measures are difficult to compare across nations and many of the respondents to surveys on happiness might not be aware of the ultimate drivers of wellbeing—for example ecosystem services such as nutrient cycling and water filtration.[390] Statistical assumptions about the distribution of happiness scores might also affect inter-country rankings and need further study.[391]

Policies for taxes and subsidies that support planetary health

Well designed and implemented taxes and subsidies are an important part of the policy toolkit that can be deployed by governments to mobilise resources and align incentives for planetary health goals. Taxes can make polluters pay for negative effects on the environment; for example, a carbon tax to account for greenhouse gas emissions or taxes on waste disposal, water pollution, and any other such externalities (panel 1) imposed on present and future generations.[392] Taxes are also the main mechanism for raising public revenues, including the additional resources needed to implement policies on planetary health. Clearly, opportunities exist to realise environmental and health goals and thus recycle revenues—eg, subsidisation of universal health coverage or other welfare programmes with revenues generated by taxation of greenhouse gas emissions.[393] Additionally, taxes and subsidies also act as a key mechanism to redistribute wealth and reduce health inequities. Such redistribution could target the people most exposed to the consequences of environmental degradation, namely the poor and those susceptible to natural disasters.

Conceptually, subsidies are the mirror opposite (negative of taxes). For example, farmers who protect trees on their farms to reduce downstream erosion and improve the habitat for threatened species should receive a payment for the environmental services they have provided—effectively a subsidy.[394] Most subsidies at present are in the energy, water, agriculture, and fisheries sectors,[395] amounting to $1·9 trillion, 2·5% of global GDP, or 8% of total government revenues, excluding externalities.[396] Unfortunately, subsidies are often poorly targeted and captured by the wealthiest; for example, in 2010, only 8% of fossil fuel subsidies reached the poorest 20% of the world's population.[397] A recent (May 2015) update of earlier work by the International Monetary Fund on fossil fuel subsidies[398] suggests that these are even greater than previously estimated—$4·9 trillion (6·5% of global GDP) in 2013. The largest post-tax subsidies relative to GDP are in emerging economies where they can amount to 13–18% of GDP. The largest contribution to the subsidies is from the failure to charge sufficiently for the cost of domestic environmental damage, including premature air pollution deaths, with coal accounting for the largest energy subsidies. Although uncertainties exist, the elimination of post-tax subsidies in 2015 could boost global economic welfare by $1·8 trillion (2·2% of global GDP), even after allowing for the increased energy costs to consumers.

Subsidies might also be deemed harmful if they lock in obsolete and damaging technologies that affect the supply of natural resources or increase poverty. Win–win solutions are not always possible to find when removing subsidies; sometimes governments face trade-offs between goals. Almost 1·5 billion people still live without electricity and more than 3 billion people still rely mainly on solid fuels. Subsidisation of a transition for these groups to modern energy—even when based on modern fossil fuels (gaseous or liquid) and electricity (including based on fossil fuels)—is likely to lead to substantial reductions in black carbon and only trivial increases in carbon dioxide emissions.[399]

Planetary health offers an unprecedented opportunity for advocacy of global reforms of taxes and subsidies for many sectors of the economy—including energy, agriculture, and health—and will require comprehensive global and national measures. For example, the Institute for European Environmental Policy (IEEP) recommends that phasing out harmful subsidies in the European Union should be accompanied by use of safety nets to protect the poor, new pricing structures, financial transfers (to account for inequities within and across countries), and multilateral agreements on environmental objectives (see appendix for more on governance challenges).[400] These types of subsidy reform are underway in several countries, including Iran, Nigeria, and Tunisia (see appendix for references), but are often difficult to achieve because the subsidies that would need to be reduced or removed usually benefit vocal and powerful constituencies.

Governance to secure planetary health

Achievement of improved governance for planetary health necessitates action at global, national, and subnational levels. Action has to be taken before irreversible changes in key Earth systems occur, which will require decision making under uncertainty (panel 13) about the critical thresholds or rates of deterioration of these systems. Decision makers tend to overestimate the carrying capacity and resilience of their system because their knowledge of complex systems involved is incomplete.[407] History is replete with examples where decision makers failed to act in time, but these rarely have a simple explanation. Examples—such as the Old and New Kingdoms of Egypt; and Islamic Mesopotamia—show the importance of the complex interplay between environmental change, sociopolitical forces, civil war, dispossession of elites, breakdowns in social justice, ideological shifts, poor leadership, administrative dysfunction, and corrupt institutions in determining outcomes.[408,409] Of course many differences exist between these historical examples and our increasingly globalised economy but most of the

Panel 13: Decision making under uncertainty

Uncertainty is the rule, rather than the exception, when thinking about planetary health. Conventional approaches to decision making require more information about probabilities and effects than is likely to exist for many planetary health policies. Decision rules that do not rely on expected values address some of these challenges but still require information about the range of possible states, how states combine with policies to generate planetary health outcomes, and to assess their net benefits. In recognition of the limitations of decision rules, alternative rules for decision making under risk and uncertainty have been formulated.[401] Notably, these rules include methods aimed at low probability catastrophic events.[402] Additionally, a suite of other approaches have been based on system science. Polasky and colleagues[403] summarised three such methods:

Thresholds approach

Social–ecological systems are complex and can have non-linear dynamics. A threshold approach (eg, planetary boundaries) can be useful to organise thinking about complex systems by focusing attention on crucial boundaries that have major consequences if crossed, such as screening out actions thought to have too high a risk of inducing a shift in social–ecological systems. Uncertainty about the exact level of a threshold can restrict the usefulness of this approach.

Scenario planning

Creative and systematic consideration of complex possible futures involves the generation of plausible stories, supported with data and simulations, about how the future might unfold from present conditions under alternative human choices.[404] Scenario planning can help to depict a range of potential futures and decision makers can assess the robustness of alternative policy options by examining their effects in a range of plausible scenarios.

Resilience thinking

Resilience thinking focuses on identifying and managing critical thresholds for system performance, maintaining the capacity to adapt to surprises by conserving key processes. Resilience thinking also confers the capacity to transform to an entirely new mode of operation if existing practices become untenable. Resilience thinking can be usefully combined with decision theory, threshold approaches, and scenario planning to guide management.

The science of decision making for planetary health should be done in two phases. First, the issue should be scoped as broadly as possible to cover a large set of imaginable states and associated outcomes. Second, what is known, what is possible but unknown, along with judgments about the net benefits of different potential futures should all be combined to guide policy making. Science by itself will fail however, unless scientists understand the gap in standards of evidence and risk tolerance between the science community (high certainty), decision makers, and informed citizens.[405] Decision makers wish to avoid high political and social costs and so might act before all evidence is in. Communication of uncertainty to policy makers is challenging and scientists rarely have the skills to do so effectively. Closer interactions between scientists, the public, and policy makers than is done at present, together with innovative approaches to the communication of risk such as the use of infographics and other ways to represent uncertainties visually, show great promise for the future.[406]

underlying sociopolitical forces are still relevant now. A precautionary approach is therefore needed to reduce the risks to health and vital ecosystems in a world where vested interests undermine the political will to act and where persistent (and in some cases widening) inequities have marginalised the voices of many disadvantaged groups.[410]

The University of Oslo Commission[411] on governance for global health published in *The Lancet* focused on social and political determinants of health but also acknowledged that environmental factors could affect health. The Commission also recommended the creation of a UN multi-stakeholder platform and an independent scientific monitoring panel on global social and political determinants of health, but did not specifically propose governance mechanisms for addressing the threats to health and civilisations posed by environmental changes.

An additional body with responsibilities for monitoring and overseeing progress solely on social and political determinants of health will perpetuate their separation from environmental sustainability. The Earth Systems Governance project has proposed reforms based on seven building blocks, including UN reforms[412] to upgrade the UN Environment Programme to a specialised agency similar to WHO (but with a focus on environmental protection) and to create a high level UN Sustainable Development Council directly under the UN General Assembly. Their proposals, however, do not specifically include a role for health as both an outcome and an indicator of the long-term success of reforms. Planetary health has to be addressed in an integrated way. One possibility is to work through both the proposed UN Sustainable Development Council and the process for the development and monitoring of indicators for the SDGs. Additionally, the UN agencies, programmes, funds, and related organisations responsible for oversight of health, environment, and development should strengthen their collaborative mechanisms to ensure optimum coherence in tackling the threats to planetary health.

Lessons can be learnt from the success of the Montreal protocol to phase out substances that deplete stratospheric ozone.[413] The protocol proposed restrictions on all countries from the outset, had strong incentives for participation and compliance, and created incentives for positive steps. An amendment proposed May 9, 2014, is

Panel 14: **Why the grassroots matter**

For planetary health to become a mobilising, engaged, and effective advance in global health thinking, it will need the participation, commitment, and ownership of those most affected by threats to health from the degradation of the biosphere. The indigenous communities, the poorest billion living in the most marginal environments of the developing world, the rural poor, and the urban poor in the sprawling cities will face the greatest burdens as planetary health erodes. Grassroots movements to protect food, water, environments, and livelihoods and to address the poor governance and corrupt systems that drive the exploitation of precious resources for global elites are already underway in many settings. But to have real effect, and to change the trajectory of planetary health, these local movements will need coherence, organisation, and solidarity with the scientific and health communities. The extraordinarily effective movement for access to antiretroviral drugs, which emerged from the HIV/AIDS pandemic, is a potent example of how some of the world's poorest and most stigmatised individuals and communities were able to organise, mobilise, and successfully press for change.

In the case of HIV, by 2000, an effective (triple drug) therapy existed, but had a profoundly uneven distribution of treatment access; 95% of HIV drugs manufactured were given to patients in high-income countries, who represented only 5% of the global population living with HIV.[416] The great majority of Africans, Asians, and Latin Americans were consigned to difficult early deaths—about 40 million women, men, and children. The treatment access movement, which emerged from this unacceptable reality, took on governments, the global drug pricing and intellectual property regime, and the prevailing view that AIDS treatment was not cost effective or sustainable. The movement brought together unlikely coalitions of activists and campaigners: gay men from the USA and Europe with African women's networks; secular human rights organisations with faith-based movements; and providers with patients. 15 years later, the world is approaching the tipping point of half of the 37 million people living with HIV having access to treatment, and drug costs have reduced to US$50 per person per year.

Planetary health will have to build novel coalitions to achieve meaningful and lasting change. Communities struggling to preserve their environments and livelihoods need scientists and health leaders to engage on their issues, document their suffering, and work with them to create social change. The scientific and health communities, in turn, will be much more successful in influencing decision makers who are feeling pressure for change from their constituents than they would without the support of civil society. Better evidence is needed for the importance of planetary health than exists at present. But that evidence will need a broad based movement for social change to have the kinds of effect needed to preserve the biosphere.

addressing replacements for ozone depleting chemicals that are climate active such as for hydrofluorocarbons.[414]

Regional trade treaties should give a much higher profile to the protection of health in the near and long term than they do at present. Such treaties provide unprecedented protections for investors and intellectual property rights holders, and furthermore are often negotiated under conditions of secrecy, suggesting the need for a more proactive assessment of their implications for health and sustainability than is done at present.[415] So far, concern has understandably focused on the potential for these treaties to influence near-term determinants of health such as trade in tobacco or food products. These efforts should now be complemented by an analysis of how such trade treaties can support or undermine planetary health.

National governments can support planetary health by integrating cross-sectoral policies at the cabinet level to address key trends and drivers and communicate these to the public. Actions at the municipal level could have an important catalytic effect and present groups such as the C40 Cities Climate Leadership Group, the International Council for Local Environmental Initiatives, and the 100 Resilient Cities network can stimulate innovative policies providing so-called test beds, from which others can learn through evaluative research.

Local governance can also be strengthened by the engagement of civil society, including indigenous communities. An example of how grassroots engagement with the HIV community galvanised progress is given in panel 14. Such movements help to support so-called polycentric governance, according to which individuals and local communities solve common-pool resource issues on their own, leading to solutions that are sustainable over time.[417]

The potential to capitalise on the post-2015 Development Agenda

Progress towards the Millennium Development Goals has been mixed—across goals and between regions.[66] As the MEA pointed out, "any progress achieved in addressing the Millennium Development Goals of poverty and hunger eradication, improved health, and environmental sustainability is unlikely to be sustained if most of the ecosystem services on which humanity relies continue to be degraded".[3] The Millennium Development Goals did not effectively address unsustainable environmental trends or inequities and it is therefore essential that the post-2015 agenda supports the integration of social, economic, and environmental dimensions of sustainable development in all nations.

The Open Working Group of the UN General Assembly has suggested 17 SDGs and 169 targets,[418] but criticism exists that only a third of the targets are well developed, with the remainder either being too unspecific or requiring substantial refinement.[419] For example, target 3·9, "substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination",[418] needs to specify key pollutants and chemicals to be effective. Potential linkages between different goals and targets need to be identified; for example, successfully addressing stunting depends not only on nutritional intake but also on access to clean water and sanitation.[420]

Despite the present limitations, the SDGs provide a great opportunity to integrate health and sustainability through the judicious selection of indicators.[48] The SDG indicators, accompanying the SDGs and targets, can form the basis for collection of national data to enable monitoring of trends over time and assessment of the comparative progress of countries. Indicators relevant to planetary health fall into several categories that indicate reductions in poverty or improvement in human development (eg, through universal health coverage and increased access to education); the effectiveness of policies to increase resilience to environmental change; the effectiveness of policies to reduce or reverse environmental change, particularly where health co-benefits exist; and support for implementation through improved governance and financing.

Figure 20 shows how the proposed SDGs representing human wellbeing (inner circle) are dependent on those that provide the enabling infrastructure for development (the first ring) and the supporting natural systems (the outer ring). The proposed SDGs also suggest the need for strong governance to ensure that infrastructure related goals are not achieved at the expense of those supporting natural systems.[421]

The proposed SDGs do address many key barriers to progress that were not covered by the Millennium Development Goals but they are fragmented and require an integrating statement to bind them into a coherent whole. The concept of planetary health can provide the necessary coherence for the overarching statement for the SDGs by integrating the aim of sustained improvements in human health and wellbeing with the preservation of key natural systems, supported by good governance and appropriate policies.

Development and funding of an integrated research agenda

Addressing gaps in knowledge

Our overview has uncovered substantial gaps in knowledge that have to be addressed to improve planetary health. A transparent interdisciplinary process of research agenda setting is needed, which takes into account the needs of decision makers and builds on the restricted knowledge available. This scarcity of knowledge on planetary health is shown by the relatively small number of high quality systematic reviews available on topics related to planetary health and the high frequency of inconclusive findings within these studies, usually due to

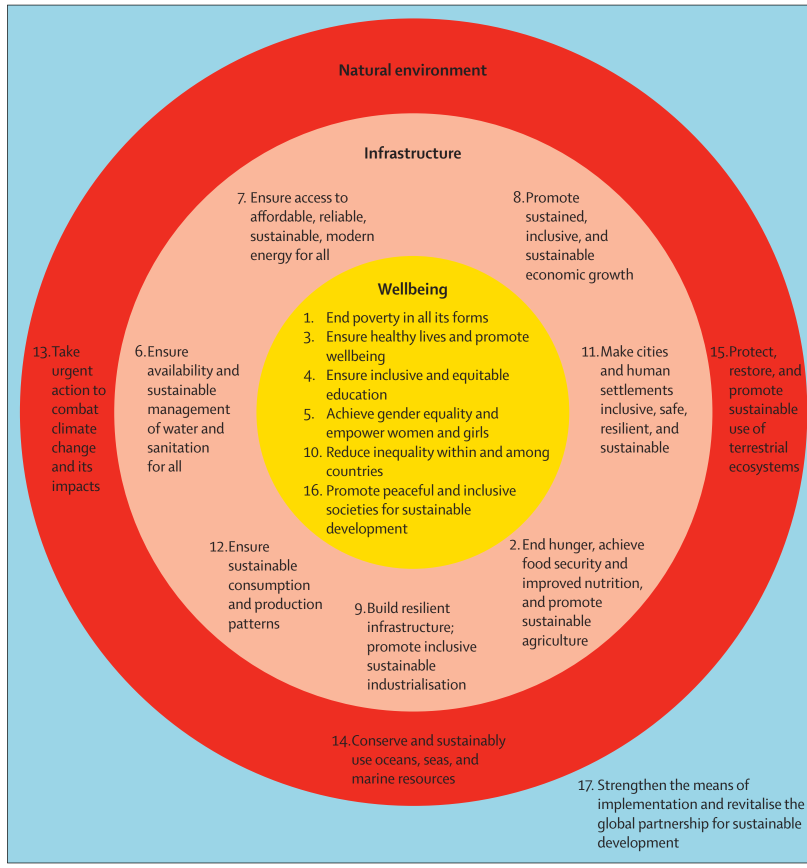

Figure 20: **Framework for examining interactions between sustainable development goals**
Note that goal 17 is excluded from this framework because it is an enabling goal. Reproduced with permission from Waage and colleagues.[421]

small sample size and low comparability between studies (see appendix for references). Our overview of systematic reviews also suggests the need for capacity strengthening to develop a global collaborative effort analogous to the Cochrane Collaboration, which oversees the co-ordination of systematic reviews that link health and environmental sustainability. Additionally, universities and research institutes need to find new ways to encourage transdisciplinary research teams to investigate scientific questions of societal importance and to develop, reward, and promote academic staff pursuing a research agenda informed by the planetary health framework.

Through our assessment of the state of knowledge relevant to planetary health we have identified several priority areas for research.

The mechanisms through which environmental change affects human health

The first priority for research is to improve evidence of how environmental changes, both singly and in combination, can affect human health through mechanisms such as changes in the availability and quality of water and food; altered transmission of vector-borne, zoonotic, and other infectious agents; and the

Panel 15: Understanding and modelling complex feedbacks—a systems approach

The interdependence between human wellbeing and ecology is highly complex, both in the nature of connections and in responses in time and space. Achievement of an improved understanding of human–ecological systems interaction is essential, just as is being achieved in climate science through computer modelling. Systems modelling (understanding and modelling complex systems, in this case socioenvironmental and economic interactions and feedbacks) has been evolving quickly during the past 20 years with the growing power of computer processors and the evolution of new mathematical modelling techniques. In 2013, a review[424] reported that 17 different systems resource models existed for city development, resource planning, and technology system optimisation, but none incorporated ecological systems and human wellbeing.

This revolution in systems modelling has reached the point where it is now possible to begin modelling the interplay between the economic (values), societal (health, welfare, and productivity), and the environmental impacts of decisions and investments to support long-term decision making.[425] The data to support such resource flow modelling can come from earth observation, crowd sourcing, ground-based sensors, census, surveys, cohort studies, and other epidemiological approaches. The opportunity these data sources provide have informed several key recommendations for actions to be taken on data offered to the UN secretary general by the UN Independent Expert Advisory Group, established in August 2014.[426] Geospatial data exists at high resolutions[427] and complimentary human demographic and health datasets are now advancing (eg, WorldPop[428]). The next step in the improvement of these models will be to improve coverage of civil registration and vital statistics at the subnational scale.[426] These data will also help to identify the inequalities in access to services and the differences in outcomes and also to improve the quality of other statistics, such as household surveys, that depend on accurate demographic benchmarks.[426] In many cases, models of complex ecological systems used to make projections of future trends use data derived statistically from putative causal associations, but these associations can change under novel conditions and thus predictions might be questionable. Models that are based on an understanding of the underlying processes that cause a system to behave in particular ways are increasingly needed.[429]

effects of changes on the frequency and intensity of extreme events in both aquatic and terrestrial ecosystems. The advancement of research on decision making under uncertainty is crucial, which will be the norm in the case of non-linear, complex, interacting forcers (panel 13).

Objectives for this research could be to characterise the causal mechanisms by which (interactions of changes in) natural systems affect health; enhance the understanding of the role of environmental change in complex emergencies such as forced migration, conflict, and civil unrest; assess threshold values for crucial ecosystem services,[422] such as availability and access to food and water; and forge links with existing initiatives such as Future Earth, a new 10 year international research initiative to develop the knowledge needed to respond effectively to global environmental change and "for supporting transformation towards global sustainability".[423]

Quantifiable human health effects can be taken into account as part of the economic analysis that goes into the decision-making process for policies affecting the environment and natural resource use; these effects inform the development of environmental indicators of human health risk, which could be used in predictive modelling, monitoring, and assessment of interventions (panel 15). Assessment of the effects of environmental change on equity can help identify who is most at risk and where, and guide resource allocation. The assessment of trade-offs between short-term gains and longer-term benefits can support transparent decision making. The results from research can inform best practices on land use and ecosystem protection and restoration.

Strategies to reduce environmental damage and harmful emissions including assessment of co-benefits

The second priority for research is to assess the ability of cross-sectoral policies, new technologies, and products to reduce environmental damage and harmful emissions in different geographic and socioeconomic contexts, with a particular focus on health co-benefits (and potential co-harms), including the economic consequences of valuation of these co-benefits. Research should include the identification of effective economic (including changing behavioural incentives) and governance approaches to promote planetary health, including how best to reduce and recycle harmful subsidies; develop and implement appropriate taxes and subsidies that promote sustainability, improve health, and reduce inequities; support local sustainable development initiatives; and regulate harmful activities. Supporting references are given in the appendix.

Achievement of a full characterisation of how policies to protect planetary health can cause a range of changes in the state of natural systems and can affect a range of critically important dimensions of human health in the long term will allow researchers to assess the extent to which these policies have the intended effects. The insights generated can also help identify unintended adverse results of policies under consideration, which can then be mitigated or avoided. Environment and human health co-benefits can justify integrated approaches to policy solutions across disciplines and sectors. Furthermore, the results can inform new opportunities for technology transfer and capacity building and stimulate innovation.

Strategies and technologies to promote resilience and support adaptation to environmental change

The third priority for research is to assess strategies that use ecosystem approaches to reduce vulnerability of populations to environmental change and that engage local communities, particularly in low-income countries. Outcomes should represent the range of potential benefits and potential unintended results after a systematic impact assessment.

The results will assist policy makers in making investments to reduce risk, assess trade-offs between different outcomes, and deal with scenarios with uncertain stressors and outcomes. Resilience thinking can be combined with decision theory, threshold approaches, and scenario planning to guide management under uncertainty related to multiple environmental changes.[430]

If communities are provided with the capacity to recognise and respond to emerging threats from global environmental change before they occur, progress can be achieved in several domains (social, economic, and environmental) simultaneously. Community engagement can empower disadvantaged and marginalised groups.

Indicators of human welfare and natural systems

The fourth priority for research is to develop and use more robust indicators of human welfare and the integrity of underpinning natural systems than exist at present and explore how these measures should be weighted across time (discount rates). Such attempts would necessarily involve additional and improved inputs from ecologists, epidemiologists, and environmental scientists in the monetisation and valuation of non-market goods and services affected by ecosystem degradation.

Although GDP is widely recognised to be a poor indicator of human progress and the Human Development Index also has several limitations, less consensus exists on what is a better substitute; whether or not different discount rates should be used in different settings; and what are the appropriate methods for the monetisation of non-monetary outcomes. Nonetheless, policy makers often use heuristics and rely on conventional economic calculus (GDP, high discount rates, and the default zero value for environment) to inform their choice of policies because alternatives are either not available or not universally accepted.

Translational research and implementation science

The final priority for research should be to prioritise translational research and implementation science to address the on-the-ground realities of what is feasible and relevant in the settings facing the greatest threats to planetary health. The dissemination, communication, and implementation of knowledge has to be central to research.

Research can and does end up with recommendations that cannot to be translated into policy and action because the research did not fully capture the barriers to policy and behavioural change and how to address them. An unacceptable gap exists between the unprecedented amount of knowledge of diseases (including their control) and the implementation of that knowledge, especially in poor countries. Directed and innovative research is needed to analyse the causes of this situation and to point toward solutions at the global and local levels, both within and outside the health sector.

Opportunities for action by key constituencies

Several key constituencies can have pivotal roles in promoting planetary health: health professionals; academics and research funders; governments; the UN; and corporations and citizens, including those who are often marginalised by prevailing sociopolitical systems and who are most susceptible to disruptions in natural systems.

Health professionals can have an influential role in promoting planetary health. Using their voice individually and collectively, through advocacy and outreach, they can help mobilise a wide community of actors. To achieve this influence, health professionals need to become well informed about the dangers posed by global environmental change to the health of those they serve and the potential for health co-benefits from policies to prevent damage to natural systems. Additionally, by speaking out as they have when faced with other threats to health, health professionals can build on a track record of achievement in areas such as tobacco control, injury prevention, and addressing the health effects of weapons of mass destruction. Finally, they can help to build capacity to address the present neglected agenda of environmental health and poverty related diseases.

Research funders and the academic community frame what questions get asked by scientists and can steer development of new ways of addressing major gaps in knowledge, scientific awareness, and academic focus. Planetary health as a field straddling many uncoordinated disciplines demands investment and the development of a culture of interdisciplinary research. The health research community should forge links with the full range of relevant disciplines in the natural, physical, and social sciences to understand complex systems and assess potential policy solutions.

The UN and Bretton Woods bodies are optimally placed to define metrics (including but not restricted to the process of developing the SDGs) and to build early and long-term warning and response systems across all key sectors that affect planetary health. By strengthening and updating their use of integrated assessment methods of environmental impacts, they can place the health of people and of natural systems more centrally in their decision-making processes than they do at present.

Governments can help planetary health by putting it at the centre of national policy discourse, such as by giving responsibility for integrated monitoring and communication of trends in health, socioeconomic development, and natural systems and the development of policies to secure planetary health to a body answering directly to the head of state.

Investors and corporate reporting bodies have made progress in requiring companies to report on many non-financial aspects of their performance within the worlds of integrated and sustainability reporting. The Global Reporting Initiative,[431] the Dow Jones Sustainability Index,[432] and related bodies need to review and update their metrics on the corporate effects of determinants of planetary health and work with major investors to ensure that financing follows assessments of long-term prevention or reduction of risks to human health and natural systems.

Citizens often feel powerless to act in the face of global forces, but real opportunity exists to build on successful civil society movements that have transformed the prospects for health for many who were previously marginalised (panel 14).

Conclusions—policy propositions to advance planetary health

Propositions to address imagination (conceptual) challenges

To advance planetary health, policies should:

- Account for depreciation of natural capital and nature's subsidy so that economy and nature are not falsely separated. Policies should balance social progress, environmental sustainability, and the economy.
- Support planetary health by addressing the unfinished agenda of environmental health challenges (which are mainly related to poverty), increasing resilience to emerging threats, and tackling the driving forces of environmental change (resource use, population, and technology)—thus enhancing the integrity of the natural systems on which humanity ultimately depends.
- Facilitate action before irreversible changes in key natural systems occur—in the presence of uncertainty about critical thresholds or rates of change in natural systems—to reduce the risks of major catastrophic effects on human civilisation caused by failures of complex systems, both natural and human.
- Scale up resilient food and agricultural systems that address market failures leading to both undernutrition and overnutrition, reduce waste, diversify diets, and minimise environmental impacts.
- Complement the curative, biomedical, molecular approach to health—which is increasingly reliant on precision medicine—with a focus on addressing environmental and social roots of ill health through a preventive approach.
- Develop more resilient health systems, above and beyond the present discourse on universal health coverage, integrating health care and environmental care, particularly at the front-line primary level. Environmental health needs to be integrated into health budgeting and purchasing processes.

Propositions to address research and information challenges

To advance planetary health, policies to address research and information needs should:

- Expand transdisciplinary research activities and capacity substantially as a matter of urgency. Research should not delay action; in situations where technology and knowledge can deliver win–win solutions and co-benefits, moving ahead and assessing implementation of potential solutions can support rapid scale-up.
- Address other substantial gaps in knowledge through research such as to define the links between health and environmental change, improve understanding of potential non-linear state shifts in the natural systems underpinning human health, and develop potential adaptation strategies for populations susceptible to environmental change.
- Build integrated surveillance systems that collect rigorous health, socioeconomic, and environmental data for defined populations over long time periods to provide early detection of emerging disease outbreaks or changes in nutrition and non-communicable disease burden and to assess the integrated health, environmental, and socioeconomic effect of policies and technologies.
- Capitalise on the opportunity of the SDGs to monitor indicators relevant to planetary health in an integrated way and report on progress nationally and internationally.
- Document and acknowledge uncertainty, and embrace decision-making frameworks that operate under uncertainty to reduce risks to planetary health.
- Improve risk communication to policy makers and the public and to support policy makers to make evidence-informed decisions, including by increasing capacity to do systematic reviews and provide rigorous policy briefs.

Propositions to address governance challenges

To advance planetary health, policies are needed that:

- Achieve improved governance for planetary health through cross-sectoral action at global, national, and subnational levels. Governance should help with a precautionary approach to reduce the risks to health and natural systems in a world where vested interests undermine the political will to act and where inequities have marginalised the voices of many disadvantaged groups.
- Implement creative financing—eg, reduction of harmful subsidies, revenue recycling, payment of providers of ecosystem services, and taxation of polluters—to support rapid transition to a more sustainable world economy than exists at present.
- Promote transformative change through combinations of different approaches using a range of regulatory, fiscal, and tax policies; mass media campaigns; and individual behaviour change interventions. These strategies should be assessed by rigorous research to define their effectiveness and tailored in view of the findings.

- Incentivise and provide evidence-based methods to encourage more robust adherence within the private sector than exists at present to high standards of environmental stewardship and health protection and build capacity in private sector entities based in low-income and middle-income settings.
- Engage civil society and community organisations by promoting public discourse, participation, and transparency of data and systems models to allow monitoring of trends and to encourage polycentric governance building on local capabilities to steward environmental resources and protect health.

Contributors

The original idea for the concept of planetary health was devised by RH. The first draft of this Commission report was written by SW and AH. All authors contributed fully to the overall report structure and concepts, to the writing of subsequent drafts, and approved the final draft. Additional text was written by the contributing authors.

Contributing authors

Contributed to the Commission report: Alex Martinez (text on water and health), Faraz Usmani (panel 13), Lukasz Aleksandrowicz (figure 16), Marina Maiero (panel 3), Diarmid Campbell-Lendrum (panel 3), David Cooper (panel 3). Sarah H Olson (panel 6), Wayne Twine (panel 4), Lori M Hunter (panel 4), Stephen Tollman (panel 4), and Shannon Doocy (panel 12). Contributed to the appendix: Tim Shorten (overview of past studies related to planetary health), Christopher Golden (fisheries and health), Simon J Lloyd (case study: transformative change, socio–ecological systems, and nutrition), Christi Electris (case study: transformative change, socio–ecological systems, and nutrition), Gillian Christie (case study: personalized digital technology to improve planetary health), Kevin Patrick (case study: personalized digital technology to improve planetary health), Vera Oziransky (case study: the co-benefits of addressing health and environment in cities), and Qu Cheng (relieving poverty through ecosystem restoration in the Loess Plateau).

Declaration of interests

All authors declare that the work of the Commission on Planetary Health was supported by The Rockefeller Foundation. SW, AH, and GMM were compensated for their time working on the Commission. AH, GMM, and PG are also members of the *Lancet* Commission on Health and Climate Change. AH has received funds from the Medical Research Council and from the Wellcome Trust for research on global environmental change and health. RH is the editor of *The Lancet*. GMM chaired the Royal Society science-policy report on Resilience to Extreme Weather, is a trustee of the World Wide Fund for Nature UK, a member of the UK Government Natural Capital Committee (England), and a member of Council of the Natural Environment Research Council (NERC) and the Royal Society; she has received funding from the NERC, the Department for Environment, Food & Rural Affairs, and the Leverhulme Trust. FB and RM are employees of The Rockefeller Foundation. SM has received funding from The Rockefeller Foundation, the Bill & Melinda Gates Foundation, the Winslow Foundation, and the Wellcome Trust for research into the human health impacts of global environmental change. DY is senior vice president of the Vitality Group, part of Discovery Ltd, where he leads the Vitality Institute. Previously, he was senior vice president of Global Health and Agriculture Policy at PepsiCo and head of global health at The Rockefeller Foundation. SN is also a member of the *Lancet* Commission on Pain and Palliative Care and is (as president and founder of Heartfile) a recipient of a grant from The Rockefeller Foundation. JV is a former employee of The Rockefeller Foundation. HF was a resident at The Rockefeller Foundation, Bellagio Center during March, 2015, and has previously received funding from The Rockefeller Foundation. HF is a board member of the Bullitt Foundation and the Washington Global Health Alliance. SAO (through WCS and HEAL) has received funding from The Rockefeller Foundation. The other authors declare no competing interests.

Acknowledgments

We would like to acknowledge the assistance of Charlanne Burke, Bhaskar Vira, Frans Berkhout, Judith Rodin, Jeff Waage, Colin D Butler, Anthony Costello, Trevor Hancock, Jonathan Patz, Zaid Chalabi, Jane Falconer, Chris Grundy, Mark Mulligan, Andrew Thorne-Lyman, Timothy Bouley, Evan O'Donnell, and participants of The Economist Intelligence Unit meeting on The Future of Planetary Health held in Bellagio, July 7–10, 2014. We would also like to thank the Canadian Public Health Association for kindly making available a prepublication draft of their report Global Change and Public Health: Addressing the Ecological Determinants of Health.

References

1 International Commission on Stratigraphy. International stratigraphic chart. 2013. http://www.stratigraphy.org/ICSchart/ChronostratChart2013-01.pdf (accessed June 22, 2015).
2 Crutzen PJ. Geology of mankind. *Nature* 2002; **415:** 23.
3 Millennium Ecosystem Assessment. Ecosystems and human wellbeing: health synthesis. In: Corvalan C, Hales S, McMichael AJ, eds. Washington DC: Island Press, 2005.
4 UKNEA. The UK National Ecosystem Assessment: technical report. Cambridge, UK: United Nations Environment Programme's World Conservation Monitoring Centre, 2011.
5 Millennium Ecosystem Assessment. Biodiversity. In: Mace G, Masundire H, Baillie J, et al, eds. Millennium ecosystem assessment: current state and trends: findings of the condition and trends working group ecosystems and human well-being. Washington, DC: Island Press, 2005.
6 Ramsar. Convention on wetlands of international importance especially as waterfowl habitat 1971. Iran, Feb 2, 1971. As amended by the protocol of Dec 3, 1982, and the amendments of May 28, 1987. http://portal.unesco.org/en/ev.php-URL_ID=15398&URL_DO=DO_TOPIC&URL_SECTION=201.html (accessed June 16, 2015).
7 IPCC. Climate change 2013. The Physical Science Basis Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, Intergovernmental Panel on Climate Change, 2013.
8 Stockholm Resilience Centre. Resilience dictionary 2015. http://www.stockholmresilience.org/21/research/what-is-resilience/resilience-dictionary.html (accessed June 9, 2015).
9 UN-REDD Programme. About REDD+. 2015. http://www.un-redd.org/aboutredd (accessed June 9, 2015).
10 Buchanan JM, Stubblebine WC. Externality. *Economica* 1962; **29:** 371–384.
11 European Commission. Towards a circular economy: a zero waste programme for Europe. 2014. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0398 (accessed Dec 22, 2014).
12 Rocha JC, Biggs R, Peterson GD. Regime shifts: what are they and why do they matter? 2014. http://www.regimeshifts.org/datasets-resources/ (accessed June 9, 2015).
13 Rodin J. The resilience dividend: being strong in a world where things go wrong. New York: PublicAffairs, 2014.
14 You D, Hug L, Chen Y, Wardlaw T, Newby H. Levels and trends in child mortality. New York: United Nations Inter-agency Group for Child Mortality Estimation, 2014.
15 Population Division of the Department of Economic and Social Affairs of the UN Secretariat. World population prospects: the 2012 revision. New York: United Nations, 2013.
16 Deaton A. The great escape: health, wealth, and the origins of inequality. Princeton: Princeton University Press, 2013.
17 Olinto P, Beegle K, Sobrado C, Uematsu H. The state of the poor: where are the poor, where is extreme poverty harder to end, and what is the current profile of the world's poor? Washington, DC: The World Bank, 2013.
18 Sukhdev P, Wittmer H, Schröter-Schlaack C, et al. Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. Geneva: The Economics of Ecosystems and Biodiversity, 2010.
19 DeFries R, Foley JA, Asner GP. Land-use choices: balancing human needs and ecosystem function. *Front Ecol Environ* 2004; **2:** 249–57.
20 Bennett EM, Peterson GD, Gordon LJ. Understanding relationships among multiple ecosystem services. *Ecol Lett* 2009; **12:** 1394–404.

21 Roser M. World poverty. 2015. http://ourworldindata.org/data/growth-and-distribution-of-prosperity/world-poverty/ (accessed March 24, 2015).

22 Steffen W, Broadgate W, Deutsch L, Gaffney O, Ludwig C. The trajectory of the Anthropocene: the great acceleration. *The Anthropocene Review* 2015; **2:** 81–98.

23 Kummu M, Ward PJ, de Moel H, Varis O. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environ Res Lett* 2010; **5:** 034006.

24 WWF. Living planet report 2014: species and spaces, people and places. Gland, Switzerland: World Wide Fund for Nature, 2014.

25 Foley JA, Monfreda C, Ramankutty N, Zaks D. Our share of the planetary pie. *Proc Natl Acad Sci USA* 2007; **104:** 12585–86.

26 Hansen MC, Potapov PV, Moore R, et al. High-resolution global maps of 21st-century forest cover change. *Science* 2013; **342:** 850–53.

27 FAO. The state of world fisheries and aquaculture—opportunities and challenges. Rome: Food and Agriculture Organization, 2014.

28 World Commission on Dams. Dams and development: a new framework for decision-making. November, 2000. http://www.unep.org/dams/WCD/report/WCD_DAMS%20report.pdf (accessed March 16, 2015).

29 Lehner B, Liermann CR, Revenga C, et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front Ecol Environ* 2011; **9:** 494–502.

30 Pimm SL, Jenkins CN, Abell R, et al. The biodiversity of species and their rates of extinction, distribution, and protection. *Science* 2014; **344:** 1246752.

31 Millennium Ecosystem Assessment. Living beyond our means. Natural assets and human well-being. Statement from the Board. In: Millennium Ecosystem Assessment Board, ed. Washington, DC: Millennium Ecosystem Assessment, 2005.

32 Prüss-Üstün A, Corvalán C. Preventing disease through healthy environments. Towards an estimate of the environmental burden of disease. Geneva: World Health Organization, 2006.

33 Lim SS, Vos T, Flaxman AD, et al. 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* 2012; **380:** 2224–60.

34 Butler CD. Climate change and global health: a new conceptual framework—mini review. *CAB Rev* 2014; **9:** No. 027.

35 Russi D, ten Brink P, Farmer A, et al. The economics of ecosystems and biodiversity for water and wetlands. London and Brussels: IEEP/Ramsar Secretariat, 2013.

36 Danielsen F, Sørensen MK, Olwig MF, et al. The Asian tsunami: a protective role for coastal vegetation. *Science* 2005; **310:** 643.

37 Dean RG. New Orleans and the Wetlands of Southern Louisiana. *The Bridge* 2006; **36:** 35–42.

38 Millennium Ecosystem Assessment. Human health: ecosystem regulation of infectious diseases. In: Patz JA, Confalonieri U, eds. Ecosystems and human well-being: current status and trends. Washington, DC: Island Press, 2005.

39 CBD–WHO. Connecting global priorities: biodiversity and human health, a state of knowledge review. 2015. https://www.cbd.int/health/SOK-biodiversity-en.pdf (accessed June 6, 2015).

40 UNEP. Global environment outlook 4. United Nations Environment Programme. 2007. http://www.unep.org/geo/GEO4/report/GEO-4_Report_Full_en.pdf (accessed March 16, 2015).

41 UNEP. Global Environment Outlook 5. 2012. http://www.unep.org/geo/pdfs/geo5/GEO5_report_full_en.pdf (accessed March 16, 2015).

42 IPCC. Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change. In: Field CB, Barros VR, Dokken DJ, et al, eds. Climate Change 2014. Cambridge, UK and New York, USA: Cambridge University Press, 2014: 1132.

43 Myers SS, Gaffikin L, Golden CD, et al. Human health impacts of ecosystem alteration. *Proc Natl Acad Sci USA* 2013; **110:** 18753–60.

44 Raudsepp-Hearne C, Peterson GD, Tengö M, et al. Untangling the environmentalist's paradox: why is human well-being increasing as ecosystem services degrade? *Bioscience* 2010; **60:** 576–89.

45 Bereuter D, Glickman D. Healthy food for a healthy world: leveraging agriculture and food to improve global nutrition: The Chicago Council on Global Affairs. 2015. http://www.thechicagocouncil.org/sites/default/files/GlobalAg-HealthyFood_FINAL.pdf (accessed April 19, 2015).

46 Gerland P, Raftery AE, Sevčíková H, et al. World population stabilization unlikely this century. *Science* 2014; **346:** 234–37.

47 The Royal Society. People and the Planet: The Royal Society. 2012. https://royalsociety.org/~/media/Royal_Society_Content/policy/projects/people-planet/2012-04-25-PeoplePlanet.pdf (accessed Oct 2, 2014).

48 Dora C, Haines A, Balbus J, et al. Indicators linking health and sustainability in the post-2015 development agenda. *Lancet* 2015; **385:** 380–91.

49 Lang T, Rayner G. Ecological public health: the 21st century's big idea? An essay by Tim Lang and Geof Rayner. *BMJ* 2012; **345:** e5466.

50 WHO. Constitution of the World Health Organization. Geneva: World Health Organization, 1946.

51 Horton R, Beaglehole R, Bonita R, Raeburn J, McKee M, Wall S. From public to planetary health: a manifesto. *Lancet* 2014; **383:** 847.

52 Haines A, Whitmee S, Horton R. Planetary health: a call for papers. *Lancet* 2014; **384:** 479–80.

53 Brundtland GH. Report of the world commission on environment and development: our common future. Oxford; New York: World Commission on Environment and Development, 1987.

54 McMichael AJ. Planetary overload. Global environmental change and the health of the human species. Cambridge, UK: Cambridge University Press, 1993.

55 Watts N, Adger WN, Agnolucci P, et al. Health and climate change: policy responses to protect public health. *Lancet* 2015; published online June 22. http://dx.doi.org/10.1016/S0140-6736(15)60854-6.

56 Shea BJ, Grimshaw JM, Wells GA, et al. Development of AMSTAR: a measurement tool to assess the methodological quality of systematic reviews. *BMC Med Res Methodol* 2007; **7:** 10.

57 Steffen W, Richardson K, Rockström J, et al. Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science* 2015; **347:** 1259855.

58 Rockström J, Steffen W, Noone K, et al. A safe operating space for humanity. *Nature* 2009; **461:** 472–75.

59 Sanford T, Frumhoff PC, Luers A, Gulledge J. The climate policy narrative for a dangerously warming world. *Nature Climate Change* 2014; **4:** 164–66.

60 IGBP. IOC, SCOR. Ocean acidification summary for policymakers—third symposium on the ocean in a high-CO_2 world. Stockholm, Sweden: International Geosphere-Biosphere Programme, 2013.

61 Secretariat of the Convention on Biological Diversity. An updated synthesis of the impacts of ocean acidification on marine biodiversity. Montreal: Convention on Biological Diversity, 2014.

62 Kawaguchi S, Ishida A, King R, et al. Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Climate Change* 2013; **3:** 843–47.

63 FAO. Review of world water resources by country. Rome: Food and Agriculture Organization, 2003.

64 OECD. Chapter 5: water. OECD environmental outlook to 2050. Paris: Organisation for Economic Co-operation and Development Publishing, 2012.

65 El-Zein A, Jabbour S, Tekce B, et al. Health and ecological sustainability in the Arab world: a matter of survival. *Lancet* 2014; **383:** 458–76.

66 UN. The millennium development goals report 2014. Geneva: United Nations, 2014.

67 Davidson NC. How much wetland has the world lost? Long-term and recent trends in global wetland area. *Mar Freshw Res* 2014; **65:** 934.

68 Tilman D, Clark M. Global diets link environmental sustainability and human health. *Nature* 2014; **515:** 518–22.

69 Savilaakso S, Garcia C, Garcia-Ulloa J, et al. Systematic review of effects on biodiversity from oil palm production. *Environmental Evidence* 2014; **3:** 4.

70 Foley JA, Defries R, Asner GP, et al. Global consequences of land use. *Science* 2005; **309:** 570–74.

71 van Lynden GWA, Odeman LR. United Nations Environment Programme. The assessment of the status of human-induced soil degradation in south and southeast Asia. Wageningen, Netherlands: ISRIC, 1998.

72 Koch A, McBratney A, Adams M, et al. Soil security: solving the global soil crisis. *Global Policy* 2013; **4:** 434–41.

73 Montgomery DR. Soil erosion and agricultural sustainability. *Proc Natl Acad Sci USA* 2007; **104:** 13268–72.

74 Lambin EF, Meyfroidt P. Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci USA* 2011; **108:** 3465–72.

75 Lal R. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience* 2010; **60:** 708–21.

76 Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science* 2004; **304:** 1623–27.

77 Mullan D. Soil erosion under the impacts of future climate change: Assessing the statistical significance of future changes and the potential on-site and off-site problems. *Catena* 2013; **109:** 234–46.

78 Bouwman L, Goldewijk KK, Van Der Hoek KW, et al. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proc Natl Acad Sci USA* 2013; **110:** 20882–87.

79 Bennett EM, Carpenter SR, Caraco NF. Human impact on erodable phosphorus and eutrophication: a global perspective. *Bioscience* 2001; **51:** 227.

80 UNEP. Global chemicals outlook—towards sound management of chemicals. 2013. http://www.unep.org/hazardoussubstances/Portals/9/Mainstreaming/GCO/The%20Global%20Chemical%20Outlook_Full%20report_15Feb2013.pdf (accessed Dec 23, 2014).

81 Daughton CG, Ternes TA. Pharmaceuticals and personal care products in the environment: agents of subtle change? *Environ Health Perspect* 1999; **107** (suppl 6)**:** 907–38.

82 United States Environmental Protection Agency. Toxics release inventory (tri) program. http://www2.epa.gov/toxics-release-inventory-tri-program (accessed April 1, 2015).

83 Diamond ML, de Wit CA, Molander S, et al. Exploring the planetary boundary for chemical pollution. *Environ Int* 2015; **78:** 8–15.

84 Lebel J. Health: an ecosystem approach. Ottawa, Canada: International Development Research Centre, 2003.

85 Cook RA, Karesh WB, Osofsky SA. Conference summary: one world, one health: building interdisciplinary bridges to health in a globalized world. One world, one health. Sept 29, 2004. http://www.oneworldonehealth.org/sept2004/owoh_sept04.html (accessed March 28, 2015).

86 Secretariat of the Convention on Biological Diversity. Global biodiversity outlook 3. Montreal: Convention on Biological Diversity, 2010.

87 Secretariat of the Convention on Biological Diversity. Global Biodiversity Outlook 4. Montreal: Convention on Biological Diversity, 2014.

88 Mace GM, Reyers B, Alkemade R, et al. Approaches to defining a planetary boundary for biodiversity. *Glob Environ Change* 2014; **28:** 289–97.

89 Barnosky AD, Brown JH, Daily GC, et al. Scientific consensus on maintaining humanity's life support systems in the 21st century. Information for policy makers. 2013. http://mahb.stanford.edu/consensus-statement-from-global-scientists/ (accessed Sept 5, 2014).

90 Barnosky AD, Hadly EA, Bascompte J, et al. Approaching a state shift in Earth's biosphere. *Nature* 2012; **486:** 52–58.

91 Rocha J, Yletyinen J, Biggs R, Blenckner T, Peterson G. Marine regime shifts: drivers and impacts on ecosystems services. *Philos Trans R Soc Lond B Biol Sci* 2014; **370:** 20130273.

92 Bradshaw CJ, Giam X, Sodhi NS. Evaluating the relative environmental impact of countries. *PLoS One* 2010; **5:** e10440.

93 Institution of Mechanical Engineers. Global food. Waste not, want not. London: Institution of Mechanical Engineers, 2013.

94 GEA Writing Team. Chapter 1—energy primer. In: Johansson TB, Nakićenović N, eds. Global energy assessment. Cambridge, UK: Cambridge University Press, 2012.

95 HLPE. Biofuels and food security. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. 2013. http://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-5_Biofuels_and_food_security.pdf (accessed Dec 17, 2014).

96 Cassidy ES, West PC, Gerber JS, Foley JA. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environ Res Lett* 2013; **8:** 034015.

97 UN Department of Economic and Social Affairs Population Division. World urbanization prospects: the 2014 revision. 2014. http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf (accessed Dec 19, 2014).

98 Capon AG. The way we live in our cities. *Med J Aust* 2007; **187:** 658–61.

99 Bradshaw CJA, Brook BW. Human population reduction is not a quick fix for environmental problems. *Proc Natl Acad Sci USA* 2014; **111:** 16610–15.

100 O'Neill BC, Dalton M, Fuchs R, Jiang L, Pachauri S, Zigova K. Global demographic trends and future carbon emissions. *Proc Natl Acad Sci USA* 2012; **107:** 17521–26.

101 Bryant L, Carver L, Butler CD, Anage A. Climate change and family planning: least-developed countries define the agenda. *Bull World Health Organ* 2009; **87:** 852–57.

102 Mace GM, Terama E, Coulson T. Perspectives on international trends and dynamics in population and consumption. *Environ Resour Econ* 2013; **55:** 555–68.

103 de Sherbinin A, Carr D, Cassels S, Jiang L. Population and environment. *Annu Rev Environ Resour* 2007; **32:** 345–73.

104 Alcott B. Jevons' paradox. *Ecol Econ* 2005; **54:** 9–21.

105 IPCC. Summary for Policymakers, In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al, eds. Climate change 2014, mitigation of climate change contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 2014.

106 Montgomery MR. The urban transformation of the developing world. *Science* 2008; **319:** 761–64.

107 Campbell-Lendrum D, Corvalán C. Climate change and developing-country cities: implications for environmental health and equity. *J Urban Health* 2007; **84** (suppl 3)**:** i109–17.

108 Sánchez-Rodríguez R, Seto KC, Simon D, Solecki W, Kraas F, Laumann GS. Science plan: urbanization and global environmental change. Bonn: International Human Dimensions Programme on Global Environmental Change. 2005. http://www.ihdp.unu.edu/publications/?id=379 (accessed Dec 19, 2014).

109 McDonald RI, Green P, Balk D, et al. Urban growth, climate change, and freshwater availability. *Proc Natl Acad Sci USA* 2011; **108:** 6312–17.

110 Dodman D. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environ Urban* 2009; **21:** 185–201.

111 Krey V, O'Neill BC, van Ruijven B, et al. Urban and rural energy use and carbon dioxide emissions in Asia. *Energy Econ* 2012; **34:** 272–83.

112 UNFPA. State of world populations 2007. Unleashing the potential of urban growth. 2007. http://www.unfpa.org/sites/default/files/pub-pdf/695_filename_sowp2007_eng.pdf (accessed April 19, 2015).

113 The Royal Society. Resilience to extreme weather. 2014. https://royalsociety.org/~/media/policy/projects/resilience-climate-change/resilience-full-report.pdf (accessed Nov 30, 2014).

114 Patz JA, Frumkin H, Holloway T, Vimont DJ, Haines A. Climate change: challenges and opportunities for global health. *JAMA* 2014; **312:** 1565–80.

115 Stone B, Hess JJ, Frumkin H. Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? *Environ Health Perspect* 2010; **118:** 1425–28.

116 The Rockefeller Foundation. 100 resilient cities (100RC). 2015.http://www.100resilientcities.org/pages/about-us (accessed Feb 14, 2015).

117 McMichael AJ. Population health in the Anthropocene: gains, losses and emerging trends. *The Anthropocene Review* 2014; **1:** 44–56.

118 IPCC. Summary for policy makers. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change 2014: impacts, adaptation, and vulnerability. 2014. http://www.ipcc.ch/report/ar5/wg2/ (accessed Nov 30, 2014).

119 Landrigan PJ, Etzel RA, eds. Textbook of Children's Environmental Health. Oxford: Oxford University Press, 2013.

120 Gómez-Olivé FX, Angotti N, Houle B, et al. Prevalence of HIV among those 15 and older in rural South Africa. *AIDS Care* 2013; **25:** 1122–28.
121 Timko JA, Kozak RA, Innes JL. HIV/AIDS and forests in Sub-Saharan Africa: exploring the links between morbidity, mortality, and dependence on biodiversity. *Biodiversity* 2010; **11:** 45–48.
122 Kahn K, Collinson MA, Gómez-Olivé FX, et al. Profile: Agincourt health and socio-demographic surveillance system. *Int J Epidemiol* 2012; **41:** 988–1001.
123 Hunter LM, Twine W, Patterson L. "Locusts are now our beef": adult mortality and household dietary use of local environmental resources in rural South Africa. *Scand J Public Health Suppl* 2007; **69:** 165–74.
124 Twine W, Hunter LM. Adult mortality, food security and the use of wild natural resources in a rural district of South Africa: exploring the environmental dimensions of AIDS. In: Niehof A, Rugalema G, Gillespie S, eds. AIDS and rural livelihoods: dynamics and diversity in sub-Saharan Africa. London: Earthscan, 2010: 153–70.
125 Hunter LM, Twine W, Johnson A. Adult mortality and natural resource use in rural South Africa: evidence from the Agincourt Health and Demographic Surveillance Site. *Soc Nat Resour* 2011; **24:** 256–75.
126 Twine W, Hunter LM. Adult mortality and household food security in rural South Africa: Does AIDS represent a unique mortality shock? *Dev South Afr* 2011; **28:** 431–44.
127 WHO. Nutrient requirements for people living with HIV/AIDS: report of a technical consultation. Geneva: World Health Organization, 2003.
128 Singer AW, Weiser SD, McCoy SI. Does food insecurity undermine adherence to antiretroviral therapy? A systematic review. *AIDS Behav* 2014; published online Aug 6. DOI: 10.1007/s10461-014-0873-1.
129 Green R, Cornelsen L, Dangour AD, et al. The effect of rising food prices on food consumption: systematic review with meta-regression. *BMJ* 2013; **346:** f3703.
130 Black RE, Victora CG, Walker SP, et al, and the Maternal and Child Nutrition Study Group. Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet* 2013; **382:** 427–51.
131 FAO. Climate change and food security: a framework document. 2008. http://www.fao.org/forestry/15538-079b31d45081fe9c3dbc6ff34de4807e4.pdf (accessed March 12, 2015).
132 Bai ZG, Dent DL, Olsson L, Schaepman ME. Proxy global assessment of land degradation. *Soil Use Manage* 2008; **24:** 223–34.
133 Rickson RJ, Deeks LK, Graves A, Harris JAH, Kibblewhite MG, Sakrabani R. Input constraints to food production: the impact of soil degradation. *Food Security* 2015; **7:** 351–64.
134 Sanchez PA. Ecology. Soil fertility and hunger in Africa. *Science* 2002; **295:** 2019–20.
135 Godfray HC, Blacquiere T, Field LM, et al. A restatement of the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proc Biol Sci* 1786; **2014:** 281.
136 Klein AM, Vaissiere BE, Cane JH, et al. Importance of pollinators in changing landscapes for world crops. *Proc Biol Sci* 2007; **274:** 303–13.
137 Gallai N, Salles J-M, Settele J, Vaissière BE. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol Econ* 2009; **68:** 810–21.
138 Ellis AM, Myers SS, Ricketts TH. Do pollinators contribute to nutritional health? *PLoS One* 2015; **10:** e114805.
139 Smith MR, Singh GM, Mozaffarian D, Myers SS. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis. *Lancet* (in press).
140 Sheeshka J, Murkin E. Nutritional aspects of fish compared with other protein sources. *Comments Toxicol* 2010; **8:** 375–97.
141 McCauley DJ, Pinsky ML, Palumbi SR, Estes JA, Joyce FH, Warner RR. Marine defaunation: animal loss in the global ocean. *Science* 2015; **347:** 1255641.
142 Worm B, Barbier EB, Beaumont N, et al. Impacts of biodiversity loss on ocean ecosystem services. *Science* 2006; **314:** 787–90.
143 Costello C, Ovando D, Hilborn R, Gaines SD, Deschenes O, Lester SE. Status and solutions for the world's unassessed fisheries. *Science* 2012; **338:** 517–20.
144 Pauly D, Hilborn R, Branch TA. Fisheries: does catch reflect abundance? *Nature* 2013; **494:** 303–06.
145 Worm B, Branch TA. The future of fish. *Trends Ecol Evol* 2012; **27:** 594–99.
146 Carpenter KE, Abrar M, Aeby G, et al. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science* 2008; **321:** 560–63.
147 Cinner JE, McClanahan TR, Graham NAJ, et al. Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Glob Environ Change* 2012; **22:** 12–20.
148 United States Coral Reef Task Force. The national action plan to conserve coral reefs. 2000. http://www.coralreef.gov/about/CRTFAxnPlan9.pdf (accessed March 27, 2015).
149 Ekstrom JA, Suatoni L, Cooley SR, et al. Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change* 2015; **5:** 207–14.
150 Daviglus M, Sheeshka J, Murkin E. Health benefits from eating fish. *Comments Toxicol* 2010; **8:** 345–74.
151 Thurstan RH, Roberts CM. The past and future of fish consumption: can supplies meet healthy eating recommendations? *Mar Pollut Bull* 2014; **89:** 5–11.
152 Brashares JS, Arcese P, Sam MK, Coppolillo PB, Sinclair AR, Balmford A. Bushmeat hunting, wildlife declines, and fish supply in West Africa. *Science* 2004; **306:** 1180–83.
153 Roberts CM. Oceans of Life. London: Penguin, 2013.
154 Battisti DS, Naylor RL. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 2009; **323:** 240–44.
155 Lloyd SJ, Kovats RS, Chalabi Z. Climate change, crop yields, and undernutrition: development of a model to quantify the impact of climate scenarios on child undernutrition. *Environ Health Perspect* 2011; **119:** 1817–23.
156 Huybers P, McKinnon KA, Rhines A, Tingley M. US daily temperatures: the meaning of extremes in the context of non-normality. *J Clim* 2014; **27:** 7368–84.
157 Fisher BS, Nakicenovic N, Alfsen K, et al. Issues related to mitigation in the long term context, In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, eds. Mitigation contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007.
158 Ainsworth EA, Long SP. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol* 2005; **165:** 351–71.
159 Myers SS, Zanobetti A, Kloog I, et al. Increasing CO_2 threatens human nutrition. *Nature* 2014; **510:** 139–42.
160 Myers SS, Wessellsc KR, Kloogd I, Zanobettia A, Schwartz J. Rising atmospheric CO_2 increases global threat of zinc deficiency. *Lancet Glob Health* (in press).
161 Avnery S, Mauzerall DL, Liu JF, Horowitz LW. Global crop yield reductions due to surface ozone exposure: 1 year 2000 crop production losses and economic damage. *Atmos Environ* 2011; **45:** 2284–96.
162 Tai A. P. K., Val Martin M, Heald C, L. Threat to future global food security from climate change and ozone air pollution. *Nature Climate Change* 2014; **4:** 817–21.
163 Qin TFD, Plattner G-K, Tignor M, et al. IPCC, 2013: summary for policymakers. 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, UK and New York, USA: Cambridge University Press, 2013.
164 Chakraborty S, Newton AC. Climate change, plant diseases and food security: an overview. *Plant Pathol* 2011; **60:** 2–14.
165 Medina A, Rodriguez A, Magan N. Effect of climate change on *Aspergillus flavus* and aflatoxin B1 production. *Front Microbiol* 2014; **5:** 348.
166 Liu Y, Wu F. Global burden of aflatoxin-induced hepatocellular carcinoma: a risk assessment. *Environ Health Perspect* 2010; **118:** 818–24.
167 Wild CP, Gong YY. Mycotoxins and human disease: a largely ignored global health issue. *Carcinogenesis* 2010; **31:** 71–82.
168 Strosnider H, Azziz-Baumgartner E, Banziger M, et al. Workgroup report: public health strategies for reducing aflatoxin exposure in developing countries. *Environ Health Perspect* 2006; **114:** 1898–903.
169 WHO. Summary and policy implications Vision 2030: the resilience of water supply and sanitation in the face of climate change. Geneva: World Health Organization, 2009.

170 Yardley J. Beneath booming cities, China's future is drying up. *New York Times*, Sept 28, 2007. http://www.nytimes.com/2007/09/28/world/asia/28water.html?pagewanted=all# (accessed Dec 20, 2014).
171 Elliott J, Deryng D, Muller C, et al. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc Natl Acad Sci USA* 2014; **111:** 3239–44.
172 Tester M, Langridge P. Breeding technologies to increase crop production in a changing world. *Science* 2010; **327:** 818–22.
173 Rosegrant MW, Ringler C, Zhu T. Water for agriculture: maintaining food security under growing scarcity. *Annu Rev Environ Resour* 2009; **34:** 205–22.
174 Eshel G, Shepon A, Makov T, Milo R. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proc Natl Acad Sci USA* 2014; **111:** 11996–2001.
175 Gerbens-Leenes W, Hoekstra AY, van der Meer TH. The water footprint of bioenergy. *Proc Natl Acad Sci USA* 2009; **106:** 10219–23.
176 Suweis S, Rinaldo A, Maritan A, D'Odorico P. Water-controlled wealth of nations. *Proc Natl Acad Sci USA* 2013; **110:** 4230–33.
177 Prüss-Ustün A, Bartram J, Clasen T, et al. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. *Trop Med Int Health* 2014; **19:** 894–905.
178 Guynup S. India and China share a grave environmental problem—extreme water pollution. 2010. http://www.sa-lives.com/entry/44/dirty-water (accessed Dec 23, 2014).
179 Moors E, Singh T, Siderius C, Balakrishnan S, Mishra A. Climate change and waterborne diarrhoea in northern India: impacts and adaptation strategies. *Sci Total Environ* 2013; **468–469** (suppl)**:** S139–51.
180 Myers SS, Patz JA. Emerging threats to human health from global environmental change. *Annu Rev Environ Resour* 2009; **34:** 223–52.
181 King CH. Parasites and poverty: the case of schistosomiasis. *Acta Trop* 2010; **113:** 95–104.
182 Secor WE. The effects of schistosomiasis on HIV/AIDS infection, progression and transmission. *Curr Opin HIV AIDS* 2012; **7:** 254–59.
183 Bustinduy A, King C, Scott J, et al. HIV and schistosomiasis co-infection in African children. *Lancet Infect Dis* 2014; **14:** 640–49.
184 Wolfe ND, Dunavan CP, Diamond J. Origins of major human infectious diseases. *Nature* 2007; **447:** 279–83.
185 Daszak P, Zambrana-Torrelio C, Bogich TL, et al. Interdisciplinary approaches to understanding disease emergence: the past, present, and future drivers of Nipah virus emergence. *Proc Natl Acad Sci USA* 2013; **110** (suppl 1)**:** 3681–88.
186 UN Human Settlements Programme (UN-Habitat). The state of African cities 2014: re-imagining sustainable urban transitions. 2014. http://unhabitat.org/the-state-of-african-cities-2014/ (accessed Dec 20, 2014).
187 Gibbs HK, Ruesch AS, Achard F, et al. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc Natl Acad Sci USA* 2010; **107:** 16732–37.
188 FAO. State of the world' s forests 2012. Rome: Food and Agricultural Organization of the United Nations, 2012.
189 Baize S, Pannetier D, Oestereich L, et al. Emergence of Zaire Ebola virus disease in Guinea. *N Engl J Med* 2014; **371:** 1418–25.
190 Leroy EM, Epelboin A, Mondonge V, et al. Human Ebola outbreak resulting from direct exposure to fruit bats in Luebo, Democratic Republic of Congo, 2007. *Vector Borne Zoonotic Dis* 2009; **9:** 723–28.
191 Olson SH, Reed P, Cameron KN, et al. Dead or alive: animal sampling during Ebola hemorrhagic fever outbreaks in humans. *Emerg Health Threats J* 2012; **5:** 9134.
192 Rouquet P, Froment JM, Bermejo M, et al. Wild animal mortality monitoring and human Ebola outbreaks, Gabon and Republic of Congo, 2001–2003. *Emerg Infect Dis* 2005; **11:** 283–90.
193 Bausch DG, Schwarz L. Outbreak of Ebola virus disease in Guinea: where ecology meets economy. *PLoS Negl Trop Dis* 2014; **8:** e3056.
194 Wallace RG, Gilbert M, Wallace R, Pittiglio C, Mattioli R, Kock R. Did Ebola emerge in west Africa by a policy-driven phase change in agroecology? *Environ Plann A* 2014; **46:** 2533–42.
195 Pulliam JR, Epstein JH, Dushoff J, et al. Agricultural intensification, priming for persistence and the emergence of Nipah virus: a lethal bat-borne zoonosis. *J R Soc Interface* 2012; **9:** 89–101.
196 Plowright RK, Foley P, Field HE, et al. Urban habituation, ecological connectivity and epidemic dampening: the emergence of Hendra virus from flying foxes (*Pteropus* spp.). *Proc Biol Sci* 2011; **278:** 3703–12.
197 Luis AD, Hayman DT, O'Shea TJ, et al. A comparison of bats and rodents as reservoirs of zoonotic viruses: are bats special? *Proc Biol Sci* 2013; **280:** 20122753.
198 Kamins AO, Rowcliffe JM, Ntiamoa-Baidu Y, Cunningham AA, Wood JL, Restif O. Characteristics and risk perceptions of Ghanaians potentially exposed to bat-borne zoonoses through bushmeat. *EcoHealth* 2014; **12:** 104–20.
199 World Food Program. VAM food security analysis, special focus—Ebola (p. 12). 2014. http://documents.wfp.org/stellent/groups/public/documents/ena/wfp268882.pdf (accessed Dec 20, 2014).
200 Cumming-Bruce N. WHO chief calls Ebola outbreak a 'crisis for international peace'. *The New York Times*, Oct 13, 2014.
201 Pongsiri MJ, Roman J, Ezenwa VO, et al. Biodiversity loss affects global disease ecology. *Bioscience* 2009; **59:** 945–54.
202 The President's Council of Advisors on Science and Technology. Sustaining environmental capital: protecting society and the economy. Working Group Report. 2011. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_sustaining_environmental_capital_report.pdf (accessed Jan 30, 2015).
203 Keesing F, Belden LK, Daszak P, et al. Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature* 2010; **468:** 647–52.
204 Jones KE, Patel NG, Levy MA, et al. Global trends in emerging infectious diseases. *Nature* 2008; **451:** 990–93.
205 Brown L, Medlock J, Murray V. Impact of drought on vector-borne diseases—how does one manage the risk? *Public Health* 2014; **128:** 29–37.
206 Jelmayer R, Chao L. Drought-stricken São Paulo battles dengue fever outbreak. *The Wall Street Journal*, March 3, 2015.
207 Kar NP, Kumar A, Singh OP, Carlton JM, Nanda N. A review of malaria transmission dynamics in forest ecosystems. *Parasit Vectors* 2014; **7:** 265.
208 Yasuoka J, Levins R. Impact of deforestation and agricultural development on anopheline ecology and malaria epidemiology. *Am J Trop Med Hyg* 2007; **76:** 450–60.
209 Gilles HM. Epidemiology. Oxford: Oxford University Press, 1999.
210 Vittor AY, Pan W, Gilman RH, et al. Linking deforestation to malaria in the Amazon: characterization of the breeding habitat of the principal malaria vector, *Anopheles darlingi*. *Am J Trop Med Hyg* 2009; **81:** 5–12.
211 Molyneux DH. Vector-borne parasitic diseases—an overview of recent changes. *Int J Parasitol* 1998; **28:** 927–34.
212 Pattanayak SK, Yasuoka J. Deforestation and malaria: revisiting the human ecology perspective. In: Colfer CJP, ed. Human health and forests: a global overview of issues, practice and policy. London: Earthscan, 2008: 197–217.
213 Béguin A, Hales S, Rocklöv J, Åström C, Louis VR, Sauerborn R. The opposing effects of climate change and socio-economic development on the global distribution of malaria. *Glob Environ Change* 2011; **21:** 1209–14.
214 Hoberg EP, Brooks DR. Evolution in action: climate change, biodiversity dynamics and emerging infectious disease. *Philos Trans R Soc Lond B Biol Sci* 2015; **370:** 370.
215 WHO. 7 million premature deaths annually linked to air pollution. Geneva: World Health Organization, 2014.
216 Bonjour S, Adair-Rohani H, Wolf J, et al. Solid fuel use for household cooking: country and regional estimates for 1980–2010. *Environ Health Perspect* 2013; **121:** 784–90.
217 May-Tobin C. Wood for fuel. In: Union of Concerned Scientists, eds. The root of the problem: what's driving tropical deforestation today? 2011. http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/UCS_RootoftheProblem_DriversofDeforestation_FullReport.pdf (accessed Dec 23, 2014).
218 Bailis R, Ezzati M, Kammen DM. Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa. *Science* 2005; **308:** 98–103.
219 Johnston FH, Henderson SB, Chen Y, et al. Estimated global mortality attributable to smoke from landscape fires. *Environ Health Perspect* 2012; **120:** 695–701.

220 Sitch S, Cox PM, Collins WJ, Huntingford C. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature* 2007; **448:** 791–94.

221 UNEP. Ridding the world of POPs: A guide to the Stockholm Convention on persistent organic pollutants. 2010. http://www.pops.int/documents/guidance/beg_guide.pdf (accessed July 20, 2014).

222 Prüss-Ustün A, Vickers C, Haefliger P, Bertollini R. Knowns and unknowns on burden of disease due to chemicals: a systematic review. *Environ Health* 2011; **10:** 9.

223 Diallo Y, Hagemann F, Etienne A, Gurbuzer Y, Mehran F. Global child labour developments: Measuring trends from 2004 to 2008. Geneva: International Labour Office, International Programme on the Elimination of Child Labour, 2010.

224 United States Environmental Protection Agency. High production volume (HPV) challenge. April 22, 2013. http://www.epa.gov/hpv/ (accessed April 1, 2015).

225 WHO, UN Environment Programme, Inter-Organization Programme for the Sound Management of Chemicals, et al, eds. State of the science of endocrine disrupting chemicals 2012. Geneva: World Health Organization, 2013.

226 Bergman A, Heindel JJ, Kasten T, et al. The impact of endocrine disruption: a consensus statement on the state of the science. *Environ Health Perspect* 2013; **121:** A104–06.

227 World Meteorological Organization. Atlas of Mortality and Economic Losses from Weather Climate and Water Extremes (1970–2012). Geneva: World Meteorological Organization, 2014.

228 Stanke C, Kerac M, Prudhomme C, Medlock J, Murray V. Health effects of drought: a systematic review of the evidence. *PLoS Curr* 2013; **5:** 5.

229 International Federation of Red Cross and Red Crescent Societies. World Disaster Report 1997. New York: International Federation of Red Cross and Red Crescent Societies, 1998.

230 Ahern M, Kovats RS, Wilkinson P, Few R, Matthies F. Global health impacts of floods: epidemiologic evidence. *Epidemiol Rev* 2005; **27:** 36–46.

231 Cann KF, Thomas DR, Salmon RL, Wyn-Jones AP, Kay D. Extreme water-related weather events and waterborne disease. *Epidemiol Infect* 2013; **141:** 671–86.

232 UNISDR. Hyogo framework for action 2005–2015: building the resilience of nations and communities to disasters. 2005. http://www.unisdr.org/we/inform/publications/1037 (accessed Feb 11, 2015).

233 Mazhar N. Population, labor force and employment. In: Wasti SE, ed. Pakistan economic survey 2013–2014. Islamabad: Government of Pakistan, 2014: 179–93.

234 World Water Assessment Programme. Chapter 44. Pakistan, with special reference to the Indus River basin. The United Nations world water development report 4: managing water under uncertainty and risk. Paris: UNESCO, 2012.

235 World Bank. Pakistan country water resources assistance strategy water economy: running dry. 2005. http://documents.worldbank.org/curated/en/2005/11/6492396/pakistan-country-water-resources-assistance-strategy-water-economy-running-dry (accessed Dec 21, 2014).

236 FAO. Irrigation in southern and eastern Asia in figures. AQUASTAT Survey—2011. In: Frenken K, ed. FAO water reports 37: FAO Land and Water Division; Rome: Food and Agriculture Organization, 2011.

237 Memon AA. Evaluation of impacts on the lower Indus river basin due to upstream water storage and diversion. In: Sehlke G, Hayes DF, eds. Critical transitions in water and environmental resources management. Reston, VA: American Society of Civil Engineers, 2004: 1–10.

238 Zahid M, Rasul G. Changing trends of thermal extremes in Pakistan. *Clim Change* 2012; **113:** 883–96.

239 Mueller V, Gray C, Kosec K. Heat stress increases long-term human migration in rural Pakistan. *Nat Clim Chang* 2014; **4:** 182–85.

240 UN Floods Response. Pakistan floods. One year on. 2011. http://www.fao.org/fileadmin/user_upload/emergencies/docs/PakistanFloods1yrBrochure.pdf (accessed April 1, 2015).

241 Shabir O. A summary case report on the health impacts and response to the Pakistan floods of 2010. *PLoS Curr* 2013; **5:** 5.

242 Kirsch TD, Wadhwani C, Sauer L, Doocy S, Catlett C. Impact of the 2010 Pakistan floods on rural and urban populations at six months. *PLoS Curr* 2012; **4:** e4fdfb212d2432.

243 Hijioka Y, Lin E, Pereira JJ, et al. Asia. In: Barros VR, Field CB, Dokken DJ, et al, eds. Climate Change 2014: Impacts, adaptation, and vulnerability Part B: regional aspects contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 2014: 1327–70.

244 Khandekar ML. 2010 Pakistan floods: climate change or natural variability? *Can Meteorol Oceanogr Soci Bulle* 2010; **38:** 165–67.

245 Atta-ur-Rahman, Khan AN. Analysis of 2010-flood causes, nature and magnitude in the Khyber Pakhtunkhwa, Pakistan. *Nat Hazards* 2012; **66:** 887–904.

246 Hsiang SM, Burke M, Miguel E. Quantifying the influence of climate on human conflict. *Science* 2013; **341:** 1235367.

247 Imran Z. Climate change and its impact on the political dynamics of Pakistan. College Park, MD: Center for International and Security Studies, 2013.

248 IOM. Migration, environment and climate change: assessing the evidence. Geneva: International Organization for Migration, 2009.

249 UNHCR. Displacement the new 21st century challenge: UNHCR global trends 2012. The UN Refugee Agency, 2013.

250 Epule TE, Peng C, Lepage L. Environmental refugees in sub-Saharan Africa: a review of perspectives on the trends, causes, challenges and way forward. *GeoJournal* 2014; **80:** 79–92.

251 Ďurková P, Gromilova A, Kiss B, Plaku M. Climate refugees in the 21st century. Regional Academy on the United Nations. 2012. https://fusiondotnet.files.wordpress.com/2015/02/climate-refugees-1.pdf (accessed Dec 21, 2014).

252 CNA Military Advisory Board. National security and the accelerating risks of climate change. 2014. https://www.cna.org/reports/accelerating-risks (accessed July 20, 2014).

253 Kelley CP, Mohtadi S, Cane MA, Seager R, Kushnir Y. Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc Natl Acad Sci U S A* 2015; **112:** 3241–46.

254 Thomas SL, Thomas SD. Displacement and health. *Br Med Bull* 2004; **69:** 115–27.

255 Albrecht G, Sartore GM, Connor L, et al. Solastalgia: the distress caused by environmental change. *Australas Psychiatry* 2007; **15** (suppl 1): S95–98.

256 Brubaker M, Berner J, Chavan R, Warren J. Climate change and health effects in northwest Alaska. *Glob Health Action* 2011; **4:** 10.

257 Higginbotham N, Connor L, Albrecht G, Freeman S, Agho K. Validation of an environmental distress scale. *EcoHealth* 2007; **3:** 245–54.

258 Agyeman J, Devine-Wright P, Prange J. Close to the edge, down by the river? Joining up managed retreat and place attachment in a climate changed world. *Environ Plann A* 2009; **41:** 509–13.

259 Loughry M. Climate change, human movement and the promotion of mental health: what have we learnt from earlier global stressors? In: McAdam J, ed. Climate change and displacement: multidisciplinary perspectives. Portland, OR: Hart Publishing, 2010.

260 Jacob B, Mawson AR, Payton M, Guignard JC. Disaster mythology and fact: Hurricane Katrina and social attachment. *Public Health Rep* 2008; **123:** 555–66.

261 Tang B, Liu X, Liu Y, Xue C, Zhang L. A meta-analysis of risk factors for depression in adults and children after natural disasters. *BMC Public Health* 2014; **14:** 623.

262 Godfray HC, Garnett T. Food security and sustainable intensification. *Philos Trans R Soc Lond B Biol Sci* 2014; **369:** 20120273.

263 Conway G. One billion hungry, can we feed the world? Ithaca, NY: Comstock, 2012.

264 Nicolia A, Manzo A, Veronesi F, Rosellini D. An overview of the last 10 years of genetically engineered crop safety research. *Crit Rev Biotechnol* 2014; **34:** 77–88.

265 Chen X, Cui Z, Fan M, et al. Producing more grain with lower environmental costs. *Nature* 2014; **514:** 486–89.

266 Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S. Agricultural sustainability and intensive production practices. *Nature* 2002; **418:** 671–77.

267 Cookson J, Parker L, West PC. Feast or famine. *National Geographic*. 2013. http://ngm.nationalgeographic.com/2013/05/fertilized-world/nitrogen-flow-graphic (accessed May 8, 2015).

268 Carpenter SR, Bennett EM. Reconsideration of the planetary boundary for phosphorus. *Environ Res Lett* 2011; **6:** 014009.

269 FAO. Food wastage footprint Impacts on natural resources. Summary report. Rome: Food and Agriculture Organization, 2013.
270 The Government Office for Science. Foresight.the future of food and farming (2011) final project report. London: The Government Office for Science, 2011.
271 Atehnkeng J, Ojiambo PS, Ikotun T, Sikora RA, Cotty PJ, Bandyopadhyay R. Evaluation of atoxigenic isolates of *Aspergillus flavus* as potential biocontrol agents for aflatoxin in maize. *Food Addit Contam Part A Chem Anal Control Expo Risk Assess* 2008; **25:** 1264–71.
272 Searchinger T, Hanson C, Ranganathan J, et al. Creating a sustainable food future. A menu of solutions to sustainably feed more than 9 billion people by 2050. 2013. http://www.wri.org/sites/default/files/wri13_report_4c_wrr_online.pdf (accessed Dec 22, 2014).
273 Waite R, Beveridge M, Brummett R, et al. Improving productivity and environmental performance of aquaculture. World Resources Institute. June, 2014. http://www.wri.org/sites/default/files/wrr_installment_5_improving_productivity_environmental_performance_aquaculture.pdf (accessed Feb 15, 2015).
274 FAO. The state of world fisheries and aquaculture 2012. Rome: Food and Agriculture Organization, 2012.
275 Troell M, Naylor RL, Metian M, et al. Does aquaculture add resilience to the global food system? *Proc Natl Acad Sci USA* 2014; **111:** 13257–63.
276 FAO. Code of conduct for responsible fisheries. Rome: Food and Agriculture Organization, 1995.
277 Global Ocean Commission. From decline to recovery: a rescue package for the global ocean. 2014. http://www.globaloceancommission.org/wp-content/uploads/GOC_Report_20_6.FINAL_.spreads.pdf (accessed Dec 22, 2014).
278 Scientific report of the 2015 Dietary Guidelines Advisory Committee. Advisory report to the Secretary of Health and Human Services and the Secretary of Agriculture. 2015. http://www.health.gov/dietaryguidelines/2015-scientific-report/PDFs/Scientific-Report-of-the-2015-Dietary-Guidelines-Advisory-Committee.pdf (accessed March 29, 2015).
279 Bauch SC, Sills EO, Pattanayak SK. Have we managed to integrate conservation and development? ICDP Impacts in the Brazilian Amazon. *World Dev* 2014; **64:** S135–48.
280 Weber JG, Sills EO, Bauch S, Pattanayak SK. Do ICDPs work? An empirical evaluation of forest-based microenterprises in the Brazilian Amazon. *Land Econ* 2011; **87:** 661–81.
281 Dunne JP, Stouffer RJ, John JG. Reductions in labour capacity from heat stress under climate warming. *Nat Clim Chang* 2013; **3:** 563–66.
282 Av H. Itterbeeck JV, Klunder H, et al. Edible insects: future prospects for food and feed security. Rome: Food and Agriculture Organization, 2013.
283 van der Spiegel M, Noordam MY, van der Fels-Klerx HJ. Safety of novel protein sources (insects, microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production. *Compr Rev Food Sci Food Saf* 2013; **12:** 662–78.
284 Fowler C, Mooney P. The threatened gene: food, politics, and the loss of genetic diversity. Cambridge: Lutterworth Press, 1990.
285 Penafiel D, Lachat C, Espinel R, Van Damme P, Kolsteren P. A systematic review on the contributions of edible plant and animal biodiversity to human diets. *EcoHealth* 2011; **8:** 381–99.
286 Kennedy G, Burlingame B. Analysis of food composition data on rice from a plant genetic resources perspective. *Food Chem* 2003; **80:** 589–96.
287 Englberger L, Schierle J, Marks GC, Fitzgerald MH. Micronesian banana, taro, and other foods: newly recognized sources of provitamin A and other carotenoids. *J Food Compos Anal* 2003; **16:** 3–19.
288 Traoré M, Thompson B, Thomas G. Sustainable nutrition security: Restoring the bridge between agriculture and health. Rome: Food and Agriculture Organization, 2012.
289 De Steur H, Blancquaert D, Strobbe S, Lambert W, Gellynck X, Van Der Straeten D. Status and market potential of transgenic biofortified crops. *Nat Biotechnol* 2015; **33:** 25–29.
290 Béné C, Barange M, Subasinghe R, et al. Feeding 9 billion by 2050—putting fish back on the menu. *Food Security* 2015; **7:** 261–74.
291 Hallström E, Carlsson-Kanyama A, Börjesson P. Environmental impact of dietary change: a systematic review. *J Clean Prod* 2014; **91:** 1–11.
292 Siegel KR, Ali MK, Srinivasiah A, Nugent RA, Narayan KM. Do we produce enough fruits and vegetables to meet global health need? *PLoS One* 2014; **9:** e104059.
293 Vieux F, Soler LG, Touazi D, Darmon N. High nutritional quality is not associated with low greenhouse gas emissions in self-selected diets of French adults. *Am J Clin Nutr* 2013; **97:** 569–83.
294 Milner J, Green R, Dangour AD, et al. Health effects of adopting low greenhouse gas emission diets in the UK. *BMJ Open* 2015; **5:** e007364.
295 Jagger P, Atmadja S, Pattanayak SK, Sills EO. Learning while doing: evaluating impacts of REDD projects. In: Angelsen A, ed. Realizing REDD: national strategy and policy options. Bogor: Center for International Forestry, 2009: 283–92.
296 Snider AG, Pattanayak SK, Sills EO, Schuler JL. Policy innovations for private forest management and conservation in Costa Rica. *J For* 2003; **101:** 18–23.
297 Pattanayak SK, Wendland KJ. Nature's care: diarrhea, watershed protection, and biodiversity conservation in Flores, Indonesia. *Biodivers Conserv* 2007; **16:** 2801–19.
298 Bauch SC, Birkenbach AM, Pattanayak SK, Sills EO. Public health impacts of ecosystem change in the Brazilian Amazon. *Proc Natl Acad Sci USA* (in press).
299 Allan BF, Keesing F, Ostfeld RS. Effects of habitat fragmentation on Lyme disease risk. *Conserv Biol* 2003; **17:** 267–72.
300 Kim PS, Jacob DJ, Mickley LJ, et al. Sensitivity of population smoke exposure to fire locations in Equatorial Asia. *Atmos Environ* 2015; **102:** 11–17.
301 Miteva D, Loucks C, Pattanayak SK. In review. Impacts of forest certification in Indonesia. *PLoS One* (in press).
302 Chen L, Wei W, Fu B, Lu Y. Soil and water conservation on the Loess Plateau in China: review and perspective. *Prog Phys Geogr* 2007; **31:** 389–403.
303 Ma L. The study of poor-area change and off-poverty mechanism in Loess Plateau. *Econ Geogr* 2001; **21:** 23–27.
304 World Bank. Implementation completion report (IDA-26160) on a credit in the amount of SDR 106.3 million (US$ 150 million equivalent) to the People's Republic of China for a Loess Plateau Watershed Rehabilitation Project. 2003. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2003/05/01/000160016_20030501180454/Rendered/PDF/257011CN1Loess1d0Rehab0Project01ICR.pdf (accessed Dec 24, 2015).
305 Liu S, Gong P. Change of surface cover greenness in China between 2000 and 2010. *Chin Sci Bull* 2012; **57:** 2835–45.
306 Kang L, Wang Y, Wei Y. Forest and grass coverage change after the implementation of Loess Plateau Watershed Rehabilitation Project. *J Soil Water Conserv* 2009; **16:** 76–78.
307 UNDP. Shinyanga soil conservation programme (HASHI), Tanzania. 2012. http://equatorinitiative.org/images/stories/winners/83/casestudy/case_1348161099.pdf (accessed Nov 23, 2014).
308 Shindell D, Kuylenstierna JC, Vignati E, et al. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 2012; **335:** 183–89.
309 Wilkinson P, Smith KR, Davies M, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *Lancet* 2009; **374:** 1917–29.
310 Climate and Clean Air Coalition (CCAC). Scientific Advisory Panel Briefing: kerosene lamps and SLCPS. 2014. http://www.unep.org/ccac/Portals/50162/docs/ccac/NOV2014-SAP%20Kerosene%20briefing.pdf (accessed Dec 22, 2014).
311 Woodcock J, Edwards P, Tonne C, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *Lancet* 2009; **374:** 1930–43.
312 Goodman A, Brand C, Ogilvie D, iConnect consortium. Associations of health, physical activity and weight status with motorised travel and transport carbon dioxide emissions: a cross-sectional, observational study. *Environ Health* 2012; **11:** 52.
313 UN Environment Programme. Report on the costs of inaction on the sound management of chemicals. 2013. http://www.unep.org/chemicalsandwaste/Portals/9/Mainstreaming/CostOfInaction/Report_Cost_of_Inaction_Feb2013.pdf (accessed April 19, 2015).
314 Jepson PC, Guzy M, Blaustein K, et al. Measuring pesticide ecological and health risks in west African agriculture to establish an enabling environment for sustainable intensification. *Philos Trans R Soc Lond B Biol Sci* 2014; **369:** 20130491.

315 Arriagada RA, Sills EO, Pattanayak SK, Cubbage FW, González E. Modeling fertilizer externalities around Palo Verde National Park, Costa Rica. *Agric Econ* 2010; **41:** 567–75.

316 UN Environment Programme. Strategic approach to international chemicals management. 2006. http://www.saicm.org (accessed April 19, 2015).

317 UN—Department of Economic and Social Affairs Population Division. World urbanization prospects the 2009 revision. Highlights. New York: United Nations, 2010.

318 Jarrett J, Woodcock J, Griffiths UK, et al. Effect of increasing active travel in urban England and Wales on costs to the National Health Service. *Lancet* 2012; **379:** 2198–205.

319 Cheng JJ, Berry P. Health co-benefits and risks of public health adaptation strategies to climate change: a review of current literature. *Int J Public Health* 2013; **58:** 305–11.

320 Berry H. Pearl in the oyster: climate change as a mental health opportunity. *Australas Psychiatry* 2009; **17:** 453–56.

321 De Silva MJ, McKenzie K, Harpham T, Huttly SR. Social capital and mental illness: a systematic review. *J Epidemiol Community Health* 2005; **59:** 619–27.

322 Bowler D, Buyung-Ali L, Knight T, Pullin AS. The importance of nature for health: is there a specific benefit of contact with green space? *Environmental Evidence* 2010; CEE review 08-003 (SR40).

323 Elmqvist T, Fragkias M, Goodness J, et al, eds. Urbanization, biodiversity and ecosystem services: challenges and opportunities. Netherlands: Springer, 2013.

324 Bowler D, Buyung-Ali L, Knight T, Pullin AS. How effective is ‘greening’ of urban areas in reducing human exposure to ground level ozone concentrations, UV exposure and the ‘urban heat island effect’? *Environmental Evidence* 2010; CEE review 08-004 (SR41).

325 Haase D. Shrinking cities, biodiversity and ecosystem services. In: Elmqvist T, Fragkias M, Goodness J, et al, eds. Urbanization, biodiversity and ecosystem services: challenges and opportunities. Netherlands: Springer, 2013: 253–75.

326 Colding J. Local assessment of Stockholm: revisiting the Stockholm urban assessment. In: Elmqvist T, Fragkias M, Goodness J, et al, eds. Urbanization, biodiversity and ecosystem services: challenges and opportunities. Netherlands: Springer, 2013: 313–36.

327 McDonald RI, Shemie D. Urban water blueprint: mapping conservation solutions to the global water challenge. Washington, DC: The Nature Conservancy, 2014.

328 The Global Commission on the Economy and Climate. Better growth, better climate. The new climate economy report. 2014. http://newclimateeconomy.report/misc/downloads/ (accessed Oct 29, 2014).

329 Singh S, Darroch JE. Adding it up: costs and benefits of conraceptive services. estimates for 2012. New York: Guttmacher Institute and United Nations Population Fund, 2012.

330 O’Neill BC, Liddle B, Jiang L, et al. Demographic change and carbon dioxide emissions. *Lancet* 2012; **380:** 157–64.

331 Kimball AM, Heymann D. Ebola, International Health Regulations, and global safety. *Lancet* 2014; **384:** 2023.

332 UNICEF. In Ethiopia, a far-reaching health worker programme has helped reduce child mortality across the country. http://www.unicef.org/infobycountry/ethiopia_70372.html2013. (accessed Dec 21, 2014).

333 Jamison DT, Summers LH, Alleyne G, et al. Global health 2035: a world converging within a generation. *Lancet* 2013; **382:** 1898–955.

334 Redwood-Campbell L, Abrahams J. Primary health care and disasters-the current state of the literature: what we know, gaps and next steps. *Prehosp Disaster Med* 2011; **26:** 184–91.

335 Haines A, Epstein PR, McMichael AJ. Global health watch: monitoring impacts of environmental change. *Lancet* 1993; **342:** 1464–69.

336 Diboulo E, Sie A, Rocklov J, et al. Weather and mortality: a 10 year retrospective analysis of the Nouna Health and Demographic Surveillance System, Burkina Faso. *Glob Health Action* 2012; **5:** 6–13.

337 UN Conference on Environment and Development. Earth Summit ‘92. London: Regency Press, 1992.

338 Knox JH. Report of the Independent Expert on the issue of human rights obligations relating to the enjoyment of a safe, clean, healthy and sustainable environment. New York: United Nations, 2012.

339 Macpherson CC, Akpinar-Elci M. Caribbean heat threatens health, well-being and the future of humanity. *Public Health Ethics* 2015. Published online April 13. DOI: 10.1093/phe/phv008.

340 Ikeme J. Equity, environmental justice and sustainability: incomplete approaches in climate change politics. *Glob Environ Change* 2003; **13:** 195–206.

341 Woodward D. Incrementum ad absurdum: global growth, inequality and poverty eradication in a carbon-constrained world. *World Econ Rev* 2015; **4:** 43–62.

342 Raworth K. A safe and just space for humanity—can we live within the doughnut? 2012. https://www.oxfam.org/sites/www.oxfam.org/files/dp-a-safe-and-just-space-for-humanity-130212-en.pdf (accessed July 20, 2014).

343 Dearing JA, Wang R, Zhang K, et al. Safe and just operating spaces for regional social-ecological systems. *Glob Environ Change* 2014; **28:** 227–38.

344 Munich RE NatCatSERVICE. Loss events worldwide 1980–2013: 10 costliest events ordered by overall losses. 2014. https://www.munichreamerica.com/site/mram/get/documents_E-205039058/mram/assetpool.mr_america/PDFs/5_Press_News/Press/natcat012014/1980_2013_events_and_losses.pdf(accessed Feb 11, 2015).

345 Knabb R, Rhome J, Brown D. Hurricane Katrina: August 23–30, 2005 (tropical cyclone report). United States National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service. National Hurricane Center. December 20, 2005. http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf (accessed Nov 18, 2014).

346 Brunkard J, Namulanda G, Ratard R. Hurricane Katrina deaths, Louisiana, 2005. *Disaster Med Public Health Prep* 2008; **2:** 215–23.

347 Lane K, Charles-Guzman K, Wheeler K, Abid Z, Graber N, Matte T. Health effects of coastal storms and flooding in urban areas: a review and vulnerability assessment. *J Environ Public Health* 2013; **2013:** 913064.

348 American Society of Civil Engineers (ASCE) Hurricane Katrina External Review Panel. The New Orleans hurricane protection system: what went wrong and why: Reston, VA: ASCE, 2007. http://web.archive.org/web/20070702194739/http://www.asce.org/files/pdf/ERPreport.pdf 2007 (accessed Nov 19, 2014).

349 Bush GW. Statement on federal emergency assistance for Louisiana. White House Office of the Press Secretary. August 27, 2005. http://georgewbush-whitehouse.archives.gov/news/releases/2005/08/20050827-1.html (accessed Nov 19, 2014).

350 Wohlson B. Evacuation planning and engineering for hurricane Katrina. *The Bridge* 2006; **36:** 27–34.

351 US Government. The federal response to Hurricane Katrina: lessons learned. 2006. http://georgewbush-whitehouse.archives.gov/reports/katrina-lessons-learned/ (accessed Nov 19, 2014).

352 Federal Emergency Management Agency. The National Response Framework (NRF): 2nd edition. Department of Homeland Security. May, 2013. http://www.fema.gov/media-library-data/20130726-1914-25045-1246/final_national_response_framework_20130501.pdf (accessed Nov 19, 2014).

353 Costanza R, Mitsch WJ, Day JW Jr. A new vision for New Orleans and the Mississippi delta: applying ecological economics and ecological engineering. *Front Ecol Environ* 2006; **4:** 465–72.

354 Costanza R, Pérez-Maqueo O, Martinez ML, Sutton P, Anderson SJ, Mulder K. The value of coastal wetlands for hurricane protection. *Ambio* 2008; **37:** 241–48.

355 Day JW Jr, Boesch DF, Clairain EJ, et al. Restoration of the Mississippi Delta: lessons from Hurricanes Katrina and Rita. *Science* 2007; **315:** 1679–84.

356 Nelson DR, Adger WN, Brown K. Adaptation to environmental change: contributions of a resilience framework. *Annu Rev Environ Resour* 2007; **32:** 395–419.

357 Klinger C, Landeg O, Murray V. Power outages, extreme events and health: a systematic review of the literature from 2011–2012. *PLoS Curr* 2014; **6:** 6.

358 Kruk ME, Myers M, Varpilah ST, Dahn BT. What is a resilient health system? Lessons from Ebola. *Lancet* 2015; **385:** 1910–12.

359 Toloo GS, Fitzgerald G, Aitken P, Verrall K, Tong S. Are heat warning systems effective? *Environ Health* 2013; **12:** 27.

360 World We Want. An analysis of the impact of the floods on MDGs in Pakistan. 2011. http://www.worldwewant2015.org/file/311136/download/338159 (accessed Dec 24, 2014).

361 IFRC. Mangrove planting saves lives and money in Viet Nam. New York: International Federation of Red Cross and Red Crescent Societies, 2002.

362 Medlock JM, Vaux AGC. Assessing the possible implications of wetland expansion and management on mosquitoes in Britain. *Eur Mosq Bull* 2011; **29:** 38–65.

363 UNFCCC. Decision 28/CP.7. Guidelines for the preparation of national adaptation programmes of action. Jan 21, 2001. http://unfccc.int/resource/docs/cop7/13a04.pdf (accessed Feb 14, 2015).

364 Thompson TM, Rausch S, Saari RK, Selin NE. A systems approach to evaluating the air quality co-benefits of US carbon policies. *Nat Clim Chang* 2014; **4:** 917–23.

365 West JJ, Smith SJ, Silva RA, et al. Co-benefits of global greenhouse gas mitigation for future air quality and human health. *Nat Clim Chang* 2013; **3:** 885–89.

366 Parry I, Veung C, Heine D. How much carbon pricing is in countries' own interests? The critical role of co-benefits. Washington, DC: International Monetary Fund, 2014.

367 Whitehead JC, Pattanayak SK, Van Houtven GL, Gelso BR. Combining revealed and stated preference data to estimate the nonmarket value of ecological services: an assessment of the state of the science. *J Econ Surv* 2008; **22:** 872–908.

368 Van Houtven G, Powers J, Pattanayak SK. Valuing water quality improvements in the United States using meta-analysis: is the glass half-full or half-empty for national policy analysis? *Resour Energy Econ* 2007; **29:** 206–28.

369 Smith VK, Pattanayak SK, Van Houtven GL. Structural benefit transfer: An example using VSL estimates. *Ecol Econ* 2006; **60:** 361–71.

370 Pattanayak SK, Pfaff A. Behavior, environment, and health in developing countries: evaluation and valuation. *Annu Rev Resour Economics* 2009; **1:** 183–217.

371 Sturm R, An R, Segal D, Patel D. A cash-back rebate program for healthy food purchases in South Africa: results from scanner data. *Am J Prev Med* 2013; **44:** 567–72.

372 Hamoudi A, Jeuland M, Lombardo S, Patil S, Pattanayak SK, Rai S. The effect of water quality testing on household behavior: evidence from an experiment in rural India. *Am J Trop Med Hyg* 2012; **87:** 18–22.

373 Pattanayak SK, Yang J-C, Dickinson KL, et al. Shame or subsidy revisited: social mobilization for sanitation in Orissa, India. *Bull World Health Organ* 2009; **87:** 580–87.

374 Biran A, Schmidt W-P, Varadharajan KS, et al. Effect of a behaviour-change intervention on handwashing with soap in India (SuperAmma): a cluster-randomised trial. *Lancet Glob Health* 2014; **2:** e145–54.

375 Free C, Phillips G, Galli L, et al. The effectiveness of mobile-health technology-based health behaviour change or disease management interventions for health care consumers: a systematic review. *PLoS Med* 2013; **10:** e1001362.

376 Jacobson MZ. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *J Geophys Res* 2002; **107:** ACH 16-1–ACH 16-22.

377 Marteau TM, Hollands GJ, Fletcher PC. Changing human behavior to prevent disease: the importance of targeting automatic processes. *Science* 2012; **337:** 1492–95.

378 Raskin PD, Electris C, Rosen RA. The century ahead: searching for sustainability. *Sustainability* 2010; **2:** 2626–51.

379 Coyle D. GDP: a brief but affectionate history. Princeton and Oxford: Princeton University Press, 2014.

380 Stiglitz J, Sen A, Fitoussi J-P. The measurement of economic performance and social progress revisited. Reflections and overview. Commission on the Measurement of Economic Performance and Social Progress. 2009. http://www.stiglitz-sen-fitoussi.fr/documents/overview-eng.pdf (accessed March 30, 2015).

381 Dasgupta P. Human well-being and the natural environment, 2nd edn. Oxford: Oxford University Press, 2001.

382 Arrow K, Dasgupta P, Goulder L, et al. Are we consuming too much? *J Econ Perspect* 2004; **18:** 147–72.

383 UN General Assembly. Happiness: towards a holistic approach to development. Note by the Secretary-General. 2013. http://www.un.org/esa/socdev/ageing/documents/NOTEONHAPPINESSFINALCLEAN.pdf (accessed April 19, 2015).

384 Natural Capital Initiative. Ecosystem services and the delivery of health benefits: Towards optimised health and environment planning. Summary report for policy makers based on a workshop held on 28th September, 2010. 2011. http://www.naturalcapitalinitiative.org.uk/wp-content/uploads/2014/06/NCI-ESandH-report-2.pdf (accessed Oct 29, 2014).

385 Sukhdev P, Wittmer H, Miller D. The economics of ecosystems and biodiversity (TEEB): challenges and responses. In: Helm D, Hepburn C, eds. Nature in the balance: the economics of biodiversity. Oxford: Oxford University Press, 2014.

386 Dasgupta P. Nature's role in sustaining economic development. *Philos Trans R Soc Lond B Biol Sci* 2010; **365:** 5–11.

387 Talberth J, Cobb C, Slattery N. The genuine progress indicator 2006. A tool for sustainable development. 2006. http://genuineprogress.net/resources/the-genuine-progress-indicator-2006/ (accessed Dec 23, 2014).

388 Porter ME, Stern S. Social progress index 2014: social progress imperative, 2014. http://www.socialprogressimperative.org/publications (accessed July 20, 2014).

389 New Economics Foundation. The happy planet index: 2012 report. A global index of sustainable well-being. 2012. http://www.happyplanetindex.org/assets/happy-planet-index-report.pdf (accessed Dec 23, 2014).

390 Costanza R, Kubiszewski I, Giovannini E, et al. Development: time to leave GDP behind. *Nature* 2014; **505:** 283–85.

391 Bond T, Lang K. The sad truth about happiness scales. Working paper 19950: National Bureau of Economic Research. 2014. http://www.nber.org/papers/w19950 (accessed Dec 23, 2014).

392 Organisation for Economic Co-operation and Development. Environmental taxation a guide for policy makers. 2011. http://www.oecd.org/env/tools-evaluation/48164926.pdf (accessed April 19, 2015).

393 Yates R. Recycling fuel subsidies as health subsidies. *Bull World Health Organ* 2014; **92:** 547A.

394 Ferraro PJ, Lawlor K, Mullan KL, Pattanayak SK. Forest figures: ecosystem services valuation and policy evaluation in developing countries. *Rev Environ Econ Policy* 2011; **6:** 20–44.

395 The McKinsey Global Institute, McKinsey & Company's Sustainability & Resource Productivity Practice. Resource revolution: meeting the world's energy, materials, food, and water needs. 2011. http://www.mckinsey.com/insights/energy_resources_materials/resource_revolution (accessed April 19, 2015).

396 IMF. Energy subsidy reform: lessons and implications. Washington, DC: International Monetary Fund, 2013.

397 IEA. World energy outlook. Paris: International Energy Agency, 2011.

398 Coady D, Parry I, Sears L, Shang B. IMF Working paper. WP/15/105. How large are global energy subsidies? May, 2015. http://www.imf.org/external/pubs/ft/wp/2015/wp15105.pdf (accessed June 10, 2015).

399 Pachauri S. Household electricity access a trivial contributor to CO2 emissions growth in India. *Nat Clim Chang* 2014; **4:** 1073–76.

400 Withana S, ten Brink P, Franckx L, et al. Study supporting the phasing out of environmentally harmful subsidies. A report by the Institute for European Environmental Policy (IEEP), Institute for Environmental Studies—Vrije Universiteit (IVM), Ecologic Institute and Vision on Technology (VITO) for the European Commission—DG environment. Final report. Brussels. 2012. http://ec.europa.eu/environment/enveco/taxation/pdf/report_phasing_out_env_harmful_subsidies.pdf (accessed Dec 22, 2014).

401 Starmer C. Developments in non-expected utility theory: the hunt for a descriptive theory of choice under risk. *J Econ Lit* 2000; **38:** 332–82.

402 Chichilnisky G. An axiomatic approach to choice under uncertainty with catastrophic risks. *Resour Energy Econ* 2000; **22:** 221–31.

403 Polasky S, Carpenter SR, Folke C, Keeler B. Decision-making under great uncertainty: environmental management in an era of global change. *Trends Ecol Evol* 2011; **26:** 398–404.

404 Jeuland MA, Pattanayak SK. Benefits and costs of improved cookstoves: assessing the implications of variability in health, forest and climate impacts. *PLoS One* 2012; **7:** e30338.

405 Kinzig AP, Perrings C, Chapin FS 3rd, et al. Sustainability. Paying for ecosystem services—promise and peril. *Science* 2011; **334:** 603–04.

406 Spiegelhalter D, Pearson M, Short I. Visualizing uncertainty about the future. *Science* 2011; **333:** 1393–400.

407 Galaz V. Global environmental governance, technology and politics: the Anthropocene gap. Cheltenham, UK: Edward Elgar, 2014.

408 Butzer KW, Endfield GH. Critical perspectives on historical collapse. *Proc Natl Acad Sci USA* 2012; **109:** 3628–31.

409 Butzer KW. Collapse, environment, and society. *Proc Natl Acad Sci USA* 2012; **109:** 3632–39.

410 Conway EM, Oreskes N. Merchants of doubt: how a handful of scientists obscured the truth on issues from tobacco smoke to global warming. New York: Bloomsbury Press, 2010.
411 Ottersen OP, Dasgupta J, Blouin C, et al. The political origins of health inequity: prospects for change. *Lancet* 2014; **383:** 630–67.
412 Biermann F, Abbott K, Andresen S, et al. Science and government. Navigating the anthropocene: improving Earth system governance. *Science* 2012; **335:** 1306–07.
413 Sunstein C. Of Montreal and Kyoto: a tale of two protocols. *HELR Harvard Environ Law Rev* 2007; **31:** 1–66.
414 Summary EPA. North American 2014 HFC submission to the Montreal protocol. http://www.epa.gov/ozone/downloads/HFC_Amendment_2014_Summary.pdf (accessed March 18, 2015).
415 Friel S, Gleeson D, Thow AM, et al. A new generation of trade policy: potential risks to diet-related health from the trans pacific partnership agreement. *Global Health* 2013; **9:** 46.
416 UNAIDS. Report on the global HIV/AIDS epidemic. June, 2000. http://data.unaids.org/pub/Report/2000/2000_gr_en.pdf (accessed Feb 13, 2015).
417 Ostrom E. Beyond markets and states: polycentric governance of complex economic systems. *Am Econ Rev* 2010; **100:** 641–72.
418 UN. Open Working Group proposal for Sustainable Development Goals. New York: United Nations, 2014.
419 ISSC I. Review of the Sustainable Development Goals: the science perspective. 2015. http://www.icsu.org/publications/reports-and-reviews/review-of-targets-for-the-sustainable-development-goals-the-science-perspective-2015 (accessed March 15, 2015).
420 Rah JH, Cronin AA, Badgaiyan B, Aguayo VM, Coates S, Ahmed S. Household sanitation and personal hygiene practices are associated with child stunting in rural India: a cross-sectional analysis of surveys. *BMJ Open* 2015; **5:** e005180.
421 Waage J, Yap C, Bell S, et al. Governing the UN Sustainable Development Goals: interactions, infrastructures, and institutions. *Lancet Glob Health* 2015; **3:** e251–52.
422 Mace GM, Hails RS, Cryle P, Harlow J, Clarke SJ, Manning P. Review: towards a risk register for natural capital. *J Appl Ecol* 2015; **52:** 641–53.
423 Future Earth—who we are. 2014. http://www.futureearth.org/who-we-are (accessed 22 Dec 2014).
424 Koppelaar R, Kunz H, Ravale T. Review of current advanced integrated models for city-regions. London: The Ecological Sequestration Trust, 2013.
425 Passmore S, Schmidt A. January 2015 status report. Report to DIFID and Cities Alliance. London: The Ecological Sequestration Trust, 2015.
426 The Secretary-General's Independent Expert Advisory Group on a Data Revolution for Sustainable Development. A world that counts: mobilising the data revolution for sustainable development. http://www.undatarevolution.org/report/ (accessed Feb 14, 2015).
427 Nature. Climate and earth system modelling. http://www.nature.com/subjects/climate-and-earth-system-modelling (accessed Feb 14, 2015).
428 WorldPop. 2015. http://www.worldpop.org.uk (accessed Feb 14, 2015).
429 Evans MR. Modelling ecological systems in a changing world. *Philos Trans R Soc Lond B Biol Sci* 2012; **367:** 181–90.
430 Fischer J, Peterson GD, Gardner TA, et al. Integrating resilience thinking and optimisation for conservation. *Trends Ecol Evol* 2009; **24:** 549–54.
431 Global Reporting Initiative. Sustainability reporting framework. https://www.globalreporting.org (accessed Feb 13, 2015).
432 Robeco SAM. Dow Jones sustainability indices. http://www.sustainability-indices.com/about-us/dow-jones-sustainabilityindices.jsp (accessed Feb 13, 2015).