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Environmental Health, Planetary Boundaries and Limits to Growth

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Glossary

Anthropocene The human-dominated era in which we now live. There is debate over when this started, but the most widespread views are either the mid-18th century when carbon dioxide levels started to rise sufficiently to alter Earth System function, due to the Industrial Revolution, or the first human created nuclear explosion, in 1945. The word combines the root "anthropo," meaning "human" with the root "-cene", the standard suffix for "epoch" in geologic time.

Ecosystem services The benefits or "services" which ecosystems (functionally linked combinations of species) provide to humans, either indirectly or directly. These are normally grouped into four: "supporting" (e.g. soil formation, nutrient recycling, and water purification), "provisioning" (e.g. food or fiber from crops or forests), "regulating" (e.g. the reduction in the harm, "provided" by forests, wetlands and mangroves against floods, landslides, droughts and tsunamis), and "cultural" (e.g. aesthetic, recreational and spiritual benefits that humans derive from contact with some forms of nature).

Energy return on energy investment The ratio of useful energy obtained to the energy expended in obtaining that useful energy. The concept is particularly associated with the work of systems ecologist Charles A.S. Hall.

Health A word derived from "whole" referring to a desired and robust, resilient state of function, normally of humans, animals or plants, both individually and as populations. Some also apply the term to ecosystems, or even the Earth System.

Limits to growth The name of a study, commissioned by the Club of Rome and published as a book in 1972. It summarizes modelling work that explored the complex interactions between human civilization and the physical world in which it is inextricably embedded. The book's title reflects its main conclusion: on a finite planet, despite abundant solar energy, growth of the human enterprise is not infinite.

Novel entity A term introduced and defined in 2015 as a planetary boundary, evolving from chemical pollution in previous planetary boundary publications. It was defined as "forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects."

Planetary boundaries Earth System processes, modifiable by human actions, whose boundaries, if not exceeded, constitute a "safe operating space for humanity". This term, first published in 2009, is conceptually linked to the Limits to Growth framework.

The Limits to Growth (LTG)

The Limits to Growth (1972) was commissioned by the Club of Rome and written by a research team led by Donella Meadows, at the Massachusetts Institute of Technology (MIT). It was not the first work to grapple with the idea that physical limits apply to the human economic and social system, but it drew extensive attention and remains the best-selling environmental book of all time. The book summarized outcomes of modeling work that explored the complex interactions between human civilization and the physical world in which it is inextricably embedded. The MIT team concluded that significant systemic problems were emerging from accelerating industrialization, population growth, under-nutrition, the depletion of non-renewable resources and environmental contamination and decline.

Pollution was taken as the principal indicator of environmental decline. Specific pollutants that were well-measured at the time included carbon dioxide concentrations, nuclear wastes, dichlorodiphenyltrichloroethane (DDT) production, lead in the Greenland icecap and mercury consumption. Direct environmental decline was also seen in marine settings: diminishing dissolved oxygen in oceans, eutrophication of waterways and falling catches of wild fish in some regions. Land-use change (although a significant contributor to rising carbon dioxide (CO₂) levels in the atmosphere then as now) and biodiversity loss were both less conspicuous problems in 1970 than they have since become; though a crisis in available arable land was then acknowledged. But the team stressed the general ignorance at that time of where the planetary limits would lie.

The model (known as World3 and based on a version developed by the pioneering systems analyst Jay Forrester) was run with various combinations of the data, ranging from "business as usual," through numerous partial improvements, to two final scenarios in which population was stabilized, the expansion of industrial production was halted, resources were conserved, and advanced, pollution-sparing technologies were extensively applied. These last runs, where all ameliorative options were adopted, were the

only ones that allowed civilization to continue without crisis. If the human economy maintained business as usual, the team found, it would collide with the physical realities of a finite planet by the second half of the 21st century, triggering social collapse.

Initially, the book received a positive response and some of the recommendations were adopted by several countries. Canadian Prime Minister Pierre Trudeau and US President Jimmy Carter each commissioned studies of the impact of physical limits on the global future and their national prospects. Although these studies examined the outlook only as far as 2000, their conclusions to that date confirmed those of the original LTG study. Right from the start, however, economists were critical, even abusive, creating a negative impression that persists in some quarters, today—despite the rapidly accumulating evidence of the basic robustness of the LTG projections and assumptions. Robert Gillette, who attended the LTG launch for the journal *Science*, noted that the “assumption of inevitable economic growth” represents “the very foundation” of economics. Any “limit” to growth challenged this foundation. It is unsurprising that most economists attacked the ideas vigorously, an assault that illustrates the conflict between the core assumptions of economists and those of the physical sciences.

Economics adopts a standard model where production and consumption exist in a circular flow, without a natural context. It is a world of business and individual, producer and consumer, labor and goods. The physical world, which supplies resources and provides a site where wastes can be discharged, is not seen as essential and does not affect the equations, though, occasionally, the concept of “externalities” (which can be negative or positive) is mentioned.

Ecological economists reject the argument that human activity is independent of nature, which they consider a conceit. Instead, nature is accepted as the indispensable foundation of human activities. Physics really matters; questions of depletion and pollution are inescapable.

Several researchers have compared the MIT projections with what has actually happened since, establishing that the correlation between the standard run and real world trends over the intervening years is extremely close. One of these researchers, Graham Turner, compared the standard run’s modeled trajectory with 40 years of historical data (see Fig. 1). He concluded that the data for 1970–2010 approximated the standard run of the LTG model, although the figure shows a slight but favorable divergence for the trajectory of non-renewable resources, such as fossil fuels, phosphate and concentrated, rich sources of ores.

Systems ecologists Charles Hall and John Day also compared the standard run with actual data to 2008. Despite the common perception that the LTG work had failed, the model’s performance was not invalidated, unlike models made by economists which are rarely, if ever, accurate over such a long time span. In 2018, Jørgen Randers, part of the original LTG team, using an updated model, compared the LTG projections with real world data up to 2017. He found that real world outcomes have approximated the second LTG scenario, the “standard run with extra resources,” or “pollution crisis.”

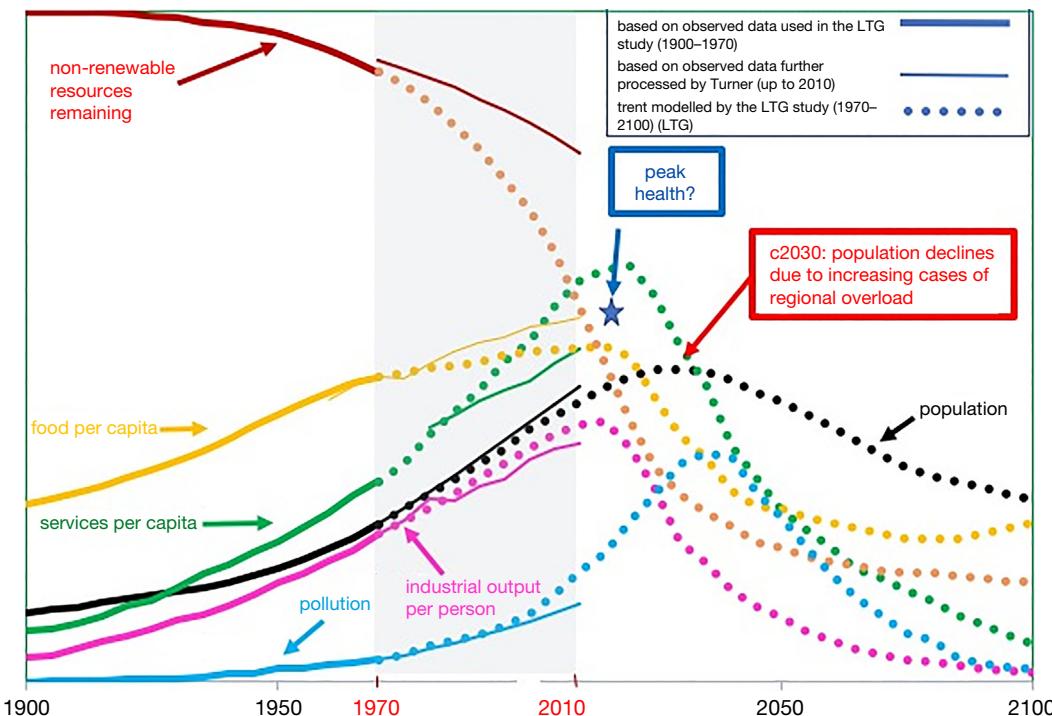


Fig. 1 Adapted from Turner, this figure shows the standard run of the LTG model over 200 years. It is based on real data for 1900–2010; analyzed by Meadows et al. for 1900–70 and updated by Turner with data to 2010. It also introduces the concept of “peak health.” This is the point at which human population well-being reaches its zenith, if the LTG model (of decline this century) proves reliable. Although the timing is imprecise, peak health will precede the exact moment of maximum population. Peak health and unwanted population decline are not inevitable; even today they could be postponed, perhaps indefinitely, by enlightened policies and technological breakthroughs.

Many resource analysts have identified declining “energy return on energy investment” as a key to understanding the slowing of the rate of improvement of living standards for most people in high-income countries. In turn, these indicators reflect the decline in easily accessible fossil fuels. This subject will be returned to.

It is important to understand that the broad trends described in the figure and used in the LTG model do not capture the entire world. No model can. These trends were chosen because they captured many aspects of the material world, both human and natural, including feedback loops and potential crises that might threaten the human economy and thus wellbeing. Indicators of these trends were chosen for a number of reasons, including researchers’ attempts to choose representative indicators that would faithfully reflect the trends, the need for parsimony and, especially back in 1972, the difficulty of finding accurate data.

The decline in population that is modeled is a logical consequence of the decline in resources per capita, whether non-renewable, or as food, industrial output and services. If these inputs decline, the modelers assume, so will human population, which depends on them.

The Ecological Footprint

The concept of the ecological footprint is among the most important developments in thinking related to the LTG. Devised in the 1990s by William Rees and Mathis Wackernagel, this measure enables ecological impacts (individual, national or global) to be quantified and compared. On one hand, it estimates the ecological assets required to produce the resources consumed by any discrete population; this includes food and fiber plants, livestock and fish, timber and other forest products, space for urban infrastructure and whatever “sinks” are needed to absorb the waste produced, especially carbon dioxide emissions. The unit of measurement adopted is the area of biologically productive land and water, usually expressed in hectares. On the other hand, the ecological footprint also estimates the productivity of a country’s actual ecological assets (cropland, grazing land, forest land, fishing grounds, and built-up land). Researchers using the ecological footprint methodology calculated that, while the world’s biocapacity averages 1.7 ha. per capita, high-income “developed” countries greatly exceed this average. Examples include the United States (8.8 ha. per capita) and the United Kingdom (5.1 ha. per capita). The US, which has far more productive land available than the United Kingdom, appropriates 1.27 times its own biocapacity through imports, and the United Kingdom almost three times. Many island nations and arid countries such as Saudi Arabia exceed their biocapacity by a factor of more than ten. The ecological footprint has the strengths and weaknesses of any aggregate indicator: the concepts and units are easy to understand by policy-makers and the public, but it does not encompass all aspects of human environmental impact (methane, e.g., is not integrated). This matrix needs to be used in conjunction with other indicators.

Another related development is the framework called “planetary boundaries,” devised by a large team led by Johan Rockström (see following section).

The Relevance of LTG to Environmental Health

Although the environmental health literature has long identified links between health and indicators used in the LTG model, such as food, services, and pollution, there has been little recognition among the health community, including within public health, of the possibility of a reduction in population this century. Such reductions, as mentioned above, are forecast by most LTG scenarios, including the standard run (see [Fig. 1](#)). Such a reduction, were it to occur, will have impacts on public health.

There are a few exceptions to this generalization. In 1972, the human ecologist Frederick Sargent, in an article in the American Journal of Public Health, warned that human “interventions in and manipulations of the processes of the planetary life support-system (ecosystem) have produced a set of complex problems” (page 629). In 1973, the visionary socialist economist Barbara Ward co-authored “Only One Earth” with the microbiologist, pioneering “Earth physician” and Pulitzer Prize winner, René Dubos. This book stated in part “the charge to the [1972 Stockholm] Conference was clearly to define what should be done to *maintain the earth as a place suitable for human life not only now, but also for future generations*” (emphasis added) (page xiii). Health is implicit in this statement, as is sustainable development.

In 1993 McMichael, who was influenced by Dubos, echoed Sargent’s term, writing in the foreword to his influential book Planetary Overload, that “The most serious potential consequence of global environmental change is the erosion of Earth’s life-support systems. Yet, curiously, the nature of this threat to the health and survival of the world’s living species—including our own—has received little attention” (page xiii). A quarter of a century later, little has changed. Although keynote talks by McMichael and John Last at the 1993 conference of the International Epidemiological Association warned of the dangers to global public health of global environmental change, there has been barely any recognition or follow up, at the broad integrated dimension.

LTG receives little recognition now. A literature search for the term “limits to growth” in association with “health” reveals little other than work involving the authors of this contribution and their close collaborators. This is unfortunate. The persistence of single-issue approaches to address complex problems retards our ability to act effectively. This is the case where there is singular focus on climate change. The impact on human health and wellbeing is modified by many interacting factors—including population, global demand and availability of resources and services and the waste and pollution we generate. Other than noting the exponential growth of carbon dioxide in the atmosphere, LTG did not address climate change as such, but it modeled these factors as part of a complex system.

Although infrequently, the issues of resource depletion and population pressure have featured in some medical curricula, from at least the 1950s, preceding publication of the LTG by over a decade. Pioneering writers and speakers have included Colin Bertram, Peter Parsons, and Roger Short. John Guillebaud, the world's first clinician professor of family planning and reproductive health, has repeatedly spoken on the issue of both consumption and population, to diverse audiences including medical practitioners, nurses, medical students and others, since 1971.

In 2011, a special issue of the American Journal of Public Health focussed on peak oil, an important aspect of LTG. A scattering of other articles in the health literature have mentioned peak oil, but LTG is far more than peak oil. It is also far more than global warming.

The reasons for the general failure of the public health literature to engage with LTG are complex but include an incorrect belief that LTG was discredited, over-specialization within the public health community, political suppression of the core ideas, and a lack of funders. The issue has had very few champions. This lack of engagement is not from lack of evidence.

Planetary Boundaries and Health

The term planetary boundaries (PBs) was first published in 2009. These boundaries were defined, initially, as referring to nine Earth System processes (see **Table 1**), each of which had been, is and will be modified by human actions. The first planetary boundary paper (published in 2009 in *Ecology and Society*, subtitled "exploring the safe operating space for humanity") explicitly acknowledges its debt to the LTG framework. A "safe operating space" implies the existence of multi-dimensional limits, just as does the word "boundaries". Nonetheless, the links between PBs and the LTG are mostly implicit.

Although the focus of the PB work is on identifying the criteria for a "safe operating space" for humanity, rather than that of other living species, the concept acknowledges that humans depend on the diversity of life on Earth. The first PB argued to be outside the safe operating space is biological diversity.

Analogous to nine bodily systems (renal, hepatic, neurological and so on) the large multidisciplinary team (29 co-authors) that was responsible for the first PB articles argued that these Earth System processes can still provide useful services, even if functioning outside their optimal range. However, pushed too far, even one aberrant bodily function can cause death, and just one extremely disturbed Earth System process might trigger catastrophic consequences for humanity. Perhaps, for example, a precipitous loss of insects could disrupt pollination, food supply, and the survival of birds and other vertebrates. In turn, loss of birds might trigger additional crop losses, as their biological control of insects and other pests (i.e., of pests that do survive) is lost. Another example is the reduced complexity of the microbiome of those who live in cities and other modified environments. This in turn has been hypothesized to be a causal role in the emergence of auto-immune diseases such as Type 1 diabetes.

Further, just as with bodily processes, Earth System components are linked to, interact with, and are influenced by common causes. Humans may live for decades with chronic illness, but die quickly if multi-organ failure develops. So too, Earth System processes interact, but exceeding multiple planetary boundaries, either simultaneously or in close proximity, risks precipitating a steep decline towards a civilization-crippling condition. Other writers have also commented on the similarities between the Earth and the human system, including James Lovelock, the originator of the Gaia hypothesis and an early user of the term "planetary medicine."

Table 1 shows links between planetary boundaries, LTG and human health.

Table 1 Links between planetary boundaries, LTG indicators and health impacts

<i>Planetary boundary (PB) direct link to LTG indicator (italicized, brackets)</i>	<i>Most obvious connections with other PBs</i>	<i>Indirect link with other key LTG indicators</i>	<i>Link with human health discussed here?</i>
Aerosol loading (<i>pollution</i>)	Climate change, novel entities	Industrial output, food production (fossil fuels required for both)	No
Biodiversity loss—terrestrial, marine	Land use, climate change	Food per person, to nourish growing population	Yes
Biogeochemical flows (N, P)	Land use	Food per person, population size	No
Climate change (<i>pollution effect</i>)	Ocean acidification, land use	Food and industrial output	Yes
Freshwater use	Land use	Food, industrial output per person, population	No
Land system change	Climate change, biodiversity loss, biogeochemical flows	Food per person	Yes
Novel entities (<i>pollution</i>)	Chemical pollution	Industrial output, food per person	Yes
Ocean acidification (<i>pollution effect</i>)	Climate change	Pollution	No (effect on marine foodchain)
Stratospheric ozone depletion (<i>pollution effect</i>)	Novel entities	Pollution	Yes

The exact extent to which we are breaching planetary boundaries is still being explored. The team's 2015 paper argued that two problems are already extremely dangerous (red zone) and two others are well on the way (amber zone), also noting that the designated boundaries are inter-related and most have overlapping implications.

Planetary Boundaries Red Zone: Biosphere Integrity

The team considers loss of biosphere integrity as the most critical problem. Rates of extinction are reckoned to be at least 100 times the background rate, possibly as much as 10,000 times. Populations of vertebrate species declined by more than half between 1970 and 2012 and the biomass of wild mammals is now only about 2% of the total, which is dominated by humans and livestock. That remaining 2% is under siege, including for substances such as rhinoceros horns and pangolin scales, which have alleged therapeutic benefit, even though chiefly constituted of keratin, just as are fingernails. Biological diversity of lower order organisms (within soils, among pollinators, and in the species traditionally utilized for plant-origin food, resources and medicines) are similarly in decline. Also under deliberate attack are forests, especially species with valuable timber, or growing on land that can be used for crops, including oil palm. Many forests are also at unintended risk, due to roads and global warming, each of which also exacerbates the risk of fire. Global warming is also likely to further hasten biodiversity loss. In some cases biodiversity decline and climate change, acting together or independently, also promote the survival of new pests. Infestations of tree borers, able to survive warmer winters in large numbers, render trees, forests and their associated animal life more vulnerable to disease and fire.

Humans, a form of life, depend on the fabric of other life on earth for their survival—for food, clean air and water, and numerous other ecosystem "services" (see glossary and below), as well as for novel substances, including drugs. At some level of bio-alteration the reduction in ecosystem services will reduce in a non-linear way that could cascade in a manner harmful to all civilization. Smaller scaled examples include the collapse of regional fisheries or the decimation of regional harvests by novel diseases or pests, such as in Ireland in the late 1840s. The Khapra beetle, a pest from South Asia that has evolved insecticide resistance threatens significant (up to 30%) loss of rice, post-harvest, in some regions. Devastating drought in the "dry corridor" of Guatemala, El Salvador and Honduras has been blamed for contributing to the influx of migrants attempting to enter the United States between 2014 and the present (2019).

Planetary Boundaries Red Zone: Biogeochemical Cycles

For Rockström, Steffen and colleagues the second most pressing danger is the radical disruption of the biogeochemical cycles, particularly nitrogen and phosphorous. In nature, most nitrogen was inert in the atmosphere, though some was mobilized by bacteria and leguminous plants. Applied as fertilizer, nitrogen has greatly expanded food production, but is now cascading through our rivers, groundwater and continental shelves, initiating algal blooms and dead zones. In the case of phosphorous, the other widely dispersed fertilizer, there is an added danger—phosphate rock is a resource in decline, with grim implications for future agriculture, especially where populations will lack the financial capacity to import it, as prices rise.

Planetary Boundaries Amber Zone: Land-System Change

Land-system change is argued to be in the "amber zone," close to crossing the boundary into extreme danger, if it has not already crossed it. Millions of hectares of vegetation are still being cleared every year and wetlands continue to be drained. Stocks of "blue carbon," stored in plants and trees associated with water, such as kelp and mangroves, are also under threat.

Land-system changes enable more food, fiber and other financially valued products to be grown, but amplify the harm to several PBs: biological integrity, climate and biogeochemical cycles. Oil palm plantations are displacing tropical forests in Asia, Africa and, increasingly, Latin America, where clearing already provides cattle pasture, soybean and sugar cane. Such plantations involve the death of vast numbers of individual animals and the annihilation of immense tracts of tropical forest. This boundary is underpinned by the declining remainder of tropical, temperate and boreal forests. These forests have a major role in land surface-climate coupling.

In addition, agricultural land-system change may ultimately result in land degradation giving rise to erosion, loss of topsoil, sedimentation of waterways and degradation of coastal zones. In dryland regions, degradation is referred to as desertification. Large areas are affected. The United Nations Organization considers that 1 billion people are at risk of desertification globally, half of whom live in Africa where they face major challenges to water and food security.

Increasing urbanization also drives land-system change, typically in areas of high agricultural productivity. Vast urban regions impact surface energy (through the "heat island" effect), alter hydrological and biochemical cycles, net primary productivity and biological diversity. They are also major foci of pollutants. As humanity becomes predominantly urbanized it is with these land systems that most of us have most intimate contact.

Planetary Boundaries Amber Zone: Climate Change

Also in the amber zone is climate change. Remaining below the 2°C target, which is thought to provide a reasonable chance of avoiding catastrophic climate change, necessitates technologies which do not yet exist for extracting carbon from the atmosphere. Most nascent carbon reducing technologies require considerable energy, although new forms of cement may soon be feasible and

affordable on a large scale. Research since 2015 suggests that the 2°C target may need to be adjusted downwards to provide a reasonable chance of avoiding calamitous warming, in which case climate change may already belong to the red zone.

Even if the commitments made at the 2015 Paris Conference of the Parties are all honored, it currently seems likely to many analysts that global temperatures will be 2°C hotter than pre-industrial times by 2050 and nearly 3°C higher by 2100. These estimates depend on a number of variables: whether nations will adopt more ambitious pledges in the near term; whether technologies will emerge that can, at a low energetic cost, suck carbon back out of the atmosphere; whether unknown tipping points will be crossed, forcing a temperature surge. If these variables prove unfavorable, the aspirational 1.5°C maximum target may be reached by the early 2030s. There is no guarantee that the damage can be held to approximately 2°C, in particular due to the risk of amplifying feedbacks such as the release of carbon dioxide and methane from the Arctic, and/or the drying and burning of the Amazon forest. The capacity of the ocean to absorb CO₂ is also declining. That will slow the rate of ocean acidification, but increase atmospheric heat trapping.

Even if temperature rise and rainfall intensity can be contained, crop yields will decline and many places will become unliveable due to excessive heat and humidity or coastal inundation. Glaciers that act as a bank to store water and in some cases whose melt supplies electricity to billions in Asia and South America will shrink, coral reefs and many other species will disappear, and significant—even catastrophic—sea level rise will result. In Greenland and along the entire coast of West Antarctica ice shelves are already retreating or collapsing as warm seawater intrudes underneath, grounding lines retreat, and the glaciers behind them accelerate in their march to the sea. Climate scientist James Hansen and many glaciologists warn that the disintegration of the polar icesheets involves non-linear processes, and the timing, though still unknown, may be far quicker than assumed, and may include rapid, even unstoppable collapse of ice cliffs in series of Antarctica and Greenland.

The impact upon human wellbeing resulting from stress on biological diversity will be compounded by climate change and the fragmentation of society. For example, a complex economic and social fabric enables the importation of food and other resources to an increasing number of regions, some of which have been in this vulnerable situation for decades. Such mechanisms are fragile. Today, five countries are recognized as afflicted by famine: Yemen, Somalia, South Sudan, N.E. Nigeria and two regions of the Democratic Republic of the Congo (Kasai and Tanganyika). In the long run, if climate change and other aspects of adverse ecological change intensify, then it is also possible that regions that are current net food exporters will also experience famine; if this evolves then conditions in food-importing regions will inevitably deteriorate.

Pollution

Alongside these four major crises, the researchers also identify the threat from various forms of pollution. Most of these are discussed elsewhere in this encyclopedia. However, we briefly discuss novel entities.

Novel entities, novel behaviors, novel environments and health

Novel entities is a recently introduced term, first identified as a planetary boundary by the PB team in 2015, evolving from chemical pollution in the earlier PB publications. The PB team defines novel entities as “forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects.”

Most novel entities have been generated in the Anthropocene, the human-dominated era, defined roughly as the time since the start of the widespread combustion of fossil fuels, in the 18th century. They include synthetic molecules such as chlorinated fluorocarbons (CFCs), DDT, dieldrin and other organochlorines used as biocides and compounds used in industry such as polyvinyl chloride. CFCs, by harming the stratospheric ozone layer, clearly impinge on an Earth System function (and thus indirectly on human environmental health); the destruction of the stratospheric ozone layer causes UV light to reach the earth's surface to a greater extent than prior to the widespread use of CFCs, leading to the potential for an increased incidence of skin cancer, ocular problems and immunosuppression. Here, however, we focus mainly on the biological effects of novel entities.

Novel entities are not confined to new chemical compounds, as the PB authors note. Genetically altered organisms can be conceptualized as novel entities, as are nanoparticles (such as in sunscreens and cosmetics), and blue light from computer and phone screens. Humans are also exposed to numerous other emerging environmental hazards, especially since World War II, and to human-generated ionizing radiation (X-rays were once routinely used to help fit shoes). Possible health risks of non-ionizing radiation, such as from mobile phones, are discussed briefly below, as are novel behaviors, foods and other novel environments.

A 2017 Lancet Commission report estimates that 140,000 compounds have been synthesized since 1950, with perhaps 5000 widely disseminated in the global environment. Although some are regulated, and a few have been banned, the pace of their introduction greatly exceeds that of epidemiological investigation and legal constraint. For example, the International Agency for Research into Cancer (IARC), which is closely affiliated with the World Health Organization (WHO) has recently concluded that the widely applied herbicide glyphosate (commercially known as “Round Up”) may be carcinogenic. These findings have been resisted by some companies and their agents and supporters.

Thousands of studies of novel entities have found or suggested that many are carcinogenic, while others act as endocrine disruptors or harm health in other ways. Some have been linked with massive ecosystem disruption, including colony collapse disorder (of bees) and “insectageddon.”

The Lancet Commission on Pollution reported that fewer than half of the most widely dispersed chemicals have undergone *any* testing for safety or toxicity. Interactions between such chemicals have received even less examination. The immunological and

allergenic effects of most novel entities are also barely explored, and could contribute to the changing pattern of allergic diseases, auto-immune conditions and autism.

While some novel entities have been regulated (e.g., X-rays) and banned (such as the “dirty dozen,” including the organochlorine dieldrin, which was, as a rare exception, strongly linked with breast cancer), hundreds or thousands of others are released annually onto the market. In both industrial and rural societies, almost the entire population has been exposed to hundreds of chemicals whose concentrations can be measured in tissue samples, while for thousands more, no test exists.

There is little support from policy decision makers around the world for precautionary approaches to many potential risks. For example, there are concerns that mobile phones can cause brain tissue to warm up, if the receiver is held close to the ear. However, there are also concerns about the effects of non-ionizing radiation on brain tissue, and claims of an increased risk of malignant brain tumors in heavy users of mobile phones. Cardiac and neurological disorders are also plausible consequences of the rapidly increasing use of wireless devices, including smart meters.

Infrasound from wind turbines is another novel entity. Such sounds disturb the sleep of many people who live close to them, and there may also be other harmful effects including vertigo, as well as chronic diseases worsened by chronic poor sleep. Such concerns have often been dismissed as “nocebo” (i.e., through apprehension and negative thoughts) as high quality evidence for health impacts is lacking. The precautionary principle would place the onus on industry to prove safety.

Novel behaviors, foods, organisms and environments are also emerging in the Anthropocene. Examples include reduced weight bearing exercise in childhood and adolescence (leading to a higher risk of early-onset osteoporosis), increased screen watching and the partial replacement of tangible, local friends and acquaintances for virtual social networks. Novel diets include the widespread consumption of sweetened drinks, a known factor in obesity and harmful to health, while the greater variety of foods out of season, especially of fruit, is beneficial.

There are also novel microbial and parasitic environments and novel microbiomes, each of which is likely to be associated with health benefits and risks. For example, humans and livestock farming provide opportunity for the amplification and spread of genes that convey antibiotic resistance. These genes are favored wherever antibiotics are used by humans or fed to livestock to promote growth and limit infectious disease. Antibiotic resistance genes have been shown to spread to environmental microbes in soil and water systems, to wildlife and to human and livestock pathogens. Identified mechanisms for this transfer include air-borne transport of particulate matter and direct and indirect contact with waste products. The augmented “wild” population of antibiotic resistant genes is an added risk to human health and has poorly understood implications for other environmental microbial systems. Novel or increased contact with mammalian wildlife creates further potential for interspecies transfer of pathogens, particularly viruses. This is discussed below (in biodiversity and health).

Global Warming and Health

Since the 1980s, there has been increasing recognition of ways that anthropogenic emissions of greenhouse gases (manifest in phenomena including global warming, weather wilding, jetstream oscillations, sea level rise and ocean acidification) is likely to impact human health, both positively (e.g., fewer cold waves in some areas) and negatively. There are numerous mechanisms for this.

One that is perhaps most obvious is an intensification of extreme weather events, including heatwaves, droughts, flooding, and major storms including cyclones, typhoons and hurricanes. Such events can have complex and delayed effects, such as from the savage 2017 hurricanes that flooded and devastated Houston, Texas and the US territory of Puerto Rico, as well as other regions. There is also speculation that the frequency, severity and locations of tornadoes may be affected. Very intense flooding events, where weather systems remain almost stationary, have generated the neologism “rainbomb.”

Changes in vector-borne diseases, food security, and sea level rise have long been forecast to occur due to global warming. Global warming is already affecting migration, conflict and mental health, and these effects are likely to intensify. Over the longer timescale, of decades to centuries, adverse effects are forecast to exceed benefits, perhaps by orders of magnitude, especially if the ice sheets in Greenland and Antarctica continue to melt.

There are many ways health effects related to climate change can be categorized, such as through changes in temperature and humidity, vector ecology, water quality, water and food supply impacts, severe weather effects, air pollution, allergens, and migration, conflict and related mental health implications. A simpler classification has three main classes, conceptualized as “direct” (e.g., heatwaves), “indirect” (e.g., changes in vector ecology) and a third category, causally more displaced, with the potential for the largest burden of disease, through means such as large-scale conflict, migration and famine. In this classification, effects on mental health are regarded as “cross-cutting.” Dislocation from one’s home due to a storm surge or a prolonged blackout (some parts of Puerto Rico lacked power for months following 2017 Hurricane Irma) can lead to depression and even suicide. Such stress is also likely to exacerbate domestic violence, especially if associated with increased economic insecurity. Increased rates of post-traumatic stress and anxiety are also likely in survivors.

Even worse than the mental trauma of a single extreme weather event are the health consequences, including to mental health, from conflict, famine and forced migration. Of course, such “tertiary” effects have multi-dimensional causes, from ancient rivalries to recent and emerging contests over scarce resources, often aggravated by “youth bulges” and brutal repression.

All writers on these “tertiary” topics, publishing in the academic literature, recognize the complexity of this issue, and frequently try to convey this by using the term “risk multiplier” to indicate how changes in climate can worsen (or in some cases reduce) the

co-factorial causal contributors to conflict. That is, climate change is conceptualized as similar to a catalyst or enzyme. Famines, wars and migration can all occur without climate change, but in some cases climate change can make these phenomena much worse. In some cases, such as sea level rise, climate change can be conceived as by far the dominant factor. However, even for vulnerable low-lying Pacific islands, co-factors such as high population growth have contributed to vulnerability and the risk of migration, for example by depleting fresh water lenses, leading to the salinization of garden soil.

Many important diseases, including parasitic, vector-borne and zoonotic diseases are associated with invertebrates such as ticks, mosquitoes and blackflies, or higher order vertebrates. Ticks transmit diseases such as Lyme disease, mosquitoes transmit many illnesses such as malaria and yellow fever, while black flies transmit river blindness (onchocerciasis). The distribution of these insects and animals are shaped, not only by climate but by many other aspects of their ecology. Often, the identification of the precise attribution to climate change is elusive and possibly fruitless. Less intuitively, the epidemiology of many vector-borne diseases, including malaria, dengue fever and Zika virus is also influenced by the ambient temperature in another way, by determining the growth rate of the parasite or virus *within* the cold-blooded vector. More rapid growth of these pathogens (i.e., in slightly warmer vectors) can, in some cases, lead to additional cycles of transmission, leading to explosive increases in cases.

Another way to think of these organisms is that their numbers and disease potential exist within a window or "sleeve" of climate and ecological suitability. It would be wrong to think that a warmer or wetter climate will inevitably increase the burden of these infectious diseases. As temperatures rise, insect populations may too, but only to a point. Beyond that point, vector populations may in fact decline. Similarly, excessive rain may reduce vector habitat (e.g., flushing the population away), as may unusually prolonged droughts (drying out the habitat). However, the epidemiology of vector-borne diseases is also influenced by human factors, such as insecticides (including impregnated bednets) and molluscicides, and by treatments such as vaccines (e.g., for yellow fever) and anti-malarial drugs such as quinine.

Biodiversity Loss and Health

The impact of biodiversity loss on human health is being realized slowly. The dimensions of biodiversity (the diversity of genes, species and ecosystems) are not experienced or understood by most individuals, or policy makers, and challenge health researchers. As such, the impacts are dispersed across multiple scales of biodiversity and multiple dimensions of health and wellbeing much of which is discussed elsewhere in this contribution.

The PB team has examined the *genetic diversity* within and between species and ecosystems and its *functional role* within a global system, separately. They conclude that the loss of genetic diversity has exceeded a safe limit, with uncertainty remaining over how this impacts the function of ecosystems. The alarming rate and extent of loss of genetic biological diversity has been discussed earlier. The loss of genetic diversity undermines the resilience of ecosystems. Under relentless ecological change, biological diversity is replaced by ecosystems dominated by fewer, highly adaptive species, inadvertently or purposefully promoted by human activities. These include domestic species, pests and wild synanthropes, humans and the novel entities described above.

Genetic diversity is also the source of pharmaceutical discovery as well as the storehouse of traditional medicines. Most nature-derived pharmaceuticals come from plants; some come from traditional medicine practice but much is the product of systematic searching, modification and trial. Nature produces an inspirational variety and complexity of molecules to further manipulate. The diverse origins of the pharmaceutical armory against HIV AIDS includes Betulinic acid, derived from the bark of the tree *Betula pubescens*; Bevirimat, extracted from a Chinese herb *Syzygium claviflorum*; and Ganoderic acid β , isolated from the fruiting bodies and spores of the fungi *Ganoderma lucidum*.

Such a utilitarian appreciation likewise extends to livelihoods dependent on different aspects of biodiversity. For some, particularly vulnerable groups and those in remote locations, survival is dependent on the ability to harvest freely (or illegally) from the natural environment.

Rich biological diversity is often helpful for the resilience of ecosystems functions, sometimes called "services." In the early 2000s, the Millennium Ecosystem Assessment, a global collaboration of over 1000 scientists, grouped these into four kinds, which they called supporting, provisioning, regulating and cultural. Food production is classified as a provisioning service. For such a service, biological diversity is required for (supporting or underpinning) soil health, pest control (a regulating service), pollination and the genetics of livestock and crops. Other products of provisioning services include clean water, bio-fuels and crop residues used to provide energy. Other regulating services include carbon sequestration, climate regulation and disaster risk reduction. Nutrient recycling is another example of a supporting ecosystem service. A sacred grove or an iconic species of deep significance to the beholder illustrate cultural services.

Disease-regulation as an ecosystem service is contested, but some diseases, such as Lyme disease, are more prevalent in diminished and simplified ecosystems. The net effect of deforestation often favors mosquitoes that serve as vectors of human diseases including previously obscure pathogens such as Zika and Chikungunya viruses, or encourages urbanization or farm-foraging by fruit bat hosts of henipah viruses Nipah and Hendra. There is also a complex relationship between ecological change and malaria, which is, by far, the most important mosquito-transmitted disease. As discussed above, climate change also impacts these vector borne diseases.

Changes (driven by reductions) in biodiversity have increased zoonotic infectious disease risk especially due to intensive animal husbandry. Livestock, which now dominate global vertebrate biomass, and intensive production, create the opportunity for viral amplification and mutations resulting in new and previously unrecognized animal diseases and zoonoses. These include H5N1

(avian flu, via chickens), H1N1 (swine flu, via chickens and pigs), possibly Sudden Acute Respiratory Syndrome (SARS, via farmed civet cats and racoon dogs), Nipah virus in Malaysia (via pigs) and Middle East Respiratory Syndrome (MERS, via camels).

Novel or increased contact with mammalian wildlife creates further potential for interspecies transfer of pathogens, particularly viruses. Such contact is facilitated by accelerated land-use change and wildlife harvesting and sometimes aided by domestic animals acting as amplification hosts. Disease may transmit directly to humans or indirectly through domestic animals. Many opportunities for viruses to jump between species may be required before a significant disease emerges. Tropical areas of high biodiversity and under human pressure are considered “hotspots” for such diseases. Novel zoonoses of wildlife origin such as HIV AIDS, Ebola and SARS corona virus have been the subject of strong interest in the late 20th century and early 21st century. The examples above have resulted in pandemics. Many other smaller viral “spillover” events have occurred with localized impact only.

Natural or wild areas also reduce stress, depression and anxiety in those who visit them. This effect appears to be dependent on cultural and socioeconomic characteristics of the visitor and has deeper, religious dimensions for many Indigenous people. As discussed earlier, the human microbiome links us to the external world. Personal microbiodiversity is enriched by environmental and dietary diversity and, through mechanisms of immune regulation and the gut-brain axis, has a significant impact on physical and mental health. The benefits of experiencing biodiversity within natural settings appear to be physiological as well as psychological. However, the living environs of most people is one of reduced biodiversity, and for many most time is spent indoors.

It is the capacity of Earth’s natural systems, the aggregate of species and ecosystem biodiversity, to provide resilience despite changing environmental conditions that should be of the most fundamental concern to health and well-being. The biosphere must absorb our wastes, including carbon emissions; buffer coastlines from extreme weather events; provide clean air, water, a moderate climate, and the renewable resources humanity seeks to consume. It is therefore of great concern that the Global Ecological Footprint Network (see “The Ecological Footprint” section) estimates that 150% of [global] biocapacity is consumed per annum.

Declining Energy Yield From Energy Expended

Today, many determinants of health and wellbeing, including effective health services and their inputs, such as consumables and pharmaceuticals, are dependent on abundant and affordable energy. Millions of people living in poverty, especially in sub-Saharan Africa and South Asia, suffer multi-system consequences of air pollution, both indoor and outdoor, from smoke generated by their own household and by other households. In many locations, this is aggravated by the burning of fossil fuels such as coal and oil. Many people, particularly women and children, undertake daily laborious effort to obtain fuel and water. Access to electrical power, and even gas for cooking would bring significant improvements in health to the 1.3 billion people living without electricity.

Probably the least understood aspect of limits to growth is the concept and importance of declining energy return on energy investment (EROEI). The number given for EROEI is the ratio of useful energy obtained versus primary energy expended (see Box 1).

Box 1 Energy return on energy investment

The major energy carriers in use today are fossil fuels, especially coal, oil and gas. These are used not only for transport, heating and electrical power (over 60% globally), but also as a chemical stock to manufacture plastics and to make fertilizer. But, just as in the past when our ancestors bred, trained, housed and fed donkeys and draft horses for assistance with laborious tasks, fossil fuel needs to be wrested from the environment, whether drilled for, dug by hand or removed by robotic shovels. These processes themselves take energy. In addition, energy released or captured from these sources needs to be distributed and the infrastructure to do that needs to be maintained. Coal needs to be transported and burned, with some of its energy captured through combustion. Electrical energy needs to be distributed and regulated irrespective of its source (including solar, wind, hydro and tidal). To manufacture wind turbines or solar panels requires energy, as does the mining infrastructure described above. Life-cycle assessment allows a full quantification of the energy invested in any form of energy extracted, which is clearly significant.

In the heyday of fossil fuels, oil and coal were easy to extract, and their EROEI was high—some analysts report an average EROEI of over 100 in the late 19th century. In contrast, a review published in 2016 in *Nature Communications* found that, globally, up until 2017, solar panels may have yielded no energy beyond that required for their manufacture and installation. In other words, under the least optimistic scenario, solar panels, cumulatively, have been a sink for energy, rather than a source until very recently. More encouragingly, the EROEI for solar appears to have increased considerably in the last decade, perhaps to 30 or 35, especially in locations with high insolation, such as in the tropics. The climate footprint of solar is much lower than of coal and will continue to decline, especially as the efficiency of panels increases and the electricity they generate is used to manufacture additional ones.

The EROEI for wind is widely agreed to be even higher than for solar, so these two sources have promise as major substitutes for fossil fuel energy, even though researchers still debate whether renewables will yield energy abundant enough to fuel the current consumption-oriented economy. In addition, Ugo Bardi and Sgouris Sgouridis argue that the window for a successful transition is narrow: a very large investment of available energy is required, while still maintaining adequate energy for ongoing services. Moreover, the world’s economic system may fail to allocate the necessary resources in the necessary timeframe (by 2050 in this analysis). Bardi and Sgouridis are skeptical that market forces can effect this transition. They calculated that, as of 2017, capital investment is only about one tenth of what is required. Energy investment is also inadequate. Though not impossible, any transition to renewables will be challenging and requires a substantially greater rate of energy and capital investment than is currently allocated.

There is a widespread understanding that fossil fuels have been crucial to the human colonization and domination of the biosphere. The importance of energy is explicit in the work of many environmental writers, and implicit in the military actions of many great powers, who have frequently acted with violence or duplicity to acquire or maintain energy resources, from the Middle East to the Timor Sea. Without fossil fuel, modern civilization could not have evolved in the way it did, whether to create highways, intensive agriculture, skyscrapers or the space age.

Although, in the Middle Ages, the harnessing of water power for work from milling grain to sawing wood ("sawmilling") was widespread, such industry was necessarily confined to suitable riversides. Ancient mariners crossed straits and sometimes oceans, powered by oars and blown by the wind, but the scale of maritime trade was minuscule compared with that made possible by steam, oil and nuclear-powered vessels.

While this dependence on energy is well-known, though rarely highlighted in economic histories, the fact that EROEI is steadily declining is rarely mentioned in mainstream media or outside of specialist journals; it is claimed that fracking and shale oil now negate peak oil, though insufficient attention is paid to the instability of an industry reliant on proliferation of drilling sites and rising costs. The decline of EROEI may be disconcerting to a public ill-prepared for the future austerity which such a decline implies. Such consequences would not only affect health services, but the myriad other processes necessary for health which rely on affordable energy, including agriculture.

Conclusion

Concern about the impact of global ecological change on health is growing. So too is an understanding of the need for multi-sector collaborations. Few groups are yet addressing the deeper issues of PBs. However, many once disparate groups are converging as they seek to improve equity in health with a focus on global problems of biodiversity decline, environmental degradation and climate change. "Planetary Health," promoted by the prestigious medical journal *The Lancet*, is currently prominent. Others include Eco-Health, One Health and the in Vivo Planetary Health group.

Predicting future human health (or survival) under the status quo is difficult. Ecological systems typically demonstrate non-linear responses to perturbations and it is likely that current consumption patterns will precipitate dramatic shifts in biodiversity, ecological function and health-supporting services. Impacts of environmental change are disproportionately experienced by poor and rural communities. Advocacy and action to *prevent* these health risks is an essential role for those concerned with public health.

This entry has reviewed the issue of Limits to Growth, its more modern formulation as Planetary Boundaries and the relevance of both concepts to global population health. It has used these frameworks to classify and extend some environmental health risks. These include novel entities and behaviors, and global risks including climate change, biodiversity loss, land-system change and biogeochemical cycles. These risks are escalating and we recognize the shortfall in assessing the health risk of new pollutants, entities and behaviors. When considered together with economic and population growth, and with ever-increasing resource and energy use, these environmental health risks may foreshadow significant population decline. By using the LTG and PB frameworks in this contribution, society can frame preventative measures on the scale at which this is required. Without urgent change, future global population health, and survival, is imperiled.

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