Promoting Global Population Health While Constraining the Environmental Footprint

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Abstract

Populations today face increasing health risks from human-induced regional and global environmental changes and resultant ecological nonsustainability. Localized environmental degradation that has long accompanied population growth, industrialization, and rising consumerism has now acquired a global and often systemic dimension (e.g., climate change, disrupted nitrogen cycling, biodiversity loss). Thus, the economic intensification and technological advances that previously contributed to health gains have now expanded such that humanity's environmental (and ecological) footprint jeopardizes global population health. International data show, in general, a positive correlation of a population's health with level of affluence and size of per-person footprint. Yet, beyond a modest threshold, larger footprints afford negligible health gain and may impair health (e.g., via the rise of obesity). Furthermore, some lower-income countries have attained high levels of health. Many changes now needed to promote ecological (and social) sustainability will benefit local health. Continued improvement of global health could thus coexist with an equitably shared global environmental footprint.

GEC: global environmental change(s)

Environmental footprint: a population's total environmental impact, combining cumulative depletion of nonrenewable resources, the ecological footprint, and other environmental harm

Systemic: Complex dynamic interactive patterns involving phenomena such as feedbacks, thresholds, emergence and self-organization

Nonrenewable resources: natural capital such as fossil fuels, aquifers (with no or negligible recharge), species that may go extinct, and high-grade reserves of phosphate, uranium, metals, and rare earths

Renewable resources: natural capital such as ecosystems, fertile soil, fresh water, and clean air. Sustainable if not excessively abused

GPH: global population health

Ecological footprint (EF): bio-productive land required to produce food and other ecological resources and to assimilate wastes, such as greenhouse gases

INTRODUCTION

The ancient Chinese adage "May you live in interesting times" certainly applies to human populations living today. In recent decades, the localized environmental degradation that typically accompanies the growth of population size and affluence has been radically supplemented by human-induced global environmental changes (GEC). The most widely discussed element of GEC—human-induced climate change—is only one of a wider set of large-scale environmental changes that pose risks to human well-being, health, and survival.

The human enterprise is now so great and intensive, with a commensurately large, collective, environmental footprint, that significant environmental impacts are occurring at regional and whole-planet levels. Much of this environmental disruption, damage, and depletion is systemic and cumulative. It includes changes to atmospheric composition (causing both climate change and stratospheric ozone depletion), distortions to the global cycling of various elements (e.g., nitrogen and phosphorus), ocean acidification, and the pervasive global spread of persistent chlorinated organic chemical pollutants (78). It also includes the depletion of many nonrenewable resources (33, 67) and of various renewable resources which, often, are slow to recover or to be replenished.

These changes are symptoms of a planetary environment that cannot continue to absorb the increasing, aggregated demands and effluent of human populations. These systemic changes, in turn, pose a fundamental risk to global population health (GPH) everywhere, as components of nature's life-supporting systems are weakened or disrupted (52). The nature of these environmental threats is thus fundamentally different than those that arise from the more familiar, localized, environmental contamination (65). In general, the resultant health impacts will, and do, impinge more severely and sooner on vulnerable populations and regions. Meanwhile, the world's richer (and mostly healthier) countries continue to make disproportionately greater contributions to many forms of GEC, as illustrated by climate change and its estimated health impacts (54, 68).

We have well-accepted ways of measuring the health impacts of particular environmental exposures in populations. Measuring the aggregated environmental impact of a population's way of living is less easy. One intuitively attractive index that integrates various concurrent types of impacts on environmental processes and systems is the ecological footprint (EF) (98, 99), a variant of the more general concept of the environmental footprint. The EF estimates the total amount of Earth's productive surface (global hectares) required to supply a population with materials (food, water, fibers, timber, etc.) and to absorb its effluent. Some other related indicators are outlined in **Table 2**, in the third section below. All are indicative and informative; none is ideal. The EF is conservative because it largely omits depletion of nonrenewable forms of natural capital, including fossil fuels, rare earths (91), and concentrated forms of elements such as phosphorus (14) and uranium.

The EF can be conceptualized and applied at many spatial scales, from global population to individual. The aggregated pressure by the world's local/regional populations on the natural environment accounts for the emergence of GEC over the past half-century. This development, unprecedented in human experience, reflects the fact that humankind now has a combined EF that is ~40% greater than the planet's biocapacity to supply, regenerate, recycle, and absorb (108).

The key dimensions of this extraordinary surge in human pressures on the Earth system are indicated by these estimates of multipliers during the twentieth century:

- Population size (1.5 billion to 6 billion): × 4
- Energy-intensity of global economy: × 3
- Gross global (economic) product: × 15
- Greenhouse gas (CO_2) emissions: × 12
- Global human ecological footprint size: From <0.5 Planet Earths (circa 1950) to 1.3 (2008) Planet Earths

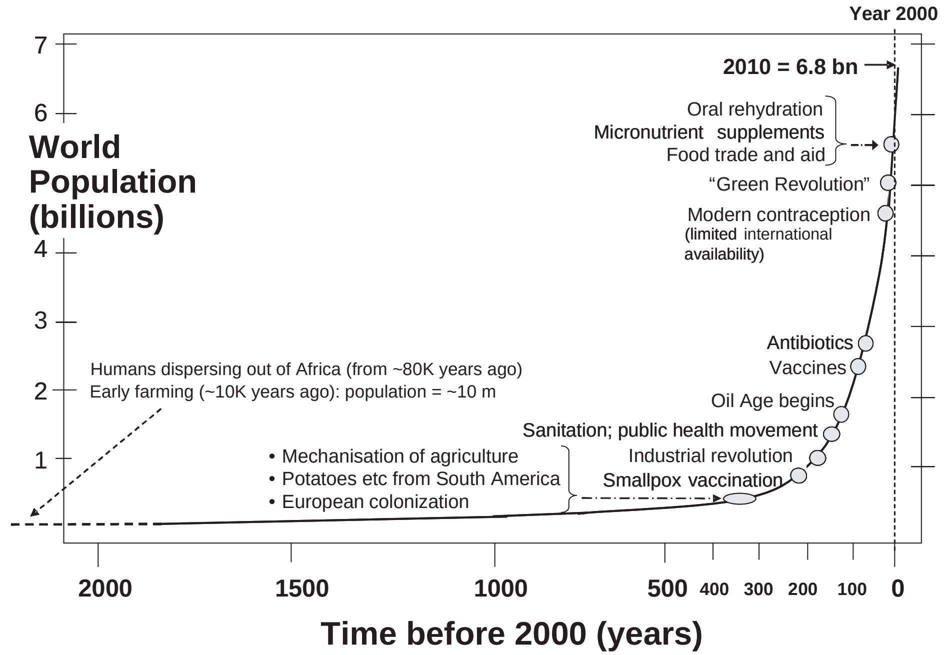

Figure 1

Graph (smoothed) of human global population increase over the past 2000 years, showing the main influences on survival and (hence) on population increase.

Humans have evolved from being (like other large mammals) a local "patch disturber" (74) to now being, uniquely, a disturber of the biosphere (50, 89) (see **Figure 1**). Hence some leading Earth scientists refer to the current geological era as the Anthropocene (17, 89)—the era in which Earth's structure and function are significantly influenced by one species, *Homo sapiens*. This expanding global EF poses a fundamental challenge to the natural environmental underpinnings, and hence the sustainability, of GPH.

In this review, we explore this unprecedented turn of events, wherein collateral localized environmental damage accompanying gains in wealth, knowledge, and health evolves to systemic global environmental damage that erodes the natural long-term basis of that health. We therefore address, in particular, two related questions. First, are high (and globally shared) levels of population health compatible with a globally sustainable ecological footprint? Second, is there evidence that affluent populations can reduce their ecological footprint, yet sustain (or even enhance) their health? The challenge posed by these questions embodies both a dilemma and an apparent paradox.

The dilemma is that the technological expansion and wealth creation that potentiated past gains in GPH now loom, in expanded and environmentally disruptive form, as growing threats to health. Much of the earlier health gain benefited from increases in energy- and technologically intensive economic activity. The net effect, despite local environmental damage, was an increase in life expectancy. Today, though, the continuing expansion of those technologies and of population size is causing environmental disruption on a scale that seriously jeopardizes GPH.

Meanwhile, the seeming paradox is that, while these collective disruptions to the global environment increase (78), national indices of

Biocapacity: the biological capacity of an area to supply, regenerate, recycle, and absorb on a continuing basis

Earth system: linked global eco-social system, involving the interplay between natural capital and human-created resources

Sustainability: Maintaining the content and conditions of eco-social systems and entities, enabling structure and function to continue into the future

GHG: greenhouse gas

population health are mostly improving. These health gains reflect, in part, the continuing (often time-lagged) benefits from earlier health-related scientific and social advances: including public and domestic hygiene, vaccination, housing quality, antibiotics, primary health care, and, more recently, the benefits from antismoking campaigns, screening programs, and life-preserving tertiary care (45, 104). Hence, even as long-term health prospects are being weakened by the advent of GEC, immediate health gains are occurring in response to improved public health practice, primary health care, and environmental safety.

Below are other probable contributory explanations.

- Much of the health impact of global environmental change is of an indirect, often deferred, kind. It thus differs from the mode of action of the more familiar and usually localized environmental hazard, typically involving a specific physico-chemical exposure acting directly, and often with little time delay. For example, impairment of food yields and hence human nutrition by a gradual change in climatic conditions will produce neither obvious nor directly attributable cases of disease. Rather, the incidence of childhood growth delay, stunting, and susceptibility to various infectious diseases will tend to rise incrementally. Meanwhile, other environmental and social changes will usually also occur, tending to blur any inference of causal specificity. This lack of an overt, often step-wise, increase in adverse health outcome contrasts with the direct induction of clinically definable disease outcomes from, for example, severe air pollution or from the accumulation of methyl mercury in fish, as in Minamata Bay, Japan, in the 1950s (11, 101).
- Adverse health impacts can be deferred by compensatory human actions, especially by those populations able to apply offsetting cultural, technological, and economic changes. For example, local food shortages can be offset by trade or aid. High-income populations can afford to buy fuel on the international market and maintain good nutrition, even if food and oil prices rise substantially (as occurred in 2008) (97).
- Furthermore, many adverse health impacts will occur in vulnerable populations remote from the major source of the environmental change. For example, much of the health risk from the early phase of global climate change is expected to be displaced spatially from the major greenhouse gas (GHG) source countries for reasons of geography, meteorology, and intrinsic population vulnerability (54).

In the following sections, we explore, first, the nature and extent of today's pressures on the natural environment, focusing particularly on the EF as a metric for quantifying and comparing. This problem, of overstepping nature's mark, has a long history in human experience. What distinguishes today's footprint patterns is the scale of that problem and the rapidity of its increase as most countries around the world industrialize, urbanize, intensify their food production, and continue to increase in population size. We then briefly review recent trends in health around the world. The central question then arises: Are health gains necessarily dependent on enlargement of footprints? The evidence we examine suggests otherwise.

GLOBAL ENVIRONMENTAL CHANGES: CONTEXT, TYPES

During the process of economic and social development experienced by today's high-income countries, the prevailing character of environmental health hazards has evolved across three phases (87). Environmental health risks from local squalor, factory-industrial exposures, and microbial contamination of food and water predominated in the early industrial period (21, 93). As economies grew and fossil fuels became central to industrial capitalism, environmental air pollution and the chemical fouling of waterways took on a more community-wide, even regional, character. Today, even as localized environmental hazards are managed in richer countries, populations everywhere are contributing to the third generation of hazards, GEC.

Via that third phase, the quality of many local environments, especially in higher-income populations, can now be maintained while displacing much of the ecological footprint of that area's population to other regions. This displacement creates the illusion that growth in affluence is environmentally benign, whereas much of the environmental damage underlying the production of food or consumer goods or the conduct of travel and tourism is displaced to the provider populations. Much of the current heavy air pollution in urbanizing eastern China is from energy generated to produce the goods that are then sold, at low cost, to high-consuming countries. Indeed, recent estimates indicate that the environmental and human toll of air pollution in modern China is eroding its fully costed annual gross domestic product (GDP) growth by 3%–7% (37).

The main large-scale environmental changes resulting from human pressures on the natural environment are summarized in **Table 1**. The best known is global climate change, caused by the continuing, indeed currently escalating, loading of the lower atmosphere (troposphere) with more GHGs than can be absorbed by terrestrial and marine sinks or readily disposed of via atmospheric chemistry. Average world temperature has increased by almost 0.7°C since 1950, and, from a range of evidence, climate scientists attribute most of this warming to human actions (3, 40).

International awareness and concern about human-induced stratospheric ozone depletion and global climate change came into policy-oriented focus in the 1980s (107). Subsequently, various other large-scale environmental concerns have emerged. The following two examples are illustrative.

First, human actions are now greatly transforming the global cycles of various elements (in addition to carbon), particularly the cycling of nitrogen, phosphorus, and sulfur through the biosphere (78). Human agricultural and industrial activity now generates as much biologically activated nitrogen (i.e., nitrogenous compounds, such as ammonia) as do lightning, volcanic activity, and nitrogen fixation on natural vegetation roots. Second, a more recent focus of concern has been the ongoing acidification of the world's oceans, caused by absorption of increasingly abundant atmospheric carbon dioxide. Global average ocean

Table 1 Main types of human-induced global environmental change

■ Climate change, due to increased radiative forcing (heat-trapping) in lower atmosphere (troposphere) by elevated levels of greenhouse gases
■ Destruction of stratospheric ozone (by industrial, mostly halogenated, chemicals), thereby allowing an increased flux of biologically-damaging solar UV radiation
■ Acidification of oceans (via increased uptake of the human-generated additional atmospheric carbon dioxide): a threat, along with ocean warming, to the future vitality and productivity of marine fisheries
■ Major changes to global cycles of important elements: including nitrogen, sulfur, phosphorus
■ Accelerating losses of biodiversity, causing changes/disruptions in ecosystems, due to habitat loss, overharvesting, climate change, and other human-induced pressures
■ Degradation and loss of much arable land, due to overexploitation, erosion, urban-industrial spread
■ Depletion of freshwater supplies, due to aquifer emptying, diminished river flows (exacerbated by climate change: glacier melt, evaporation), and wetlands loss
■ Accelerating depletion of nonrenewable resources, especially fossil fuels, phosphate and rare earths

MA: Millennium Ecosystem Assessment

pH has declined by more than 0.1 points during the past several decades, approaching a level of acidification that may endanger the exo-skeletal calcification processes in the tiny creatures at the base of the marine food web (3, 19, 66).

During 2001–2005, the internationally coordinated Millennium Ecosystem Assessment (MA) documented the extent to which human pressures have accelerated the decline in many environmental assets, including changes to ecosystems (60). The assessment revealed that several globally significant environmental trend lines peaked in the mid-1980s. On land, the annual per capita production of cereal and soy peaked and has subsequently drifted sideways and, recently, downward (8). More generally, agricultural yields are being impaired by degradation of land-based ecosystems, disrupting, impoverishing, and depleting regional water supplies and the fertility of many soils (79). The MA documented that the harvest from the world's ocean fisheries also peaked in the 1980s and has subsequently declined slowly, albeit with substantial compensatory gains from aquaculture, particularly in China (88). These emergent downturns in food-producing capacity jeopardize attempts to reduce hunger, malnutrition, and child stunting, a key target area of the U.N. Millennium Development Goals (2, 8).

The changes listed in **Table 2** all affect natural environmental processes and systems that underpin human population health. Furthermore, they often do so in concert. For example, except for ocean acidification, all the changes shown in **Table 2** can affect agricultural yields and often act jointly. Consequences include fossil fuel depletion because the price of fertilizer and food will be affected (70). The major large-scale environmental changes, their key interrelationships, and their main health impacts are summarized in **Figure 2**.

OVER-SIZED ECOLOGICAL FOOTPRINTS: HOW CLOSE TO DANGER?

The EF is a heuristic metric for visualizing, comparing, and communicating the size of the demand that humans make on the biocapacity of the world's natural environment—i.e., its capacity to supply, replenish, absorb, and stabilize (98). The concept has its modern origins in the work of Ehrlich & Holdren [1971] (20) in defining the determinants of the impact (I) of a population, of given size (P), as a function of level of material consumption (affluence, A), and types of technology (T) used to extract, produce, and distribute goods and services. Their widely cited and influential equation was

Table 2 Indicators of aggregated global environmental impact

Indicator	Components/comments	Data or conceptual	Year (reference)
I = PAT	Impact, Population, Affluence, Technology	Conceptual	1971 (20)
I = PLOT	Impact, Population, Lifestyle, Organisation, Technology	Conceptual	1998 (26)
Human Carrying Capacity	High estimates ignore human conflict and need to preserve minimum natural stocks	Multiple (reviewed in 1996) (7, 13, 83)	
Net Primary Productivity	Terrestrial photosynthetic appropriation	Global land data	1987 (96), 2001 (80)
Fresh water availability	Terrestrial appropriation	Global water data	1996 (71)
Ecological Footprint	Provisioning ecosystem services, GHG absorption	Global data	1996 (98)
Trophic level fisheries catch	Marine and freshwater	Global data	1998 (69)
Amphibian Index	936 amphibian datasets	Multi-continental data	2000 (39)
Living Planet Index	Forest, freshwater and marine ecosystems	Integrative global data	1998–2008 (47, 108)
Index of Global Environmental Change	GHGs, ozone depletion, fish trophic level, amphibian index, tropical deforestation	Integrative global data	2000 (6)

I = PAT. The subsequent development of this idea has yielded today's conceptualization and estimation of the ecological footprint, including at global scale (99). Investigators have also proposed and applied several other indices (see **Table 2**). Biocapacity is thus related to ecosystem services, especially the "provisioning" ecosystem services (59), which supply food, fiber, and biomass used as fuel. However, in addition, biocapacity (and the EF) includes a factor for waste absorption, especially of GHGs.

Algebra aside, the problem faced by human populations exceeding the long-term carrying capacity (4, 7, 13, 83) of their local environment is ancient and recurring (18, 109). Indeed, it has been a constant contributor to the subtle pressures on both biological evolution and cultural evolution. Oversized EFs have resulted in a long historical succession of tensions and crises for local and regional populations and whole civilizations, accompanied by declines in population size, health, and longevity (51, 102).

Human populations, like those of other species, appear to have an instinctive tendency to feed and breed up to the level of—and often beyond—the sustainable limits of local environmental capacity. This behavior contributes to the boom-and-bust cycles that occur often in the natural world (83). The human species, however, is distinctive in its acquisition and use of culture and technology to supplement local environmental capacity (aqueducts, irrigation, trade, imperial exploitation, chemical fertilizers, etc). In this way, populations can defer, perhaps ignoring or not recognizing, the coming crisis from living beyond nature's means (62). However, in some cases, human populations have used means to limit fertility, including customs, taboos (1), prolonged breastfeeding (85), and, perhaps, surgical means of reducing fertility (30).

The stories of Sumeria, the Mayans, Easter Island, and others are widely known (18, 102). Critical stresses on such societies have arisen particularly from shortages of fresh water, soil degradation, and declines in food yields (81). Other societies facing critical stress have sometimes managed to pull back from the brink, for example, pre-European-dominated Hawaii (44). Wise local government and community actions can stave off local environmental degradation and decline (18). Some lessons have been learned from such experiences, but history often repeats itself. In the two centuries since European colonization of Australia, the widespread clearing of land and mismanagement of river water flows, often combined with overstocking, have led to widespread land degradation and reduced agricultural productivity.

Today, for the first time, humans face this ancient challenge at the global level. The critical question is, can global society collaborate in collective international actions to reduce the size of the global environmental impact sufficiently to avert further detrimental environmental change, while maintaining the social and economic conditions necessary to sustain GPH? This challenge is heightened by the increasingly acknowledged proximity of "peak oil," with its consequent increase in the cost of energy (33, 36). Can this be done equitably between groups, populations, regions, and generations?

The EF is now widely used to monitor national and regional time trends, to compare regions and populations, and, of particular importance, to compare the magnitude of human demand on the environment with what is sustainably available from the natural environment (its biocapacity). EF size varies greatly among today's national populations. The EF of high-income countries is typically within the range of 5–10 hectares per person, whereas the world's poor populations have, on average, 0.5–1.5 hectares per person. For a global population of 6.8 billion, the available, sustainable, footprint is estimated to be 2 hectares per person (99, 108).

A recent and comprehensive assessment concluded that three-quarters of the world's people live in countries in which national consumption and waste generation now exceed that country's biocapacity (108). Thus, most populations today are subsidizing their ways of living and economic growth by depleting the

Carrying capacity: the size of the population that can be supported while sustaining the biocapacity of the specified environmental unit world's ecological capital: by emitting GHGs, overfishing, damaging soils, overusing aquifers, and, in the richer and more powerful nations, by extracting resources from politically weak and corrupt lower-income countries. In the nineteenth century, Europe indulged widely in the exploitative colonial acquisition of food, fiber, and various manufactured goods. Last century, the United States took over a large part of this role. Today, China is strategically securing foreign resource supplies and offshore land for future agricultural needs (63).

Collectively, in the mid-1980s, humankind's demands on the environment began to exceed Earth's capacity to supply and absorb on a sustainable basis (see **Figure 3**). Since then, the human population has moved from having a precariously balanced environmental budget that left nothing in reserve to today's situation in which we are seeking to survive on a substantial, growing, overdraft (12). Our global standard of living is now estimated to require the support of ∼1.3 Planet Earths (108). This practice is not sustainable. (See also **Figure 4**.)

Figure 5 shows great differences in the absolute per-person size of the EF between the three income-defined categories of countries and the general tendency during 1961–2005 for those EFs to increasingly exceed their biocapacity. In 2005, the discrepancy between per-person EF and per-person biocapacity was greatest in the high-income countries (ratio EF to biocapacity = 6.4/3.7 = 1.73) compared with the much lower figures in the middle-income (1.0) and low-income countries (1.11). Furthermore, that differential exists even though, in 1961, the estimated per-person environmental biocapacity was substantially greater in the high-income countries than in other countries.

DO HEALTH GAINS REQUIRE ENLARGED FOOTPRINTS?

Substantial gains in GPH have occurred over the past two centuries, albeit unevenly and asynchronously. Historically, in western countries, much of the health gain in those surviving infancy and early childhood has been attributed to a combination of sanitation and improved food supplies (35). Fogel (24) attributes substantial gains to the greater security and abundance of food; McKeown et al. (48) point also to gains in food quality and safety and the presumed resultant increase in resistance to infectious diseases. As the second agricultural revolution progressed, with mechanization, new cultivars, and eventually fossil fuel power, the millennia-old pattern of subsistence crises diminished and disappeared.

During the twentieth century, global average life expectancy doubled from ∼35 to almost 70 years (64, 76). These gains occurred in response to a combination of social modernization (especially health literacy and improved governance), economic expansion and intensification (with increased exploitation of the natural environment, especially the extraction and use of fossil energy, land-clearing, and intensified agricultural methods), and a range of technological advances. This longitudinal historical relationship is reflected in the well-known graph of cross-sectional data plotting country-specific life expectancy against per-capita GDP (income) (72)—a graph that shows that, on average, the population health gains attenuate markedly above a particular level of economic wealth. Of relevance to this review, serial cross-sectional graphs over successive decades indicate that, at any specified level of national wealth, the more recent the data the higher the life expectancy; that is, whereas basic economic development is essential for health improvement, other noneconomic (social, cultural, political) influences are very important.

The ongoing generalized uptrend in life expectancy, while flattening over the past decade in high-income countries, is currently rising more steeply (albeit from a lower base) in much of the rest of the world. There are, however, exceptions to this general recent uptrend. Gains in life expectancy have recently stalled or receded in much of Sub-Saharan Africa (mostly due to the scourge of HIV/AIDS) (55) and in Russia (46), various other ex-Soviet countries, North

Korea, and Iraq (mostly reflecting extremes of social-political change and disruption) (92).

Meanwhile, various low-income nations and provinces, such as Costa Rica, China, Cuba, Sri Lanka, and the Indian state of Kerala, have been notably successful in raising their population health to a high level (22, 34, 41, 77). Costa Rica and Cuba have life expectancies similar to that of the United States (76–78 years). This success has been achieved primarily by investing in education (especially of girls), establishing primary health care clinics, encouraging community development, and undertaking other public health programs. Sweden provides an interesting historical example, having progressed through the epidemiological transition in the nineteenth century while still in a preindustrial, predominantly rural and small-town, phase. Systematic gains in the Swedish population's literacy appear to have facilitated their advancement in health-related practices and living conditions. In 1840, Swedish women led the world in terms of life expectancy (64). Overall, two common threads in such countries appear to have been a relatively high cultural commitment to health as a social goal and a social welfare orientation to the process of development. Riley calls this "social growth," which includes a population's willingness to understand and adopt the relatively simple measures that increased life expectancy, mostly by preventing disease, before the era of antibiotics (61, 77).

Overall, two general conclusions arise from this historical international experience. First, gains in population health require economic advance (including access to energy and to improved food supplies) and social modernization (including literacy, effective governance, and public health programs). Second, although gains in material living conditions are important, a marginal returns phenomenon applies at higher levels of wealth and consumption.

The experience of the past several decades has introduced a new dimension to this longitudinal narrative of rising material standards of living and population health. As populations have continued to increase and as levels of production, consumption, and waste generation have increased, so have the pressures on the biosphere escalated. The consequent weakening of the natural environment's life-supporting resources and processes poses increasing, often fundamental, risks to human health. One such major risk is the environmentally and politically complex issue of food insecurity. More than one billion people, representing approximately a one-fifth increase in absolute numbers over the past decade, remain energy-undernourished (25).

Meanwhile, in both high-income and lower-income countries, the modern increase in abundance of food energy—especially in the form of refined energy-dense food products, made from selectively produced foods—is increasing the risks of various major noncommunicable diseases. In recent years, the increases in coronary heart disease, hypertensive stroke, and type 2 diabetes have been greatest in lower-income populations (5). On current trends, the burden of cardiovascular disease—which accounts for around one-third of all deaths in the world annually—will continue to shift to low- and middle-income countries (29). This trend, along with the persistence of some major infectious diseases, particularly in the poorer population segments, will further widen global health inequalities.

Risks to GPH arise from various other concomitants of the enlargement of footprints. The annual global toll of premature deaths (mostly from cardio-respiratory diseases) from urban air pollution caused predominantly by fossil fuel combustion is on the order of 800,000 deaths per year (73). Investigators have found a similarly high burden of causation and exacerbation of asthma. On another axis, researchers are seeing new and powerful influences on the mobilization and spread of some infectious disease agents associated with modern, more affluent, patterns of tourism, business travel, and long-distance trading (43, 103).

If, over the coming decades, GPH is to be optimized and sustained, three distinct dimensions of environmental influence on health must be reconciled. First, basic gains in the material standard of living (including energy use)

Epidemiological transition: shift that typically accompanies modernization—from high to low (especially childhood) mortality, thus facilitating a fertility decline, with subsequent shift in the population's profile of disease and cause of death must be achieved by lower-income populations, while limiting the health hazards from collateral and mostly local environmental pollution. Second, the form and processes of modern (increasingly urbanized) human habitat—including considerations of urban design, transport systems, housing design, food systems, and water supplies—must take primary account of impacts on health-related exposures, choices, and behaviors. Third, the large-scale environmental damage and changes now occurring pose a more fundamental threat to the foundations of GPH. Hence, the first two needs must be addressed within an overarching frame of ecological sustainability. This criterion of sustainability—acting to sustain nature's life-supporting processes—must be recognized as the environmental *sine qua non* of population health.

HEALTH RISKS DUE TO GLOBAL ENVIRONMENTAL OVERSHOOT

The level of recognition, by communities, policy makers, and most researchers, of the health risks posed by global environmental overshoot is limited at this stage (52). Understanding of the health effects caused by ecological disruption and GEC is slowly growing because of the work of the MA (15) and the growing awareness of the health risks of climate change (16).

Environmental health has previously engaged little with complex environmental systems and has not given sufficient attention to how human health risks might impinge over many future decades. The deficit reflects the small numbers of health researchers engaged in this research arena and the difficulties in identifying and attributing specific health impacts to these generally great but slow environmental changes at this early stage of their development.

Global Climate Change

Climate change provides the best understood example of these GEC-related health risks (57). The easily understood, direct-acting, risks to health include (*a*) increases in health events and deaths during (more frequent) heat waves as well as adverse health effects on workers exposed to intensified extremes of heat; (*b*) the many consequences (including injuries, deaths, posttraumatic stress disorders) of weather disasters; and (*c*) the cardio-respiratory hazards of increased levels of some air pollutants and also of heat stress.

As shown in **Figure 1**, climate change also affects the more fundamental environmental resources and processes upon which health and survival depend, in particular, food yields, freshwater availability, and stability of the microbial world. Furthermore, as climate change progresses, along with other aspects of overshoot, various forms of social and demographic disruption are very likely to occur. Tensions and conflicts may ensue, particularly in relation to dwindling basic resources (38). Flows of migrants and environmental refugees will almost certainly increase, with an associated increase in many types of health risks (10, 49, 62). In a more extreme but not implausible scenario of largely unchecked climate change, parts of the world will become uninhabitable by humans because of extreme heat stress (84).

Initial evidence suggesting current health impacts of climate change (51) includes (*a*) an increase in annual death rates from heat waves in several regions; (*b*) shifts in the range and seasonality of some climate-sensitive infectious diseases (e.g., northward extension of the temperature-limited schistosomiasis transmission zone in eastern China, in association with warming since the 1960s, putting 21 million more persons at risk (110); (*c*) adverse mental health consequences in some farming communities affected by regional drying; and (*d*) impairment of food yields and hence risk of malnutrition-related child development in some already food-insecure populations (9). Furthermore, the apparent increase over the past several decades in the regional frequency and severity of many extreme weather events—especially cyclones, storms, floods, fires, and droughts—is also consistent with the predictions of climate change science. Those events exact great tolls, both immediate and delayed, physical and mental, on the public's health.

An itemized listing of health risks due to a particular form of GEC fails to capture the full sweep and multicausal complexion of the actual risks to GPH caused by these changes. Biodiversity losses and associated ecosystem changes will impinge on human well-being and health in many and diverse ways, direct and indirect, including those via impacts on access to medicinal compounds, food yields, water cleansing, constraints on infectious disease vectors, and the cycling of elements (82). In parts of the world, populations are already stressed by food and water shortages. Crises loom between various neighbor countries because of trans-boundary disputes over depleted shared resources, especially water. Existing combinations of continued population growth, increased settlement densities, displacement of groups because of environmental adversity, poorly managed land, water and marine resources, and militaristic impulses to secure territory and assets all create critical situations to which the impost of climate change represents a further serious environmental stress—perhaps, in some situations, a "final straw."

A key question arises here for high-income countries. Can they sustain their population's health while reducing their markedly oversized EFs to a level compatible with the needs of global environmental sustainability? This question is compounded by recognition that environmental space must be made for low-income countries to increase their levels of per-capita production, consumption, and waste generation—up to, ideally, an agreed-upon common international level. A coordinated and equitable multilateral process of this kind would illustrate the strategy of global "contraction and convergence" (58).

CAN COUNTRIES REDUCE THEIR FOOTPRINT, YET SUSTAIN HEALTH?

Given the serious potential risks to GPH if the world community allows the global EF to continue to expand, what is the balance of risks and benefits to the attained health status in reducing the global footprint? Because such reductions would need to be greatest in high-income countries, this question looms large for those countries.

Can we curtail the excessive, mounting, demands now being made on the environment by human societies and their simultaneous expectation of sustained material well-being and health? Resolution to this issue can draw on the following three insights and strategies.

1. As shown by the recent experience of various low-income societies discussed above (fourth section above), high levels of energy-intensive material production and consumption are not a prerequisite for good health.
2. Nevertheless, a moderate level of the basic amenities and resources (electricity, fuel, housing, transport, etc.) is needed, and the challenge will be to provide and use those amenities with a lower footprint. Many promising technologies and forms of social organization could facilitate this process. However, "smarter" technologies do not automatically reduce total impact because such gains can be offset by their increased use, referred to as Jevons' Paradox (94).
3. Many of the changes that societies must now make to achieve a global sustainability transition will yield direct long-term gains to GPH. There are many win-win opportunities (co-benefits) with respect to sustaining both environment and health.

The first strategy has been discussed previously. Caution is needed in relation to the second strategy. Historical experience shows that substitution of "better" technologies can have unanticipated adverse environmental and health impacts. Examples include the replacement of horse manure with the exhausts of the internal combustion engine, of whale oil for lamp lighting with fossil fuels, and several major agricultural innovations in the nineteenth and twentieth centuries (e.g., guano as fertilizer, the

TRANSITIONAL TECHNOLOGIES IN A CONSTRAINED WORLD

In Singapore, water is being recycled using membrane technology without compromise to health. The energy cost of "new water" (from recycled sewage and household water, even industrial waste water and storm water) is much lower than that of desalinization.

Germany, Denmark, and Spain are shifting to renewable power without health compromise. Iceland has long been in that position, owing to its geothermal resources. However, the reduction in footprint from a shift to solar and wind may be overstated because of accounting difficulties in the EF.

China is making a massive shift to aquaculture, which is very encouraging if it can be maintained (88).

"Vertical farms" and other forms of agricultural intensification have been suggested as a way of feeding the world even in the face of severe sea level rise (23). Although the EF will be fairly high (e.g., because of importation of feed), such intensive farms do enable very large scale production, including meat, albeit not without ethical and health costs, including the risks of new diseases and antibiotic resistance.

synthesis of ammonia, and the chemicals-and-water intensity of the Green Revolution). Many of the new materials and renewable-energy technologies may have higher environmental prices than expected, including the comparatively high footprint (including those of rare earths mining) of many fossil-fuel substitutes: photovoltaic cells, batteries for hybrid cars, motors for wind turbines, and tantalum for mobile phones (91).

Nevertheless, a number of recent, encouraging, apparently comparatively environmentally benign shifts and substitutions (see sidebar, Transitional Technologies in a Constrained World) have taken place.

The third strategy refers to an encouraging, positive, conclusion about the collateral benefits (cobenefits) to health from actions taken to reduce the EF. For example, many of the mainstream mitigation actions proposed to reduce GHG emissions will affect the health of the local (i.e., the mitigating) population in beneficial ways (32). The following illustrative examples come from a pioneering set of linked analyses conducted in 2009.

- Reduced fossil-fuel combustion (currently used for electricity generation and vehicle fuels) would significantly improve urban air quality in many cities (105). The main resultant health benefits would be reductions in chronic respiratory and cardiovascular diseases. Although worthwhile health gains would result in cities such as London, in the United Kingdom, the absolute gains would be an order of magnitude greater in large cities in India and China.
- A curtailed reliance on coal and other biomass combustion for heating and cooking in poor (predominantly rural) households in many low-income countries will greatly reduce severe, highly toxic indoor air pollution (105). Currently, such pollution causes ~1.5 million premature deaths annually, around two-thirds in children under age 5 years.
- An increase in use of mass public transit, cycling, and walking in urban environments will increase physical activity, reduce obesity, and stimulate social contacts (106). Lesser private car use should reduce road trauma. For shifts in transport modalities commensurate with the then-current proposed national emissions reduction targets, the population of London would experience an estimated 10%–20% decrease in cardiovascular deaths, along with likely reductions in depression, dementia, and breast cancer in women. In Delhi, India, a shift to more physically active mobility would yield a decrease in heart disease and stroke by 10%–25% and an approximately one-eighth reduction in diabetes (106).
- Health cobenefits would also accrue from curtailing global red meat consumption, with commensurate reduction in the livestock sector's emissions of GHGs (which account for around one-sixth of the global total GHG emissions). Global meat

consumption is now on a marked uptrend (90), particularly in China and other East Asian countries, and may extend to other lower-income countries in the near future. Meanwhile, in high-income countries, the average daily intake of red meat mostly exceeds dietary needs and is associated with increased risks of several noncommunicable diseases, particularly coronary heart disease, stroke, and colon cancer (28). Hence, a reduction in meat production and consumption, especially from ruminants (cattle, sheep, and other digastric producers of enteric methane, with its much more powerful warming effect than that of carbon dioxide), would help to abate climate change while conferring significant health benefits (28, 56). In one recent study, the estimated benefit of reducing the intake of saturated fat and cholesterol, at the level that would result from reduced animal-foods consumption in accord with national GHG emissions reduction targets in the United Kingdom and Brazil, could save 16% of years of life lost from ischemic heart disease in the United Kingdom and 17% in Brazil (28). These modeled estimates assumed a 30% reduction in production and consumption of livestock by 2030, along with technological practice changes, to reduce GHG emissions to meet the agreed emissions reduction targets.

- This change in dietary habits would also facilitate reforestation projects (by reducing the space required for animal feed production and animal pasturing), thus increasing carbon biosequestration while also helping restore the plant-based supplies for dietary diversity, various medicinal substances, and other health-related natural materials.

Obstacles to such resolution of the fundamental tension that human societies now face do exist, however. Some impediments are deeply rooted in human behaviors that evolved as successful strategies in a preagrarian world in which natural resources were mostly abundant (65). The fact that we now live in ways that exceed that erstwhile abundance is not yet well recognized in our societies' institutional forms and behaviors (78, 100). Furthermore, this lack of recognition and understanding is especially evident in the behavior of the vast majority of people in the most affluent quarter of humanity (6).

Finally, given the great disparity in national per-person EF size, an important corollary question is, "How much should countries with unsustainably large footprints reduce their footprint size?" A first reasonable step would be for each nation to live within the limits of its own national environmental carrying capacity (defined according to agreed international criteria). However, this strategy would create a permanent disparity in living standards between countries because many lower-income countries already have populations much larger than could be sustained by their national environmental base and also because the natural biocapacity of different regions differs markedly. The moral and political ideal would be a world in which all persons, irrespective of national origin, have the same natural environmental entitlement: a versatile idea (contraction and convergence) that has been mooted as the eventual fair solution to GHG emissions because the global atmosphere and climate are global public goods (27, 58).

Clearly, most countries now have both a separate and internationally shared problem with living beyond the sustainable capacity of their and the world's natural environments. This is especially the case for high-income countries and for those countries now heading rapidly in that direction (including China, India, Brazil, and Mexico).

CONCLUSION

The issues, strategies, and empirical evidence reviewed above are complex and unfamiliar to many in public health. Furthermore, much of the content is not reducible to specific measurement and enumeration. Therefore, it is not possible to provide categorical answers or time frames in response to important questions about the future compatibility of ecological sustainability and population (high-level) health sustainability.

The main components of the processes (past, present, future) reviewed above are represented in the following schema (**Figure 6**). No absolute numbers or dates are shown because (*a*) inadequate empirical data are available (and they would vary by country, culture, and region) and (*b*) the future is neither knowable nor measurable.

As ever, caution is needed in seeking to describe, estimate, and, perhaps, assign economic costs to future eventualities. Modeling these future-oriented dynamic processes requires making simplifying assumptions that ignore some (likely) aspects of reality. Modeled estimates can imply (to wider public and policy makers) unrealistic levels of certainty. Hence, an important aspect of the public health foresighting of health risks from environmental changes is to foster an updated view and understanding of the science of the resultant human impacts and society's response options. Climate change and other elements of human-induced GEC are now propelling human societies and populations into a world with a profile and scale of environmental conditions not previously experienced.

For small and relatively isolated societies, such as Hawaii and Easter Island, ecosocial changes are conceivable that could allow (or could have allowed) the maintenance of health (as measured by life expectancy and population size). However, the existence of such theoretically realizable changes in way of living does not guarantee they can be successfully implemented, as the Easter Island case shows (75).

For the world at large, understanding the challenge of unsustainability is much delayed, forcing an even steeper path to overcome it. It is possible to imagine utopian solutions, such as new technologies and unprecedented scientific breakthroughs. Many futurists have forecast such innovation, underpinning their arguments on the historical trajectories of human progress, bolstered by innumerable scientific and social breakthroughs (42, 86). Few such analysts, however, concede the degree to which this progress has been hugely aided by two environmental assets, the size of each of which is now being rapidly run down. The first such asset is the stock of living natural resources, such as forests, fish stocks, and wild lands. The second is the stock of fossil fuels, especially oil, coal, and gas (33). The challenge now, in this "Anthropocene" era (17), is to find a combination of technology and human behavior that will maintain the current level of human health and population and, at the same time, find substitutes for this vast treasure of depleting natural capital.

For the immediate purpose of this review, the response to the question(s) posed in the Introduction section above is that, no, reducing our collective ecological footprint does not necessarily mean reducing life expectancy and general state of health. (Even if it did, one could argue that a modest forfeiture of an already high level of health in rich countries is a reasonable insurance policy against much greater future loss of health from a world of unconstrained disruptive environmental changes. Furthermore, it would be an ethically desirable step to take if it made more environmental space available for poorer countries as they undergo economic and social development.)

We live in an era of a threatened, perhaps imminent, reversal in the relationship between economic growth, modern technologies, social modernization, and health. The factors that have historically underpinned population health gains are now, by dint of their much increased scale, scope, and intensity, undermining sustainable good health as we exceed Earth's capacity to renew, replenish, provide, and restore. The prospect of nonsustainability now looms on a broad front. In turn, this action threatens to reverse recent gains in health, perhaps catastrophically for some high-vulnerability populations.

Reducing health inequalities presents a further great challenge. The shift in priorities and social values necessary to achieve the abovementioned (material and economic) sustainability transition will, hopefully, indeed necessarily, be linked to a new globally shared recognition that unless the total, composite, EF is modified, global ecological sustainability will not be achieved and GPH will remain at great risk.

In practice, many aspects of human behavior, culture, and social institutions pose major impediments. Catastrophic impacts, profound and shared new insights into the nature and needs of the natural world, or radical moves to authoritarian government are all plausible responses, but each has different implications for GPH. The conclusion is unavoidable: Living within the constraints now seen to be necessary requires radical changes in consciousness and institutional reconfigurations in rich and poor countries alike. The temptation to follow current trajectories of development threatens an unraveling of progress that may first hurt the poor disproportionately, but which, if unchecked, will then harm us all (51). We need to develop a global consciousness and work collectively for survival (95).

SUMMARY POINTS

1. Human pressures on the natural environment have increased rapidly over the past century, and the global uptrend remains steep. This increase has caused the emergence of a range of worldwide, often globally integrated, changes to environmental and ecological systems.
2. Investigators have devised several indicators to measure this environmental pressure, of which the best documented is the ecological footprint. The ecological footprint is a subset of an even larger, but less well quantified, environmental footprint.
3. In most countries, much of the gain in population health over recent decades has depended substantially on an overexploitation of the natural environment (including, in particular, access to fossil fuel–based energy).
4. This environmental overexploitation means that many countries have ecological footprints that are greater, often much greater, than their estimated domestic biocapacity.
5. The recent experience of various societies shows that high levels of material consumption are not a prerequisite for health.
6. Energy, basic needs (water, food, fiber, etc.), and other material goods can increasingly be provided via technologies with lower impact.
7. Many of the technological and behavioral changes needed for sustainable living will yield direct gains to local population health.
8. It appears feasible (and morally and politically desirable), via agreed international contraction and convergence strategies, to achieve sustainability of both global environment and population health.

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89. Builds on Crutzen's definition of anthropocene to define current time as a period of "great acceleration" of opportunity and risk.

93. Likens the switch to marketism in many countries in the 1970s to "fool's gold" swallowed by a gullible public.

95. Was foundational to the concepts of the biosphere and the noösphere, a kind of global collective understanding.

98. Like many popular metrics, the EF is simplified, perhaps necessarily, for example by excluding lags, thresholds, and feedbacks.

100. Environmental problems outpace institutional evolution; we need to induce sufficient cooperation to overcome a tragedy of the global commons.

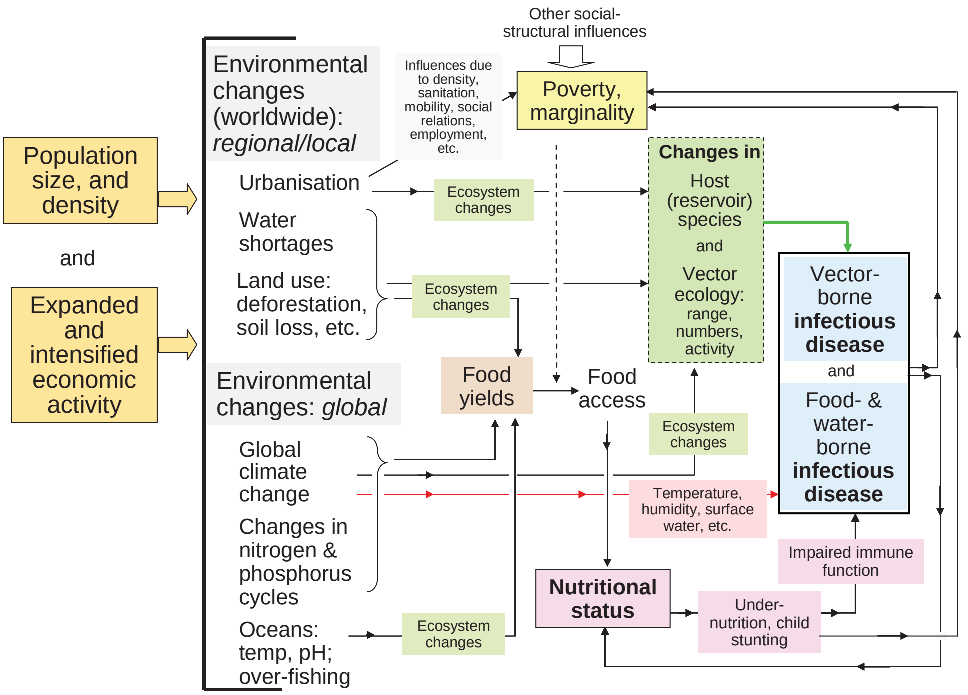

Figure 2

This figure illustrates some of the direct and indirect pathways by which large-scale environmental changes, including global climate change, can affect human health. Many stressors produce physical injury and displacement, often accompanied by trauma-induced mental health problems. The indirect impacts of climate change on health involve two major categories of different mediating factors. Changes to oceans, land use, and land cover are ecosystem and ecosystem-level processes that interact synergistically via various feedback loops. These influence factors including food availability, which in turn affects general health. Ecosystem-level processes also affect pathogens, their vectors, and intermediate-host reservoirs that drive infectious disease risk. Urbanization is another major factor that affects land-use and ecosystem functions, interacts with climate change, and contributes to demographic and socioeconomic conditions (including levels of poverty) that influence disease risk. This complex diagram should be viewed as indicative; it does not attempt to show all likely interactions and external drivers, such as sources of greenhouse gas emissions and policies, that contribute to regional and local environmental changes.

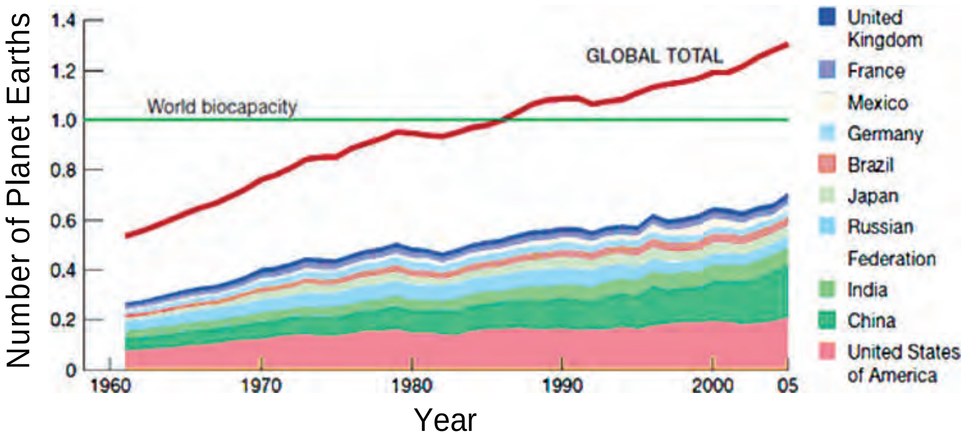

Figure 3

Time trend in estimated ecological footprint, globally and for countries with the largest total footprints in 2005. The planet's biocapacity was first exceeded in the 1980s, the decade in which various global environmental changes such as stratospheric ozone depletion, global climate change, and accelerating loss of biodiversity became apparent (108).

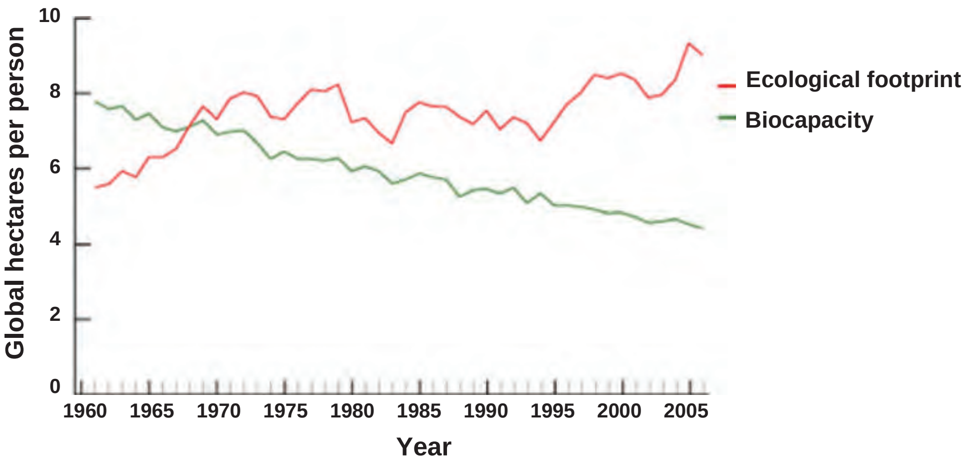

Figure 4

Time trends in per-person ecological footprint and biocapacity in the United States from 1961 to 2006. Biocapacity varies slightly each year with ecosystem management, agricultural practices (such as fertilizer use and irrigation), ecosystem degradation, and weather. Note that the United States exceeded its biocapacity much earlier than the world at large did. Living standards and health continued to improve, not only because of lags, but because of U.S. appropriation of offshore biocapacity. Source: Reference 31.

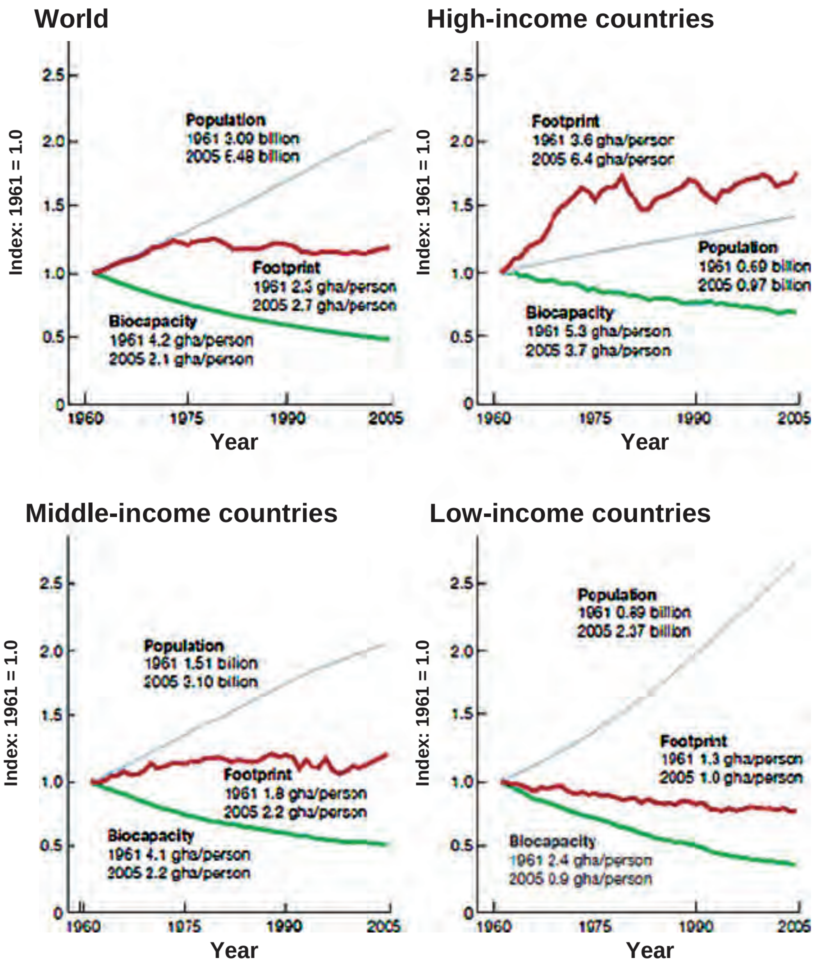

Figure 5

Time trends, during 1961–2005, in population growth, per-person ecological footprint, and per-person biocapacity of the relevant local environment: whole world (*top-left*), and three income-based groups of countries. Note that each variable is assigned a value of unity in 1961, and subsequent proportional changes are shown against the vertical index axis. Source: 108. Globally, the per-person footprint has leveled since about 1975, primarily because of the disproportionate population increase among low-income populations. However, globally the total EF has continued to rise, not least because total population has continued to rise (see **Figure 3**). gha, global hectares.

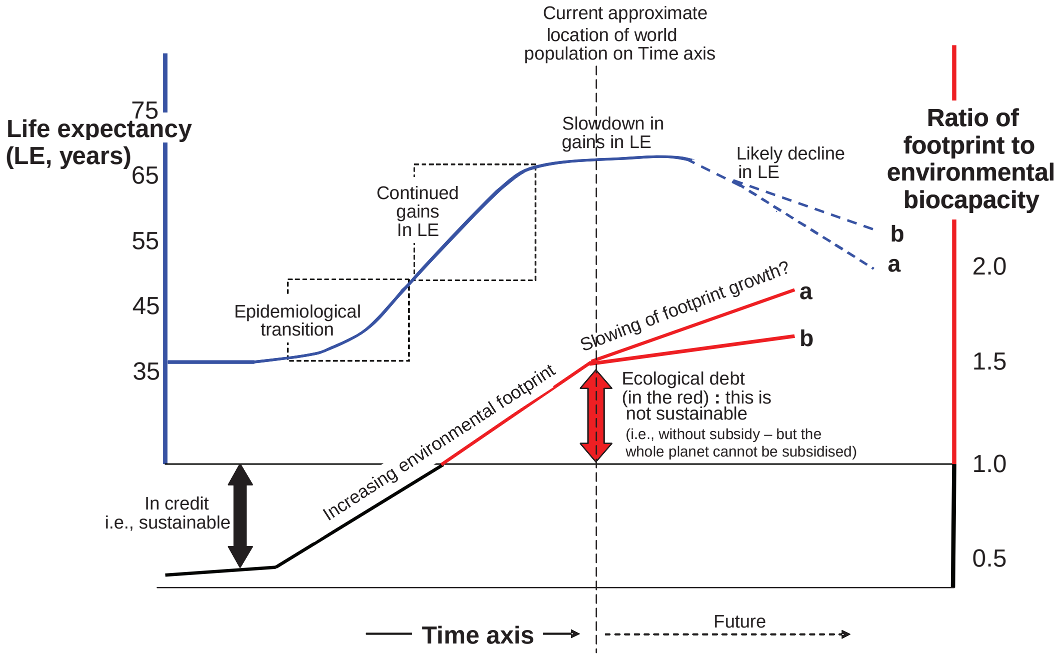

Figure 6

Schematic representation of time trends in global population health (GPH, measured here as life expectancy) and population ecological footprint during typical stages of rapid economic growth and social change (demographic and epidemiological transitions). The graph notionally applies to populations everywhere. It suggests likely adverse trends in GPH in the coming decades if the global environmental footprint continues to increase.

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