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Planetary epidemiology: towards first principles

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Abstract

Purpose of review: To combine evolutionary principles of competition and co-operation with Limits to Growth models, generating six principles and one proposition for a new sub-discipline, called "planetary epidemiology". Suggestions are made for how to quantify four principles.

Recent findings: Climate change is one of a suite of threats increasingly being re-discovered by health workers as a major threat to civilization. Although "planetary health" is now in vogue, neither it, nor its allied sub-disciplines have, as yet, had significant impact on epidemiology. Few if any theorists have sought to develop principles for Earth system human epidemiology, in its ecological, social and technological milieu.

Summary: The principles of planetary epidemiology described here can be used to stimulate applied, quantitative work to explore past, contemporary and future population health, at scales from local to planetary, in order to promote enduring health. It is also proposed that global well-being will decline this century, without radical reform.

Keywords: Earth system, environmental epidemiology, global health, limits to growth, planetary boundaries, planetary health.

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Introduction

Epidemiology has its roots in ancient observations, hypotheses and policy decisions, made using individual and small population level data. Some ancient customs appear relevant to public health, including some which generated social distance and discrimination, such as leper shunning, flight from plague and taboos around food and hygiene (1). Some principles of vaccination and immunity have been understood for over one thousand years (2, 3).

More than 350 years ago, just before the last Great Plague of London (in Britain), John Graunt, a prosperous haberdasher and administrator, published "Natural and political observations mentioned in a fallowing index, and made upon the bills of mortality" (4). Bills of mortality were completed by older women, respected for their life experience, who were charged with attributing approximate causes of death to the recently deceased. These bills, the forerunner of death certificates, were then a comparatively recent invention, recorded and sold on a weekly basis (5). Morabia writes: "Thus, when those who were financially able to move out of London read in the Bills that plague deaths had seized the poor parishes, they could organize an ordered retreat, hopefully limiting the extent of the mayhem" (6).

Graunt is now regarded as a pioneer, even a founder, of demography, statistics and epidemiology (6). He searched for and identified patterns (using methods today known as time series analysis) in data which by then had accumulated weekly, though with gaps, for more than 50 years. His feat was recognised by his election to the world's first Royal Society, based in Britain and then very recently founded, in 1660, only two years before Graunt's publication " (6). His feat is celebrated (by some) as the birth of modern epidemiology because he was the first to use population data to identify principles, rhythms and patterns of disease and mortality, hidden from day to day, short time-period bound observers (5).

Today, millennia of economic development and improved communication and transport technology have created a population of unprecedented size and connectedness, in a time increasingly called the Anthropocene (7-10). Epidemiological techniques have evolved far beyond those available to and initiated by Graunt, and increasingly rely on big data, machine learning and software to generate often subtle and sometimes contested insights into the causes of disease, and hence their possible prevention and treatment.

Driven partly by the wish to reduce human suffering and to alleviate the fear of disease, epidemiology has had many successes since Graunt's time, with many important landmarks, building on myriad insights from many disciplines. One is Bradford Hill's postulates, which seek to disentangle causation from association (11). Others are the cyclic, culturally sanctioned, prominence accorded to social, political and corporate health determinants (8, 12), from Virchow to the WHO Commission for the Social Determinants of Health (13, 14). A recent trend is the re-emerging awareness that humans are part of the natural, or ecological word, an insight that can be traced to Indigenous philosophy (15, 16).

Eco-epidemiology and its variants

This emerging field of concern about the “Earth system” (our planet’s interacting physical, chemical, and biological processes) and health has had a growing impact on public health (and some impact on epidemiology) (17), and has many names and variants (18). These variants include “eco-epidemiology” (19, 20), “ecological public health” (21) “ecohealth” (22), “ecomedicine” (23), “ecosystem health” (24), “One Health” (25) and “planetary health” (7, 26-30).

In parallel, tropical medicine has been rebadged as international health and, more recently, “global health” (31, 32). But global health can also be interpreted as different from its predecessors, by recognizing a category of risk, unfamiliar to most population health workers (32). These risks relate to transboundary influences which physical borders have little capacity to exclude, from climate change to biodiversity loss (33) and other approaching “planetary boundaries” (34).

There is also an expanding literature on the “global epidemiology” of specific diseases and health related behaviors such as drug injecting behavior. These include for infectious diseases, cancers, cardiovascular diseases and metabolic disorders. The growing crisis of widespread antibiotic resistance is also recognized as having deep social and ecological causes (35, 36).

Six principles of planetary epidemiology and one proposition

To date, few if any theorists have attempted to outline how an epidemiology of the entire human population may be conceptualised at the planetary level. Such a task is necessarily speculative. But in a time in which identified, exo-planets (even with potential liquid water) are becoming numerous (and following the recent launch of Project Blue, designed to enhance the detection of habitable planets) (37), some researchers may consider that the attempt to understand human health at the planetary scale is no longer unimaginable, nor without value.

Many thinkers, since Russell and Einstein, have warned that nuclear war has the potential to cause a new Dark Age (38) and therefore undermining the notion that humans could one day travel to the stars because we do not have a flourishing population enduring for millennia on the home planet, free from crippling fear of anthropogenic climate change and other perils.

This paper proposes six principles, tentatively advanced as fundamental arguments, that necessary underpin an understanding of epidemiology and population health at the planetary scale. These principles are each derived from fundamental biological laws and basic social relationships. In the Supplementary Material, four algebraic formulae are listed for these principles. The algebraic terms used in these equations are also introduced in the text, with abbreviations (see also table 1).

While all models are simulations and thus simplifications of reality, it is hoped that these principles and equations may be used to stimulate new work, both theoretical and applied, of benefit to the promotion of enduring public health. Applied studies may be used to explore past, contemporary and future population health, at scales from the local to the planet.

In addition to these principles, one proposition is also advanced. This is also accompanied by an equation, which, like the others is potentially quantifiable. This proposition is more controversial than the principles, although it follows logically from them.

These principles and single proposition are based on an extensive multi-disciplinary literature. While this literature cannot be thoroughly reviewed here, some of its key principles are discussed. The most important insights relate to three "fathers" of evolutionary theory; Malthus, Darwin and Wallace. More recent influences are the framers of the Limits to Growth (39), and the human ecologists and others who have warned, more recently, that continuing the recent trajectory of civilization will precipitate its collapse (40, 41). These principles and proposition are not exhaustive, and are intended to complement and perhaps cross-fertilize with conventional epidemiological methods.

This paper also seeks to differentiate itself from "planetary health". This term was coined as early as 1980 (28), but revived in recent years by the Lancet/Rockefeller Planetary Health Commission (7) and even more recently by the In Vivo Network (28). Although some recent writings on planetary health mention conflict and hint at the plight of civilization (42) the Lancet/ Rockefeller version increasingly seems to be evolving as a hybrid in the narrow space between One Health and EcoHealth (29). Planetary epidemiology is proposed here as fundamentally different to any form of planetary health because of it potentially quantitative nature, as explored in the five equations described in the Supplementary Material, and because it accepts the reality of limits to growth (34, 43, 44).

Principle 1: Malthus, evolution and the most fundamental biological principle

In 1798 Malthus published the first of six editions of "The Principle of Population" (45). Often attracting controversy, this work has been extremely influential, not least as it underpinned the theory of evolution, jointly proposed 60 years later by Darwin and Wallace (46). An early sentence in this first (1858) paper on evolution states "all nature is at war, one organism with another, or with external nature".

Even in 1858 it must have been well recognized that many, perhaps the great majority, of species form alliances, both with the same species and sometimes with others. For example, humans have long co-operated with dogs (47). The vast numbers of organisms that form the microbiome that each human (and every other animal) is associated with co-exist, in a normally stable network, involving competition and co-operation (48), with benefits, generally, to each party (host and microbiome). Humans, perhaps since their emergence as a species, also have co-operated with other humans, at many scales (49), including families, tribes, language groups, religions, nations, and multi-national coalitions.

Yet, despite this co-operation, the entirety of life, including humans, also competes for finite resources such as soil, space, nutrients and fertile. The biomass of humans ("anthropomass") was estimated in 2011 to exceed all wild terrestrial mammals, combined, by an order of magnitude (50). Many species are already extinct due to human action (51), an ongoing trend for at least 125,000 years (52).

Since that estimate in 2011, the human population has increased by several hundred million, undoubtedly at the additional expense of non-human species, although some animals and plants, such as cattle, chicken and palm oil, have flourished due to human intervention (53). To risk stating the obvious, we cannot "have our cake and eat it"; humans require food and other resources, and humans continually capture resources which would otherwise be used by non-humans.

The total quantity of many resources is declining, and the quality of many is also falling. For example, easily recoverable supplies of oil are growing scarce, driving wells off-shore, even into the deep ocean (54). On a per capita basis, these declines are even more stark. Although this fall in the stock of many resources has "fueled" much of development, an ongoing decline, at least beyond a threshold, will inevitably have adverse consequences for human well-being, as numerous authors have pointed out (41, 55, 56), including some from a health background (7-9, 20, 21, 34, 43, 57-59).

The most fundamental biological principle is thus proposed as the existence of competition for finite resources, despite countless examples of co-operation. The first principle of planetary human epidemiology follows from this basic reality.

Humans can increase their numbers (and/or average weight, longevity and affluence) but not without reducing the collective biomass of other species, even if some non-human species, favored by humans largely as food, benefit.

Principle 1 (summary): Humans compete with non-humans for finite natural resources

Principle 2: Ingenuity and natural resources

Human ingenuity (i) can be used to increase the fraction of resources (R) available to humans and non-humans. (See table for abbreviations used in the algebraic representations, mentioned in the text and presented in more detail in the appendix). There are countless such examples. Three important ones are (i) the Haber-Bosch process (that increased the nitrogen available to the human (and animal) food chain, by extracting it from air, on a much greater scale than leguminous plants do), (ii) the use of fossil fuels and phosphorus, each recovered from Earth's crust, and (iii) the development of more efficient forms of agriculture, called the Green Revolution (for plants) and intensification (for livestock and farmed fish).

Although ingenuity is mainly used to increase (and conserve) resources for humans and for species that humans use, it can also be used to increase resource availability for species with which humans compete. While this can be deliberate, such as the creation of wildlife sanctuaries supplemented by feed grown with synthetic fertilizer, it also occurs accidentally, such as via the carbon fertilization effect, the increase in photosynthetic activity that has occurred due to higher carbon dioxide concentrations (60, 61). However, the main beneficiary of this effect is to plants, and perhaps some farmed species dependent on pasture. The effect of climate change on wild animal populations is adverse, principally through alterations to their distribution (62).

Ingenuity can also increase the efficiency of resource use, such as electric lighting or forms of propulsion that require less energy. Computers have reduced the need for paper, filing cabinets and filing clerks. However, sometimes, these improvements are partly or even fully offset by increased use of the resource, a "rebound effect" or "paradox" described by Jevons, a British economist, in the 1860s in the context of declining coal and increasing efficiency of steam powered engines (63).

Human actions can also reduce the quantity and quality of resources, such as via atmospheric haze, or "global dimming" (64, 65). A component of aerosol loading is tropospheric ozone, which reduces crop growth (66). These forms of atmospheric pollution not only reduce the power of the sun (a vital important resource) but directly harm many aspects of health (67). Rising carbon dioxide concentrations also impair the nutritional quality of many foods (68, 69).

Principle 2 (summary): Ingenuity cannot indefinitely increase natural resources

Principle 3: Ingenuity, institutions and human well-being

Human ingenuity is also a resource, a product of human minds, bodies, behavior and health, rather than from "external" nature. The role of ingenuity in increasing and conserving, but also inadvertently degrading and depleting natural resources has been described. In this section, the case is made that ingenuity also contributes to the degree to which human well-being (W) can be created from any (natural) resource base.

Human well-being is context dependent, and thus not universally definable (70). However, despite imprecision, it is here proposed, from an anthropocentric perspective, that major constituents of human well-being include human population size, human life expectancy (LE), health adjusted human life expectancy (HALE) and human affluence (a). Note that the highest levels of well-being may not necessarily be obtained by maximizing any of these components, especially affluence, as conventionally defined (71). For example, attributes that contribute to well-being such as social connectivity and harmony cannot necessarily be purchased (72). The mindful consumption of limited resources (voluntary simplicity), acquired through self-restraint and savings may lead to better health than the profligate use of resources seen as endless, but purchased with credit, leading to indebtedness and anxiety. Life expectancy in Cuba, which is much poorer materially, approximates that of the U.S., even if Cuban health data are manipulated for ideological reasons, as has recently been claimed (73, 74). But many people aspire neither for voluntary simplicity nor for restricted freedom, whether in a socialist, capitalist or other settings.

Ingenuity contributes to higher well-being in manifold ways. For example, modern health care systems, industrial production of goods and services, and insights from epidemiology and public health have done much to improve and protect health, from clean water to vaccines and knowledge of nutrition.

Human "institutions" (I), such as laws, customs, culture and philosophical and religious understandings and practices are also vital contributors to human well-being (70). Many of these institutions govern material and social resource distribution. For example, in all human populations, customs and rules dictate the availability and use of food and other goods to people. Infants are fed, workers paid, and even prisoners and the aged and infirm (generally) provided with a share of available resources. Such customs do not ensure that distribution is equal, nor fair. However, overall, cohesive populations do divide resources in ways that enable group survival, and in many cases flourishing, at least for the average group member.

Warfare, more controversially, may also be considered to be a human institution, though neither benign nor beneficial. Although war leads to great human suffering, it is often conducted in order to defend or to capture additional resources, both natural (e.g. fossil fuels, fertile land, water) and human, or human-created (e.g. slaves, infrastructure and intellectual property). But, while war may preserve or enhance the well-being of a subset of the global population, it can never improve health at the global scale.

Large scale human to human violence cannot be whitewashed in any analysis of planetary epidemiology. However, if the reality of limited planetary resources, vulnerable to increasing scarcity and degradation can be better understood then it is possible that human society may take steps towards the evolution of planetary scaled co-operation. In turn, that is likely to be a step towards the reduction and eventual eradication of organized warfare.

Natural resources, enhanced and conserved by ingenuity ($R_{(i)}$), can be used to increase human numbers and may also increase other constituents of human well-being. Ingenuity and institutions can also be used to enable more efficient use of resources, to benefit humans ($R_{(h)}$). If human population increases human well-being will generally require additional $R_{(h,i)}$.

The relationship between the other components of human well-being and resources is complex, context dependent and contested. However, there is surely widespread agreement that the well-being of most of the world's population (which is materially poor) will be increased by their greater use of natural resources ($R_{(h)}$) (56),while the well-being of nearly all people, rich and poor, can be enhanced by the more skillful application of human qualities and other human provided resources, such as social inclusion and justice (75).

This topic, however, is too intricate to fully discuss here. In rare cases (such as the United States in the late 19th century) LE and population (P) have increased rapidly, but it is more common that ΔP (change in P) declines as ΔLE, ΔHALE and ΔA increase (76). But this does not necessarily mean that well-being, which is subjective, will be maximized by the demographic transition, even though living standards are generally higher in countries in which population growth is low or even negative.

The life expectancy in many parts of sub-Saharan Africa is lower than in northern Europe, while the birth rate is higher, and the average age much less. The trend for migrants to flow, and seek to flow, from Africa to Europe (rather than the reverse) does suggest greater well-being in Europe, for any arbitrarily identically sized population. Many similar phenomena occur elsewhere, such as the flow of refugees and asylum seekers from Central and South America to the U.S. Alternatively phrased, it is reasonable to argue that if two populations have identical size, the one with higher LE and HALE will have greater well-being. But this general principle may not necessarily apply at all scales.

Principle 3 (summary): The constituents of human well-being depend on natural and human resourcesPrinciple 4: Pollution and resources

Disgust, described by Darwin as one of six core emotions (1) appears to be an inborn human characteristic (77). Its existence helps explain how humans have recognized some forms of local pollution, such as with human feces (78), long before the era of microbiology. At other times, however, such as lead poisoning in ancient Rome (79), hazards were not well understood, and population health declined, partly as a result. Today, the global threat of rising greenhouse gases is partly understood at a population level, but understanding of more visible forms of pollution, such as from air particulates and plastic may be better appreciated.

Severe pollution (p) harms resource quality, as well as well-being more directly. For example, particulate air pollution reduces crop yields, and spoils the quality of inhaled air, harming respiratory, cardiac and neurological function (80, 81). However, below a threshold, pollution is generally tolerated by populations who accept it as a cost for material affluence.

The relationship between resources and increased levels of greenhouse gases is more complex. To date, higher greenhouse gas levels have enhanced photosynthesis (60), leading to greening of parts of the planet, especially at higher latitudes (82). In general, crop harvests have probably benefited from warmer weather, although there are already exceptions to this, particularly in the Russian heatwave of 2010 (83, 84). The increase to total R(h), as a result of the global warming experienced since the 19^{th} centuryis probably higher than any current offset such as from sea level rise or more forest and urban fires. But in future, perhaps the very near future, the impact of climate change on resources available for humans is likely to be overwhelmingly negative, especially if average warming exceeds 1.5^{0}C above pre-industrial levels (85).

Principle 4 (summary): High levels of pollution lower resource quality and sometimes quantity, harming well-being

Principle 5: Resource scarcity, overshoot, trade and war

All species need resources, and resource-seeking behaviors may be inherent to all species. Chemotactic bacteria on an agar plate will move towards food, and wolves attack sheep. It has been reported that collared flycatchers decide where to nest and whether to return for the next nesting season based in part on knowledge of their neighbors' reproductive success (86). In other words, this species uses information associated with resource availability to inform decisions.

Many humans cherish myths of fertile "Edens". "Biophilia" (love of life, including green, verdant places) may be inherent (87). The search for spare, potentially abundant resources has been postulated as a powerful motivator for human migration (88). The pejorative term "economic migrant" recognizes a similar driving force.

But where migration is impossible, or too costly, humans can remain conserve, recycle, and substitute resources. When necessary they will accept lower living standards. Humans can, and sometimes have, chosen fertility restriction, millennia before the development of modern contraception (89). But, in many cases, societies will opt for violence and war, rather than accept scarcity or voluntary restraint.

If local resources grow scarce, or if humans demand distant resources (such as tin, essential in the bronze age) (90) institutions can be used for their acquisition. Such institutions can be peaceful (trade) (t), or violent, such as war (w). Both can occur at multiple scales, from the local (food bartering, cattle raiding) to the global, such as modern trade in oil, or through empires and even global war.

At times, humans have "overshot" local resource supplies, triggering survival crises, most famously on Easter Island (91). As few as 2,000 people, with a population density as low as 0.01km^2 triggered the extinction of the large flightless moa in the South Island of Aotearoa (New Zealand) within 150 years of human settlement (92). An unknown environmental factor (perhaps a series of tsunamis) has been hypothesized to trigger conflict and other forms of societal perturbation widespread in Polynesia in the 14th and 15th centuries (93). Could future environmental scarcity help trigger unrest at the global scale?

Principle 5 summary: Institutions cannot always fully compensate local resource scarcity

Combining principles 4 and 5 leads to the fourth equation, and a combined principle: pollution and resource scarcity reduce well-being, unless compensated (at the local scale) by institutions such as trade, innovation, substitution or war. War, leading either to resource appropriation or destruction (or both) cannot improve human well-being on the global scale.

Principle 6: Disease, undernutrition, and planetary epidemiology

The final principle discussed here concerns undernutrition and epidemics, two phenomena that are often closely related. It is argued that if global population health determinants, such as resources (including food and shelter), ingenuity and institutions (peace, health care systems, and basic relief remedies, including food aid and humanitarian ceasefires), exist and persist at sufficient scale then large-scale epidemics and famine should be avoidable.

But such determinants and institutions are currently insufficient, despite the attempts of many actors for decades, including the United Nations agencies and philanthrocapitalists. In 1968 the ecologist Paul Ehrlich warned of catastrophic famines in the 1970s (94). However, due to the Green Revolution, food security improved almost everywhere. In the following decades Ehrlich was mostly ridiculed as a doomsayer. Today, however, there are at least five famines in the world; far more than optimists in the heyday of neoliberalism predicted (44)

In recent years, food relief convoys in sub-Saharan Africa have been attacked (95). The famine in Yemen and the catastrophe of Syria have also been worsened by the breakdown in international institutions, intended to prevent the grossest civilian suffering (96, 97). Famine has catastrophic implications for human health, including impaired immunity and, as a consequence, infectious diseases, sometimes as pandemics.

It is now well documented that the Antique Ice Age (6th century), caused by intense volcanic eruptions, reduced harvests in the Mediterranean (and China), contributing to migration, invasion, and, logically, undernutrition, in turn contributing to the Justinian plague, caused by *Yersinia pestis* (98, 99). The Black Death in mid-14th century Europe followed the great famine of 1315-22, soon after the end of the Mediaeval Warm Period (100). The devastation of "Spanish" influenza (c1916-1920) may have been contributed to conditions of widespread crowding, undernutrition and gas attacks at the close of the Great War (101).

Although both of the climatic shifts that may have contributed to these great plague epidemics involved cooling and were non-anthropogenic, human induced warming (and in some cases regional cooling, such as from any further weakening of the Gulf Stream (102)) may also create, in future, conditions for widespread undernutrition and pandemic emergence (103). Even if pandemics can be avoided or reduced by good public health practices, such services appear vulnerable if pockets of chaos, today already visible, increase (103).

Principle 6 (summary): Pandemics with high mortality have important eco-social co-factors

From principles to a proposition

Six principles of planetary epidemiology have now been introduced. Although their underpinnings exist in many literatures, they have not previously been presented in the way this paper attempts. Some aspects will be controversial and challenging, especially to audiences and policymakers who accept the dominant narrative of inevitable human progress, or that human ingenuity is a ultra-powerful wild card, able to solve any dilemma.

However, it has been argued, these six principles are soundly based on fundamental laws (such as of competition and co-operation) and on basic patterns of human behavior. Thus, it is proposed, they warrant the label “principle”. However, in addition, the paper presents what it calls a proposition, recognizing its speculative nature, and that many readers will be reluctant to consider the implications.

Proposition 1: Scarcity, well-being and health at the planetary scale

Above, it has been argued that trade, war and other forms of institutions cannot fully compensate for resource scarcity, should it occur, at the planetary level. That is, in the current state of planetary social evolution, not everyone can win, nor in some cases, even retain their previous level of well-being (i.e. if resources decline globally.) This is illustrated by the following example.

In 2010-12 the heatwave in Russia and Ukraine and the subsequent U.S. drought and unusual heat generated a moderate downturn in global food production, with an associated rise in the global food price (26, 83, 84). This price increase harmed the nutrition and living standards of monetarily poor populations, especially where their nutrition depended on food imports, such as in Egypt, and elsewhere in the Middle East.

In theory, if institutions that maintain or enhance planetary well-being were sufficiently advanced, the 2010-12 food price rise could have been substantially alleviated by practices such as increased diversion of plant foods (e.g. soy, grain) from intensive livestock production for humans. But there is no evidence that this occurred on a substantial scale.

To date, humans have eroded natural capital, approaching or even exceeding planetary boundaries, and yet aggregate human well-being has increased. This is true, despite the current famines, civil wars, record numbers of displaced people, and other atrocities of our time. It is true because (as explained above), total population, as well as life expectancy and the other components of well-being described above have improved. Despite rising global life expectancy, HALE and affluence, there are today six separate famines, a record number of refugees and displaced people (43, 104), and hotspots of "ethnic cleansing" in Myanmar (105) and potentially in Assam, India (106). There is also a devastating war in Syria, in part arising from environmental causes, including, probably, anthropogenic climate change (107, 108).

Can this improvement continue, or might a threshold be reached, beyond which a decline in well-being becomes inevitable? Such a decline was forecast to occur by approximately 2050 in the "standard run" of the Limits to Growth models developed in the early 1970s by systems theorists at the Massachusetts Institute of Technology (39, 44, 109). Like the work of Paul Ehrlich which forecast many famines in the 1970s, the Limits to Growth models have often criticized, but with far less justification. This is because it is still too soon to conclude if their models are optimistic or pessimistic. However, at least to a few health workers, the signs are deeply disturbing (44, 59, 110).

Proposition 1 (summary): The scale of human co-operation is currently insufficient to prevent declining well-being at the global scale, consequent to the fall in resources underway. The threshold at which this overall decline in resources will translate to a global decline in well-being is likely to occur in this century, unless extraordinarily effective action is rapidly taken.

Conclusion

This paper has sketched six principles of how epidemiologists might begin to consider "planetary epidemiology". It has also made one proposition. Two important elements have been excluded. One is the role of stochastic (chance) events has not been discussed, such as the emergence or sudden death (other than by assassination or in other ways occurring through conspiracies) of important social and political leaders, or the risk of a Tambora-scale volcanic eruption (111). Also lacking is a discussion of a putative "dose response" relationship governing the emergence of events such as war or epidemic given sufficient stimuli in a sufficiently "primed" milieu (103).

The most fundamental argument presented in this article is that human well-being is a product of resources, both human and natural, and that the resource supply is limited, and declining on a per capita basis (34, 43, 55, 112-114). As pollution and scarcity worsen, sustaining future population health is thus an enormous challenge. Coincident with the decline in non-human associated biomass, its "quality" appears also to be falling, such as the precipitous decline in many insect populations (115-117).

The number, authority, and consistency of warnings about these issues should be of much deeper concern than currently seems the case, including among epidemiologists (118). If the principles presented in this paper are broadly correct, and if global resources do continue to fall in quantity and quality (on a per capita basis), then falls in global human well-being appear likely, and could be accompanied by a significant decline in human population size. This possibility is almost completely ignored in the dominant "official" forecasts for our species this century, such as projections of global population size in 2100 reaching 11.2 billion, published by the UN Department of Economic and Social Affairs (119).

Some workers have proposed that we may thus be nearing "peak health" (8, 59), beyond which lies descent. Growing evidence, ancient and recent, supports this. The literature on the collapse of past civilizations is very extensive (71, 90, 120-122). The Bronze Age civilization has been explicitly suggested as an analogy for our time (90). The fall of Rome may be another (122). Although at least one expert on collapse has argued that the concerns over incipient collapse are overstated and "simplistic" (120) the same author also appears to support the view that the 1994 genocide in Rwanda was primarily caused by "ethnic hatred" (123). Such explanations are only partial, and underestimate the contributing ecological and demographic dimension to that event (124, 125). Many other authors are less sanguine concerning the potential for modern civilization to breakdown (40). To a large extent, positions on the possibility of collapse are divided between optimists and pessimists, between "cornucopians" who claim progress is inevitable and those who argue that progress and ingenuity include the capacity for self-reflection and a change of course (126).

The arguments made in this article are unlikely to alter the view of optimists. However, irrespective of ideology, it should be clear that the potential severity of these issues, and especially their health implications, makes this topic relevant to epidemiology.

Traditionally, scientists have been encouraged (and rewarded) for being dispassionate. However, epidemiology is in one important sense different to other forms of science. It is the basic science of public health, a discipline whose practitioners often possess an ethos sensitive to human suffering and its prevention. Graunt was probably driven chiefly by curiosity, but his work has helped reduce suffering. Workers attracted to planetary epidemiology are as yet few, but their numbers must grow if humans are to avoid the deep trouble that otherwise seems ahead (127). If humans are to flourish, we may need to modify our evolutionary drive in order to leave more resources for the other species upon which we ultimately depend.

Other commentators who clearly foresee the risk of civilization collapse have written "To escape a situation of lock-in with multiple, reinforcing maladapted cultural variants, societies can foresee potential decline and develop other cultural variants, thereby allowing a positive regime shift, or one with merely temporary setbacks, thus changing the course of the future (71). Many important "tools" are needed for planetary epidemiologists. Perhaps the most vital element is the capacity to think fairly and deeply about these issues, and to work on them in collaborative, interdisciplinary groups. As the late Tony McMichael observed, epidemiologists should not be "prisoners of the proximate" (17) hostage to concerns (for which investigation is often well-funded) of vanishingly small significance, in the context of what McMichael called planetary overload (57).

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Supplementary Material

Table 1. Factors used in the algebraic relationship described in this paper, and their symbols. The capitalization of some varies deliberately, as some symbols share the same first letter.

Element	Examples/comments	symbol
affluence	Access to and consumption of natural and human resources	A
Health adjusted life expectancy	Years in a coma count the same towards LE as years of vigor, but less towards HALE. This seems fair, but what is the value of years living with mild epilepsy?	HALE
ingenuity	Invention, institutions, tinkering, recognition of crisis	i
Institutions	Trade, co-operation, customs, invasion, war	I
Life expectancy		LE
pollution	Greenhouse gases, particulate matter, plastics, pesticides, other harmful chemicals, heavy metals	p
Population	Human numbers	P
Resources – natural	Sunlight, soil, water, fossil fuels, favorable climate, ecosystem services (e.g. pollinators, coastal protection)	R
Resources for humans	Photosynthesis, land and water for agriculture; fossil fuels, minerals, water for industry and drinking	$R_{(h)}$
Resources for non-humans	Resources left for "nature" defined as populations of non-human species not currently used by humans	$R_{(n\text{-}h)}$
Resources supplied by humans	Ingenuity, institutions, human labor, aged care, child care, health care, entertainment, expertise	not used
Resources –	Including by ingenuity (generally increased),	$R_{(ip)}$

modified	pollution (generally decreased, exceptions include carbon fertilization effect)	
Stochastic events	Volcanic eruptions, earthquakes, assassinations, financial crises	not used
trade	Barter, reciprocity, purchase, treaties	t
war	And other forms of organized violence, from the local (e.g. cattle raiding) to global	w
Well-being	Constituents include affluence, HALE, LE and population	W

This appendix lists the summarised versions of the six principles and the one proposition. It also shows algebraic formulae for the five of the principles (two of which are combined) and the proposition.

Principle 1: Humans compete with non-humans for finite natural resources

Let R = total planetary "natural" resources; and $R_{(h)}$ = the fraction of R used by humans, with $R_{(n-h)}$ being the fraction of R used by non-humans, so that

Equation (1) $R_{(h)} + R_{(n-h)} = R$.

Principle 2: Ingenuity cannot indefinitely increase natural resources

Although ingenuity can increase resources so that the marginal increase (Δ) in $R_{(h)}$ causes diminished harm to $R_{(n-h)}$, ingenuity is not sufficient, and may never be sufficient, to enable increased human well-being with no decline to $R_{(n-h)}$.

If $R_{(i)}$ = total planetary "natural" resources enhanced by ingenuity, then

Equation (2) $R_{(h,i)} + R_{(n-h,i)} = R_{(i)}$. $R_{(i)} < \text{infinity}$.

Principle 3: The constituents of human well-being depend on natural and human resources

The constituents of well-being can be described algebraically:

$$W = f\ (a, HALE, LE, P)$$

Well-being is also a function of natural and human resources (ingenuity and institutions)

$$W = f\ (R, i, I)$$

Combined, this means

Equation (3) $W = f(a, HALE, LE, P), R_{(h,i)}, R_{(n-h,i)}$

Principle 4: High levels of pollution reduce resource quality and sometimes quantity, harming well-being

Principle 5: Institutions cannot always fully compensate local resource scarcity

Combining principles 4 and 5 leads to the 4th equation and a simplified principle: pollution and resources scarcity reduce human well-being, unless compensated (at the sub-global scale) by institutions including trade (t), innovation, substitution or war. Well-being also depends on human resources.

Equation (4) $W_{(local)} = f(R_{(h)(i,p)}, t, w, I)_{(local)}$

Principle 6: Pandemics with high mortality have important eco-social co-factors

Proposition 1: The scale of human co-operation is currently insufficient to prevent declining well-being at the global scale, consequent to the fall in resources underway. The threshold at which this overall decline in resources will translate to a global decline in well-being is likely to occur in this century.

If $R_{(global)}$ declines then so will $W_{(global)}$. This is because even if some $W_{(local)}$ is maintained it will be at the expense of other $W_{(local)}$.

Equation (5) $W_{global} = f(R_{(h,i,p)}\ t, w, I)_{global}$

$W_{global} = \sum (W_{local\ (1)}, W_{local\ (2)}, W_{local\ (3)} \ldots W_{local\ (n)})$

If R declines, $W_{(global)}$ will also.

Conflict of Interest

Colin D Butler declares that he has no conflict of interest.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

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