Impacts of global environmental change on future health and health care in tropical countries

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The aggregate human impact on the environment now exceeds the limits of absorption or regeneration of various major biophysical systems, at global and regional levels. The resultant global environmental changes include altered atmospheric composition, widespread land degradation, depletion of fisheries, freshwater shortages, and biodiversity losses. The drive for further social and economic development, plus an unavoidable substantial increase in population size by 2050 – especially in less developed countries – will tend to augment these large-scale environmental problems. Disturbances of the Earth's life-support systems (the source of climatic stability, food, freshwater, and robust ecosystems) will affect disproportionately the resource-poor and geographically vulnerable populations in many tropical countries. Ecological disturbances will alter the pattern of various pests and pathogens in plants, livestock and humans. Overall, these large-scale environmental changes are likely to increase the range and seasonality of various (especially vector-borne) infectious diseases, food insecurity, of water stress, and of population displacement with its various adverse health consequences.

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The aggregate environmental impact of humankind has begun to change some of the world's great biophysical systems. Such large-scale systemic environmental change is unprecedented in human history. It includes worldwide loss of biodiversity, land degradation (including deforestation and desertification), depletion of fisheries, declines in major freshwater aquifers on every continent, and global dispersion of non-biodegradable chemical pollutants[1,2]. Further, we are altering the composition of the lower atmosphere and stratosphere. According to climatologists, the former has begun to cause global climate change[3]; meanwhile, the latter is increasing the amount of UV irradiation at the Earth's surface[4].

There is a profound connection between the natural world and the human economy; there can be no sustained economic development without an intact natural environment[5]. In turn, human well-being and health depend fundamentally upon the 'goods and services' provided by the world's life-support systems and upon equitable social-economic development. However, the linkages between these global change processes and between their joint impacts – direct and indirect – and the uncertain future course of human social-technical development, makes the estimation of potential consequences for human health a complex task[2].

In this paper we review the likely health impacts of global environmental changes with special reference to tropical countries, followed by a brief consideration of the general implications for health care. We focus particularly on the potential changes in infectious diseases and food supply. Currently, malnutrition causes the greatest estimated loss of disability-adjusted life years (DALYs) (15.9% worldwide), followed by diarrhoeal disease (6.8%) due to poor water, sanitation and hygiene[6].

Assessment of potential future health impacts of global change

Assessment of the likely health impacts of global change entails a set of difficulties[7–9]. These are summarised in Table 1. This type of estimation, referred to as scenario-based health risk assessment[9], yields indicative forecasts of the direction and magnitude of population health impacts. It **cannot** yield precise predictions; there is much irreducible uncertainty.

There are three main approaches to scenario-based health risk assessment[9]: (i) extrapolation, based on specific (historical) analogue situations for some aspects of global change; (ii) formal integrated mathematical modelling; and (iii) generalised assessments that draw on expert judgement.

Analogues of global change

Analogue situations are most likely to come from current or recent times. For example, there have been several recent studies of the regional health consequences of unusual climatic episodes and trends. Marked increases in the incidence and range of malaria were observed during an atypically hot and wet year in Rwanda in 1987[10]. Malaria has been moving to higher altitudes in the Eastern African highlands in association with local warming[11,12]. Certain palaeo-ecological studies have also been useful, for example in relating ancient changes in world

Table 1 Difficulties encountered in scenario-based health risk assessment in relation to global environmental change

1	The exposures are drawn from scenarios of global change processes and their impacts on other biophysical systems; they are not empirically-observable realities. Such scenarios are inherently uncertain.
2	The scenarios include some exposure circumstances outside the range of documented human experience. Extrapolation of empirically-documented health risks requires caution.
3	The exposure scenarios affect population health via diverse mechanisms – direct and indirect, immediate and delayed. Some health impacts would arise via demographic, infrastructural and economic disruption.
4	Assessment of health impacts caused by perturbations of complex ecological systems (*e.g.* changes in the geography of infectious disease vectors) must address the dynamic, non-linear, stochastic behaviour of these systems.
5	Realistic scenarios involve multiple co-existent – and often interacting – global changes. Many systems are changing simultaneously.
6	The projection of scenarios many decades into the future means that they refer to human populations living in unspecifiable future circumstances. (Future eventualities – fertility rates, new energy technologies, vaccine development, trends in urbanisation, levels of poverty, *etc.* – would all affect the vulnerability and response of human populations to global changes. These future contextual changes add further uncertainty to the assessment of future health impacts.)

temperature to changes in the taxonomic profile and geographic range of insects, including those able to act as infectious disease vectors[13].

The El Niño Southern Oscillation (ENSO) allows analogue studies of the likely health impacts of anticipated future increases in climate variability. ENSO – which comprises quasi-periodic reversals in the massive flow of warm surface water and air across the Pacific – is a major determinant of interannual climate variability around the low-mid latitude world[14]. However, the analogy is limited in that ENSO-related climatic changes occur more rapidly and with greater fluctuations than would occur under the projected conditions of global climate change. ENSO-related temperature and rainfall fluctuations have been shown to affect substantially the occurrence of malaria outbreaks in north-east Pakistan and Sri Lanka[15,16]. Approximately quinquennial cycles of malaria in Colombia correlate with ENSO fluctuations[17].

Integrated mathematical modelling

Integrated mathematical modelling is increasingly being used to estimate the future health impacts of global environmental changes[8,9]. Such modelling requires that each component of the chain of causation can be represented mathematically. Linkage of these sequential components is referred to as 'vertical' integration. Horizontal integration incorporates other co-existent global changes, other social-demographic trends, and

societal responses. The several well-recognised difficulties in integrated mathematical modelling include: model development, calibration and validation; scaling; and dealing with an unusual spectrum of uncertainty[8,9].

Integrated assessment can incorporate policy-relevant decision analytic capabilities[20], in addition to the up-front systems that simulate physical, biological and/or social processes. This could include, for example, an evaluation component to compare alternative risks and performance of alternative interventions. Many integrated assessments highlight systems-based modelling and focus on estimating the impacts of alternative scenarios or previously adopted policies[18,19]. The ultimate purpose is to provide policy-makers with an understanding of how competing assumptions, policies and social-institutional arrangements affect the behaviour and impacts of complex systems.

Various mathematical models have been used to assess the impact of climate change scenarios on transmission potential of vector-borne diseases – especially malaria, dengue and schistosomiasis[8,21]. Other such models have been used to forecast future water or food supplies under conditions of global change.

Vulnerability of populations

Populations can differ substantially in their vulnerability. A given disease system may be particularly **sensitive** to the effects of, for example, climate change based on biological or physiological characteristics. However, the ultimate **vulnerability** of a given population to that disease may be considerably modulated by constitutional characteristics and by the capacity for adaptive responses[7].

Certain populations and geographic regions will be particularly vulnerable to the impacts of global change[22]. Populations characterised by poverty, isolation, coastal location, food-insecurity, local environmental destruction and political rigidity will be vulnerable to various global change impacts. Food security indices have recently been developed based on criteria such as current and future land-use, water supply, population and climate, and groups in Zimbabwe that are vulnerable to downturns in food supply have thus been identified using regional and national surveys[23]. Populations most vulnerable to the spread of vector-borne diseases are those adjacent to endemic regions where transmission is currently limited by temperature[21,24].

Global environmental change and infectious diseases

The existing pattern of tropical infectious diseases reflects, variously, climatic and other local environmental conditions, human demography

and settlement, and the ecology of vector habitats. Although it is feasible to predict the impact of changes in a single climatic variable on parasite/vector life cycle dynamics, the net impact of simultaneous changes in several environmental systems is less tractable to modelling.

The emergence and the resurgence of various infectious diseases in recent decades has been linked, in part, to regional climatic changes[25]. New infectious agents have also been encountered because of increasingly disruptive patterns of land use[26]. This is well illustrated by the various new haemorrhagic fever viruses in South America and elsewhere associated with forest and grassland clearance and with extensive subsequent agricultural mono-cropping[27]. The several arena viruses and bunya viruses associated with agricultural extension in South America include the Argentine (Junin virus) haemorrhagic fever, spread by proliferation of infected mice (*Calomyscus callosus*) in pesticide-cleared pampas grasslands, and new haemorrhagic fevers in eastern Bolivia (Machupo virus) and Brazil (Sabia virus) due to disturbances of rodent ecology[25].

Malaria

Malaria is resurging in many countries where it had previously been eliminated or greatly reduced with vector control measures. It is now the eleventh leading cause of death worldwide[28]. More than 400 million cases of malaria are estimated to occur annually, including 2 million (mostly childhood) deaths. A malaria crisis is emerging in Africa, abetted by widespread chloroquine resistance. In India, resurgence of malaria has been linked to the combined problems of chloroquine resistance, reduced efficiency of insecticides and the adaptive spread of mosquitoes to urban areas.

Malaria and climate change Both the *Anopheles* mosquito and the plasmodium are sensitive to meteorological variables. Some evidence suggests that the recent ascent to higher altitudes of malaria or of anopheline mosquitoes in eastern Africa and Latin America reflects, in part, regional temperature increases[11,13]. Other analogue evidence, mentioned above, demonstrates the sensitivity of malaria outbreaks to short-term climatic changes.

Perhaps the best-known integrated mathematical modelling of the potential future health impacts of climate change has been in relation to changes in the geographic range of malaria[21,29,30]. These simulations have used highly-aggregated first-generation models, incorporating climate change scenarios, equations expressing the relationships of mosquito and parasite biology to temperature, and information about

pre-existing levels of malaria and acquired immunity in specified populations. These modelling studies, for standard climate change scenarios, have forecast that the potential geographic range for malaria transmission would expand over the coming century. Approximately 45% of the world's population currently live in climatically-defined zones of **potential** malaria transmission and, assuming that other factors remain constant, this would increase to an estimated 60% by later next century.

Such modelling of changes in complex transmission cycles necessarily entails many assumptions. For malaria, one assumption in this first-generation modelling has been that vector mosquito species around the world have similar characteristics; likewise all plasmodium species. Yet we know that there are differences between anopheline species in response to temperature, humidity and patterns of surface water, and that the temperature dependency of the malarial parasite's extrinsic incubation period varies between plasmodium species. By contrast, dengue fever involves just one dominant mosquito vector (*Aedes aegypti*). Hence, global maps of dengue transmission potential may be more valid than those for malaria risk.

With sufficient localised information these mathematical models can be downscaled to local conditions. The application of such a model to forecast the changes in potential malaria transmission in Zimbabwe (especially in the highlands) under climate change is shown in Figure 1[8]. The estimated change in potential transmission of falciparum malaria is shown under three specified scenarios of climate change: +2°C, +2°C with 20% more precipitation, and +2°C with 20% less precipitation.

Existing levels of public health infrastructure should prevent the re-introduction of malaria into non-tropical countries – at least over the next few decades. Real increases in malaria in response to climate change are most likely to occur in vulnerable populations at the margins of established endemic areas, particularly in tropical and subtropical regions. Relatedly, malaria would move to higher altitudes in the highland regions, thereby affecting populations that are currently free of malaria.

Malaria and change in land use As population pressures increase, more forest and other virgin land is cleared for agricultural and pastoral purposes. Likewise, dam-building and extensions of irrigation are affecting the geography of malaria and other mosquito-borne infections. Vector species composition generally changes following shifts in environmental conditions. Several *Anopheles* species – including *An. dirus* in Thailand and *An. darlingi* in South America – have disappeared following deforestation that removed the flora and fauna upon which they depended[31,32]. Other species benefit from habitat changes. For example, deforestation in the Indo-Australian region has enabled malaria-transmitting *An. punctulatus* species to become established; and

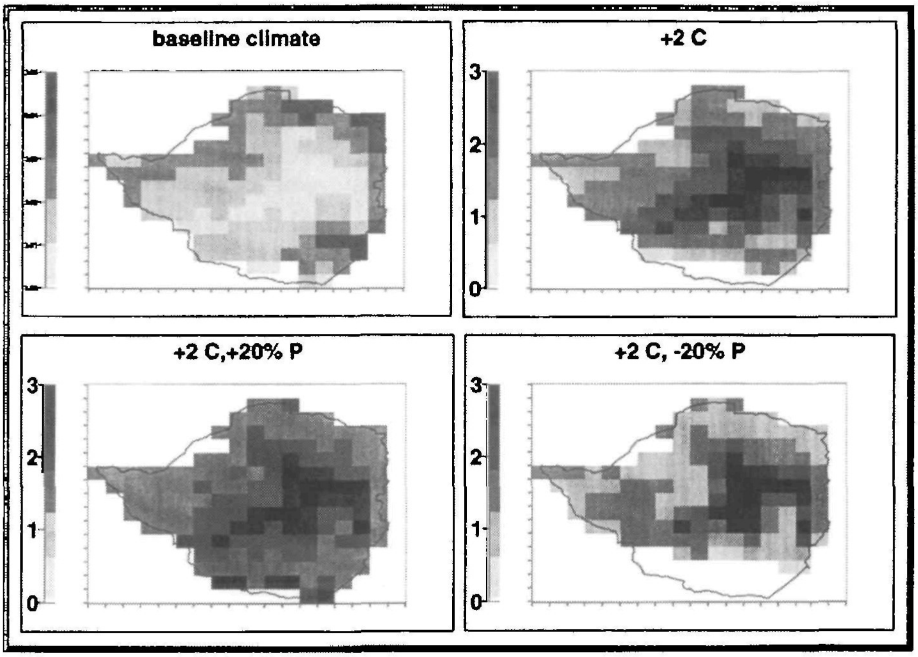

Fig. 1 Simulation modelling of changes in potential falciparum malaria transmission in Zimbabwe (especially in the highlands) under conditions of future climate change[8]. The estimated change in potential transmission of falciparum malaria is shown under three specified scenarios of climate change: +2°C, +2°C with 20% more precipitation, and +2°C with 20% less precipitation. The baseline map shows current potential malaria transmission expressed as a percentage prevalence scale. The other three maps show the projected increases in transmission potential, expressed as a multiplication factor.
***Note:** The highlands run diagonally, from northeast (top right) to southwest (bottom left).*

agricultural development, through altered land-use and irrigation practice, can affect mosquito breeding[33].

Dengue

Dengue is the world's most prevalent vector-borne viral disease, causing around 100 million cases annually in tropical and subtropical countries. Dengue has increased markedly in recent decades, particularly in Central and South America due to trends in population mobility, urbanisation, poverty and regional warming[34,35]. Dengue has been occurring at unusually high altitudes in the highlands of some countries in association with recent regional warming trends[13,36].

Both dengue virus development and *Aedes aegypti* mosquito biting rates are sensitive to temperature.[21] A simulation model of transmission

has been coupled to climatological general circulation models (GCMs) to project the altered transmission potential of this disease due to climate change. Potential transmission risk rose by 31–47% due to an approximate 1°C average global warming from the greenhouse effect. This would place up to 195 million additional people at risk for dengue fever by the middle of the next century[37].

Water resources development and disease

Changes to the hydrological environment are also important. For example, outbreaks of Rift Valley fever occurred in the Nile Valley in 1977 and in Mauritania in 1987 following the damming of major rivers. Lymphatic filariasis in the southern Nile delta has undergone a 20-fold increase in prevalence since the 1960s, primarily due to an increase in breeding sites for the vector mosquito *C. pipiens* that followed the rise in the water table due to extensions of irrigation. The situation has been exacerbated both by pesticide-resistance in mosquitoes in response to heavy pesticide use by local farmers and by rural-to-urban commuting among farm workers[38].

Finally, changes in patterns of rainfall, runoff and surface water, as a result of climate change and altered land-use patterns, would have implications for the volume and quality of freshwater supplies. In some regions, including current semi-arid regions, fresh water supplies may decline. Flooding and overloading of wastewater systems would often contaminate freshwater supplies. These disturbances would, therefore, pose risks to hygiene and would influence the occurrence of water-associated infections, especially diarrhoeal disease in children.

Land degradation, food production and health

During the 1980s, the combination of erosion, desiccation, nutrient exhaustion, and irrigation-induced water-logging and salination rendered unproductive one-fifteenth of the world's 1.5 billion hectares of readily arable farmland[1,39,40]. As population size increases, as regional climates alter in response to global climatic changes, and as biodiversity loss increases the risk of plant and animal pests and diseases, there will be further stresses on food-producing systems.

The world's per-person production of cereals – the main source of dietary energy – seems to have faltered since the mid-1980s[39,40]. The reasons for this are unclear[41]. However, it is well recognised that the successful 'Green Revolution' of the 1960s to the 1980s depended on laboratory-bred high-yield cereal grains, fertilisers, groundwater and

arable soils. In retrospect, those productivity gains appear to have depended substantially upon the expenditure of ecological 'capital', especially topsoil and groundwater.

There are mounting problems of resource depletion in the world's oceans too[1,2]. Around one-quarter of total animal protein consumed by humankind comes from the sea, and, if this declines, many low-income coastal countries will be deprived of a major food source. Already the majority of the world's great fisheries are being exploited at or beyond their limit; the total landed catch has plateaued at around 100 million tonnes throughout this decade. Aquaculture is increasing. However, it faces some unusual ecological difficulties and is much less energy-efficient (since the requisite energy inputs are plant or animal feed-stuffs).

The proportion of hungry and malnourished people in the world is slowly declining. However, because of the surge in population growth, the absolute numbers of hungry and malnourished people are **not** declining. This is exacerbated by the widening disparity between rich and poor, evident in the contrasting trends of continuing hunger and rapid increases in the prevalence of obesity in urban populations everywhere.

Future prospects

Forecasts by most international agencies foresee future food production matching increased population and rising demand at the global level over the next 2–3 decades[42]. At the regional level, however, they foresee worsening food security in sub-Saharan Africa and only marginal improvement in South Asia. The rate of recruitment of new land has slowed; there is little good land not already in use (with some exceptions in South America). Irrigation continues to be extended – despite the ecological and social costs and the likelihood of waterlogging and salination.

Many scientists argue that the constraints of soil erosion, depleted aquifers and near-maximal use of fertilisers (except in Africa, where high-volume use of fertiliser cannot be afforded and, less so, in Asia) mean that a continued 'Green Revolution' is not possible. Future gains in yield will need to leave the natural resource base intact, while also making access to food more equitable. Higher priority must be given to **sustainable** methods, including biological methods of pest and weed control, adequate crop rotation, and mixing of crops with forestry and livestock. Meanwhile, perhaps genetic engineering will deliver plant varieties that are higher-yielding and more resistant to drought, salinity, diseases, and pests.

Food yields, especially of agricultural crops, are likely to be affected by global climate change, entailing warmer temperatures, changes in

growing seasons, altered patterns of precipitation, and (in many rain-dependent regions) reduced soil moisture. Further, and less predictably, climatic changes would influence the ecology of plant pests and pathogens. Such climate-related trends, however, may not all be adverse. In the recent assessment by the IPCC, temperate or cold-climate regions might undergo increased yields in response to global warming[43]. Meanwhile, many mid-continental and semi-arid regions would become more liable to crop failure, then soil erosion with long-term loss of productivity. Irrigation-dependent agriculture would be vulnerable to any climate-related decline in rainfall and runoff, and this would be exacerbated by heightened evaporative losses in a warmer world.

Environmental overload, refugees and conflict

If environmental conditions continue to deteriorate, the likelihood of social destabilisation, population movement, and conflict will escalate. Currently there are an estimated 10–25 million people displaced by environmental degradation[44,45]. Vulnerable populations include those in small island nations or coastal regions which will be damaged by flooding due to sea level rise, those in sub-Saharan Africa which are food insecure, and those in the Asian region because of possible displacement of the monsoon system.

King and colleagues argue that some of the world's poorest populations are becoming 'demographically entrapped': that is, the weight of their current or projected numbers exceeds the carrying capacity of their environment, and, lacking trade and migratory safety valves, they, therefore, face starvation, disease or fratricide[46,47]. Last[48], too, refers to demographic entrapment, and describes how the desperate efforts of such populations 'to provide themselves with food, water, and fuelwood can degrade an already fragile ecosystem into a desert that may take centuries to recover'. This, he says, is happening in parts of sub-Saharan Africa, in alpine foothills in the Himalayas and the Andes, in crowded small nations such as Haiti and Honduras, and elsewhere in Central and South America.

In many other situations, especially in tropical countries, environmental insecurity is arising because of the encroachment of increasingly globalised economic activity. There are widespread tensions. This encompasses forest tribes in the Amazon confronted by deforestation and the intrusion of displaced landless peasants; Ladakhi farmers whose traditional sustainable methods of farming are being undercut by the trucking in of government-subsidised produce from large-scale intensive farming in India[49]; and traditional rural communities in Zimbabwe

where adverse maternal and child health consequences have resulted from insecure seasonal employment in large export-oriented plantations[50].

Implications for health care in tropical countries

Many of the health problems currently facing tropical countries are more obviously related to poverty and urban crowding than to environmental damage and diminished ecological sustainability[51]. Indeed, the health consequences of a run-down in nature's 'goods and services' do not accrue as immediately and obviously as do those due to physical and socio-economic deprivation, local environmental pollution, and unhygienic conditions. Nevertheless, there is a complex nexus between population pressure, poverty and environmental degradation, entailing various mutually reinforcing processes. If current environmental trends persist, leading to changes in environmental-climatic conditions and ecological relationships, then adverse health consequences will become more evident in vulnerable populations, especially those in low-income tropical countries.

It is not possible to quantify precisely the changes in the burden of disease and premature mortality that might arise from these global change processes. Indeed, in the foreseeable future, there will probably be further gains in life expectancy as economic growth and social modernisation proceed. The downside to this 'development' scenario for the early decades of the coming century is that, with current technologies and social practices, along with expanding populations, such gains will necessarily be made at the long-term expense of the environment. As levels of landscape occupancy change, and material consumption and waste generation increase, so the environmental and ecological impact will increase. Eventually, this must lead to adverse consequences for human health, particularly in the world's less well protected and resourced populations.

A strong public health infrastructure – international, national and local – along with active local community involvement is necessary to achieve effective surveillance and control of infectious disease, hunger and malnutrition. To counter increases in vector-borne diseases a multi-sectoral approach is needed. Biomedical solutions, such as a malaria vaccine or release of non-transmitting transgenic mosquitoes, should be combined with the conservation of ecosystems and with improved surveillance and monitoring. In order to minimise or avoid global change – for example, in the world's climate, ocean fisheries, and stocks of biodiversity – we will need an unprecedented degree of enlightened, unselfish, international co-operation. Similarly, the elimination of food insecurity will require a much improved multisectoral approach.

The other major environmental change, reflecting a worldwide process, is that of urbanisation. This process is rapidly redefining human ecology, creating both new opportunities and new health hazards. Car-based transport systems will dominate the urban landscape early next century. Cities and cars will spawn their own particular profile of public health problems, especially in low-income countries where shanty towns, crowding, poor sanitation, poverty diets, air pollution, and exposure to the physical hazards of little-regulated traffic will variously impinge on large numbers of people.

Conclusions

As the twentieth century draws to a close, we face the prospect of an unfamiliar range and scale of hazards to human health from the various global environmental changes that are now emerging. These environmental changes will tend to increase various health problems (whether local malnutrition, the geographic range of vector-borne infections, or the consequences of extreme weather events) in tropical countries. We must integrate this prospect into our thinking, planning, and preventive policy-making – without allowing it to diminish the importance of dealing with existing public health problems. Indeed, we should note that both existing and future-potential environmental health problems share many of the same underlying causes, relating to poverty, inequality, and social-economic values and practices. The existing insecurity and vulnerability of many of those populations makes more important the need to slow the environmental change processes, while also shoring up the protective and adaptive capacities of populations in tropical countries.

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