# Emerging Threats to Human Health from Global Environmental Change

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Annu. Rev. Environ. Resour. 2009. 34:223–52

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

This article's doi:
10.1146/annurev.environ.033108.102650

1543-5938/09/1121-0223$20.00

## Key Words

climate change, emerging threats, land-use change, malnutrition, vulnerability

## Abstract

Large-scale anthropogenic changes to the natural environment, including land-use change, climate change, and the deterioration of ecosystem services, are all accelerating. These changes are interacting to generate five major emerging public health threats that endanger the health and well-being of hundreds of millions of people. These threats include increasing exposure to infectious disease, water scarcity, food scarcity, natural disasters, and population displacement. Taken together, they may represent the greatest public health challenge humanity has faced. There is an urgent need to improve our understanding of the dynamics of each of these threats: the complex interplay of factors that generate them, the characteristics of populations that make them particularly vulnerable, and the identification of which populations are at greatest risk from each of these threats. Such improved understanding would be the basis for stepped-up efforts at modeling and mapping global vulnerability to each of these threats. It would also help natural resource managers and policy makers to estimate the health impacts associated with their decisions and would allow aid organizations to target their resources more effectively.

## Contents

## INTRODUCTION

The field of environmental health has traditionally focused on analyzing the risks associated with exposure to environmental toxins: heavy metals, radiation, and certain chemicals, for example, endocrine disrupters and pollutants in air, food, and water. With over 100,000 manufactured chemicals now widely distributed, few policy mechanisms to require testing of their safety, and growing evidence of the adverse impacts of some of these chemicals at very low doses, it is a critical field of endeavor. However, it has become clear that there is an equally urgent need for a new focus within environmental health—a focus on the major emerging health threats associated with large-scale, anthropogenic changes to the natural environment, including climate change, land-use change, and altered function of the world's ecosystems.

As a species, we humans have been remarkably effective at rearranging the natural world to meet our own needs. In large part, this transformation has allowed the dual trends of rapid population growth and rapid economic development that have characterized the last few centuries. These trends, in turn, have placed accelerating demands on the ecological goods and services that make our lives possible. The result of this self-reinforcing cycle of growth, appropriation of ecological services, and further growth is that the entire ecosphere—oceans, land surface, atmosphere, and freshwater systems—has been extensively modified by our activities. Earth's climate, its terrestrial surface, and the functioning of its ecosystems are all in a state of accelerating change.

We now appropriate one-third to one-half of global ecosystem production for human consumption (1). We have converted roughly 40% of the planet's ice-free land surface to croplands or pasture (2). We use roughly half of the planet's accessible surface freshwater (3). Over the past 300 years, deforestation has resulted in a net loss of between 7 and 11 million km$^2$ of forest—an area the size of the continental United States. An additional 2 million km$^2$ of forest are highly managed plantations with significantly reduced biological diversity (2). Three-quarters of monitored fisheries are being fished at, or beyond, their sustainable limits (4). To harness electricity, control flooding, and impound freshwater, we have built over 45,000 large dams (the size of a four-story building or larger) and an additional 800,000 smaller dams around the world, changing flows on roughly 60% of the world's rivers (5). As a result of habitat loss, invasive species, pollution, and climate change, we are driving species extinct at roughly 1000 times the natural rate (6).

We have also changed the planet's chemistry. We have altered global nutrient cycles across terrestrial, marine, and aquatic systems with the application (and runoff) of synthetic fertilizers. We now add more fixed nitrogen to the biosphere annually than all natural sources combined (7). As a by-product of our energy consumption and land-use practices, we have increased the composition of $CO_2$ in the atmosphere by roughly 30% over preindustrial levels, and our oceans are becoming more acidic.

Despite historical concerns that population growth and increasing consumption of resources might cause humanity to outstrip its ecological resource base, there has, to date, been little evidence at a global scale of a Malthusian collapse, at least not for humanity. To the contrary, viewed solely through the lens of human health, our transformation of the planet has largely been a success. Since 1820, global average per capita income has risen eightfold. In the year 1000, the average infant could expect to live about 24 years. Today, she can expect to survive 66 years. Infant and maternal mortality have fallen steeply, and per capita food production has risen despite more than a fivefold increase in human population since 1820 (8). These global averages hide dramatic disparities between rich and poor, and there remain large segments of the human population whose lives are curtailed by poverty, hunger, and disease. Nonetheless, by recruiting an ever larger share of the biosphere to meet human needs for food, water, fiber, building materials, etc., a rapidly growing human population has largely prospered.

As the human reconfiguration of the natural world has become increasingly profound and pervasive, however, we have begun to identify emerging threats to human health that are deeply concerning. Accelerating changes to Earth's climate, its terrestrial surface, and the functioning of its ecosystems are threatening our future access to some of the most basic components of population health: adequate nutrition, safe water, clean air, and protection from infectious disease and natural disasters. As access to these building blocks of health becomes more constrained, the health consequences for hundreds of millions of people could be far reaching.

Our growing recognition of these emerging public health threats necessitates a new field of focus within environmental health. In distinction from the traditional environmental health focus on exposure to toxins, we need to consider the broader implications of the human transformation of the natural world. This field should explore how changes in land use, climate, and the function of ecosystems may act synergistically to alter exposure to infectious disease and natural disasters, while curtailing access to food, clean air, and clean water and increasing the likelihood of population displacement and civil strife. These phenomena are difficult to study using traditional approaches because they are multifactoral and complex and often occur over very large scales that defy experimental manipulation or even complete characterization. However, collaborative research into these relationships is gaining momentum by drawing on a variety of disciplines, utilizing new tools and methods, and developing innovative approaches to determining causality (9). Some professional scientific societies are similarly emphasizing the need for hybridization across natural and social/medical disciplines, e.g., ecohealth, conservation medicine, and the concept of "one health," whereby healthy people, wildlife, and environments are considered parts of a whole.

In the first section of this article, we propose a framework for conceptualizing the connections between global environmental change and human health. We then use this framework to discuss why it has been challenging to actually demonstrate direct connections between degraded environmental conditions and negative health outcomes. In the second section, we explore what is known about the impacts of global environmental change on key facets of population health. Rather than breaking out distinct sections on land-use change, climate change, or ecosystem service disruption, we attempt to illustrate how interwoven these trends are in generating vulnerability within each of these areas of public health. Finally, we highlight challenges to, and opportunities for,

**Vulnerability:** includes health threats associated with changing environmental conditions as well as the resilience of a population to meet these threats advancing our understanding of these relationships in the future.

**Ecosystem services:** are the benefits people obtain from ecosystems; these are often grouped into provisioning, supporting, regulating, preserving, or cultural benefits

Because of space limitations, there are several relevant topics that we have chosen not to cover. These include toxic exposures from widely distributed synthetic chemicals; the impact of biodiversity loss on development of new pharmaceuticals; the impact of urban design on chronic diseases, especially obesity-related heart disease, diabetes, and cancer; and how the nutrient composition of both meat and crops may be changing in response to food production methods and changes in climate and soil. Instead, we have chosen to focus on what we believe to be the greatest emerging threats to human health from large-scale, anthropogenic changes to landscapes, climate, and natural systems.

## CONCEPTUAL FRAMEWORK

Humanity relies on the natural world to provide many of the cornerstones of population health: adequate nutrition, clean water, clean air, and protection from infectious disease and natural disasters. These and other benefits that people obtain from ecosystems have been termed ecosystem services (10). The combination of rapid land-use change and accelerating climate disruption is reducing the capacity of ecosystems to continue producing these services at their historic capacities. Comprehensive global and regional assessments of ecosystem services have concluded that the majority of services are being degraded or depleted as a result of human activity and that the rates of depletion are accelerating (11).

It is intuitive that, as these services become more constrained, human health is likely to suffer. Indeed, this concern has been widely articulated (12–15). However, studies which have looked for an association between loss of ecosystem services and adverse health outcomes have underestimated the complexity of these relationships. For example, one study sought a correlation between a measure of "ecological disintegrity" and life expectancy and found none (16). A second study found no correlation between measures of biodiversity and several measures of population health (17). One reason these studies were negative is that human populations tend to be insulated from direct impacts of ecosystem service degradation by a variety of mitigating factors (**Figure 1**).

First, it may be hard to measure a direct correlation between ecological disruption and negative health outcomes because, early in the course of economic development, most societies rapidly externalize their ecological "footprint" beyond the local ecosystems where they live. Those who have access can procure food, fuel, fiber, building materials, and even water (often in the form of water required to produce imported grain, meat, or other food products) (18) on regional or international markets, insulating them from the effects of local resource scarcity. People without access to these markets are particularly vulnerable to ecological degradation (19). In this context, the issue of scale becomes important. For those with access to international markets, ecosystem services produced at the global level may be most relevant. We will see in our discussion of food that both biosphere level and local/regional food production are relevant to health, depending on a population's socioeconomic status. Analyses that seek correlation between local ecosystem service degradation and human health may be confounded by this issue of scale.

A second reason why such studies are likely to be negative is that a number of other social, political, and economic factors insulate populations from depleted resources. Vulnerability to changing environmental conditions results from exposure to environmentally mediated health risks as well as population-level conditions that make such exposures unsafe (20). Certain vulnerabilities to ecosystem service degradation can be mitigated by infrastructure. Loss of wetlands and their water filtering capacity is less likely to cause disease among downstream populations who have access to water filtration technology. Loss of coastal barriers, such as mangroves, wetlands, coral reefs, or vegetated dunes, increases vulnerability to extreme storms but is likely to disproportionately affect

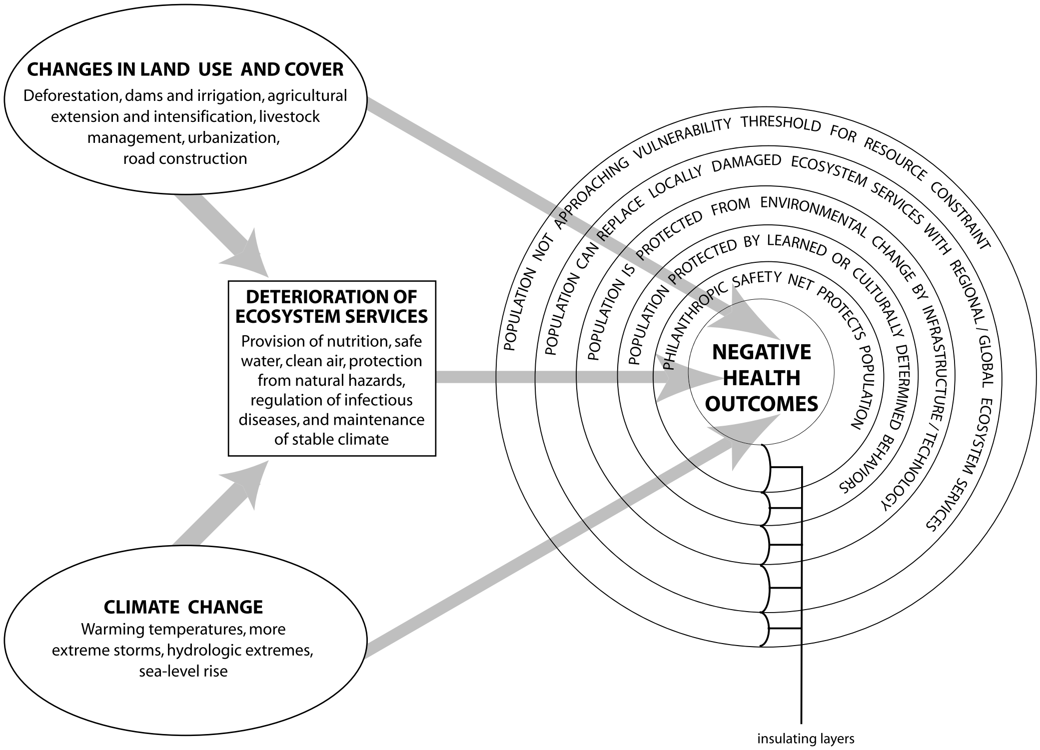

**Figure 1**

A schematic of the complex relationships between altered environmental conditions and human health. Drivers of global environmental change (e.g., land-use change or climate change) can directly pose health risks or impair ecosystem services that subsequently influence health. For hazards that affect human health, however, exposures will be modified by multiple layers of social or infrastructure barriers that can buffer or eliminate risk. Together, all components must be considered to achieve realistic assessments of population vulnerability.

those living in poor housing, which cannot sustain high winds or a storm surge.

Culturally determined or learned behaviors can also protect people from ecosystem change. Communities threatened by increased exposure to infectious disease as a result of altered environmental conditions, for example, may reduce their vulnerability through a variety of behaviors. These include treating their drinking water (by boiling or filtering) and preparing foods in protective ways, or reducing exposure to disease-transmitting organisms by wearing protective clothing, using bed nets and window screening, and staying indoors during certain hours. To the extent that these behaviors are culturally mediated, however, they may have less ability to adapt to rapidly changing environmental conditions, as these behaviors often evolve over many generations.

Governance is another mediating factor. At regional, national, and international levels, capacity and commitment to deliver resources can prevent local resource scarcity from causing human suffering. Most of the famines of the twentieth century, for example, were not driven primarily by food scarcity so much as by failures of governance (21).

Finally, it is unlikely that the relationship between different types of resource scarcity and negative health outcomes is linear. To the contrary, we would expect that for ecosystem services, like food production and clean water provision, there would be a strong correlation with health only when resources are very

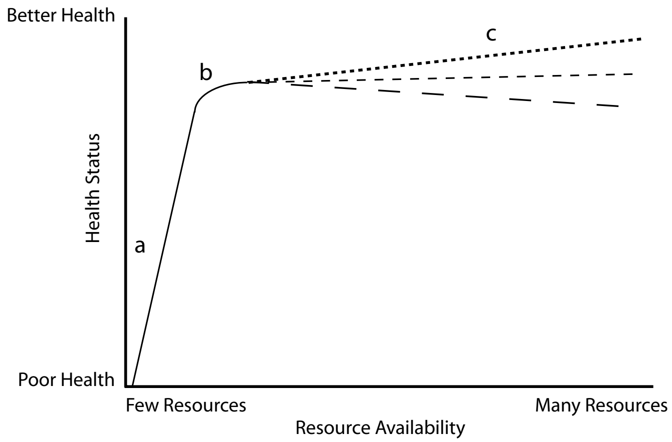

**Figure 2**

A schematic diagram of a proposed relationship between resource scarcity and human health. When resources are tightly constrained, (*a*) increases or reductions in access to them can have significant health consequences. Once access to adequate food, water, fuel, and building materials, etc., has been achieved, (*b*) the relationship between increased access and health gains becomes much less pronounced. Further increases in resource access (*c*) may lead to marginal improvements in health status, but overuse may also lead to reduced health status, e.g., excess food consumption and obesity.

constrained. Until this threshold is reached, depletion of ecosystem services might have little impact on health (**Figure 2**).

The causal chain, then, between global environmental change and health impacts can be quite complex (although in some cases it is more direct) and may be lagged in time. Land use and climate change can directly threaten human health or can produce vulnerability by degrading ecosystem services relevant to health. These threats may lead to poor health outcomes if a variety of conditions are met. To adversely affect health, resource scarcity must confront a population that is at a critical threshold of resource consumption, below which further scarcity will cause significant health impacts. The population must be dependent on its local resource base and unable to meet its needs by accessing a regional or global market. Finally, the population must lack the infrastructure, adaptive behaviors, governance, or access to international philanthropy that might otherwise protect it from the impacts of environmental degradation. Global analyses of the health impacts of changing environmental conditions that do not factor in these insulating factors are likely to be unsuccessful (**Figure 1**).

Although these mitigating factors pose a challenge in showing direct correlations between changing environmental conditions and human health outcomes, there is growing evidence that anthropogenic environmental change is negatively impacting human health in numerous ways. In the next section, we focus on critical building blocks of human health and discuss the complex array of mechanisms by which altered land use and cover, climate change, and depleted ecosystem services may interact to threaten vulnerable populations.

## GLOBAL ENVIRONMENTAL CHANGE AND POPULATION HEALTH

### Infectious Disease Exposure

"Regulation of Infectious Diseases" is defined as an ecosystem service within the Millennium Ecosystem Assessment (22). As contained in the discussion below, there is ample evidence that disruptions of ecological systems alter disease transmission. Whether we would expect disruption to increase or decrease transmission is not obvious, and there are examples of both effects in the literature. The majority of reports show increases in disease transmission as a result of changing environmental conditions. Mechanisms for this apparent directionality are not well understood and are an area of active investigation. It is also true that the complete destruction of ecological systems can significantly reduce disease transmission by eliminating entire communities of disease-related organisms. The elimination of malaria by draining swamps where mosquitoes breed is an example, although other ecosystem services of the wetlands would be lost.

Global land use and climate change drive new patterns of infectious disease exposure through a variety of mechanisms. These mechanisms include the altering of (*a*) the biophysical conditions of habitats that can affect the density or presence of disease-related organisms;

(*b*) exposure pathways, the way organisms (including humans) interact with each other; (*c*) the genetics of pathogens; (*d*) the life cycles of pathogens and vectors; and (*e*) species composition within a community of organisms (**Table 1**). Infectious diseases, which are transmitted by a vector (usually an arthropod) or have a nonhuman host or reservoir, are particularly sensitive to these types of change (23, 24). Given that such diseases affect over half the human population, alterations in their transmission can have significant impacts (25).

Space does not allow us to catalog all of the land use/climate/disease relationships that have been documented. Such a catalog could also be misleading as it might provide the illusion of an exhaustive representation when, in fact, most of these relationships remain to be investigated and described. Instead, we describe the many different mechanisms by which climate and land-use change impact infectious disease transmission. In doing so, we hope to illustrate the complex sensitivity of infectious disease transmission to environmental change. Growing interest in this issue is leading to rapid expansion of our understanding of specific environment/disease relationships.

## Changes in the Density or Presence of Disease-Related Organisms

Collectively, changes in land use and climate are altering the biological composition, structure, and complexity of much of the global land surface. They are altering temperature, precipitation patterns, soil moisture, biogeochemical cycles, nutrient concentrations, surface water chemistry, and exposure to sunlight. These parameters are often fundamental in defining the range and breeding habitat of numerous vectors, hosts, and pathogens, and as they change, we can expect changes in the density or presence of these organisms.

Because of its global importance, malaria is one area where extensive research has been done. Roughly 500 million people contract malaria each year, and over one million people die of it, mostly in Africa (26). Malaria is transmitted by a wide variety of location-specific mosquito species within the genus *Anopheles*. Many of the most pervasive types of land-use change impact the density of different *Anopheles* vectors. Deforestation in the Amazon basin increases the breeding habitat of *Anopheles darlingi*, the principal malaria vector in this region (27–29). Biting rates of *A. darlingi* in deforested areas of the Peruvian Amazon are almost 300 times higher than in intact forest, controlling for differences in human population density across varied landscapes (30). Numerous studies have also shown associations between deforestation and increased malaria exposure in sub-Saharan Africa (27, 31–34). In Asia, the story is more complex with deforestation favoring some vectors over others but frequently leading to increased transmission (35–40).

Other forms of land-use change also favor malaria transmission. Microdams in northern Ethiopia increase the concentration of the local malaria vector and are associated with a sevenfold increase in malaria in nearby villages (41). In India, irrigation projects in the 1990s improved breeding sites for the dominant malaria vector, *Anopheles culcifacies*, and led to endemic "irrigation" malaria among a population of roughly 200 million people (42). Agricultural projects have also driven malaria outbreaks. In Trinidad in the 1940s, the development of cacao plantations caused a major malaria epidemic. The cacao was planted beneath nurse trees (*Erythrina*). The nurse trees provided ideal habitat for epiphytic bromeliads, which, in turn, created excellent breeding sites for *Anopheles bellator*, the principal local malaria vector. The epidemic was not controlled until the nurse trees were reduced and plantation techniques were changed (43). In Uganda, the drainage and cultivation of papyrus swamps caused higher ambient temperatures and more *Anopheles gambiae* individuals per household than found in villages surrounding undisturbed swamps (44). In Thailand, both cassava and sugarcane cultivation reduced the density of *Anopheles dirus* but created widespread breeding grounds for *Anopheles minimus* with a resulting surge in malaria (40).

**Table 1 Mechanisms of altered infectious disease exposure resulting from environmental change**

| Mechanism by which environmental change alters disease transmission | Examples | Diseases known to be impacted by this mechanism |
|---|---|---|
| Changes in density or identity of disease-related organisms | Deforestation or irrigation projects improve breeding habitat and survival of certain anopheline mosquitoes that transmit malaria in Africa, Latin America, and Asia.<br>Deforestation in Cameroon favors one snail species over another, thereby increasing human exposure to pathogenic schistosomes.<br>Sea surface warming and nutrient loading lead to proliferation of *Vibrio cholerae* and disease outbreaks. | Malaria, schistosomiasis, dengue, Japanese encephalitis, filariasis, trypanosomiasis, leishmaniasis, cholera, plague, Rift Valley fever, dracunculosis, onchocerciasis, hantavirus, hemorrhagic viruses, Chagas disease, Oropouche/Mayaro virus, harmful algal blooms |
| Changes in exposure pathways | Incursions into wildlife habitat can lead to new exposure to zoonotic disease as seen in Ebola, simian retroviruses, and, probably, human immunodeficiency syndrome.<br>Dense urban settlements with poor sanitation, waste disposal, or water treatment can lead to increased exposure to many diseases including diarrheal disease, dengue, and leptospirosis. | Malaria, trypanosomiasis, cryptosporidiosis, giardiasis, Ebola, simian retroviruses, probably human immunodeficiency syndrome, dengue, filariasis, Chagas disease, plague, leptospirosis, typhus, diarrheal disease, food poisoning |
| Changes in the environment in which organisms live create genetic alterations, which can increase disease transmission | Livestock management relying on extensive use of antibiotics in concentrated animal feeding operations leads to the emergence of pathogens resistant to numerous antibiotics.<br>Confinement of different animal species in wet markets or pig-duck farms can lead to genetic rearrangements resulting in increased virulence or altered infectivity. | Antibiotic-resistant bacteria, influenza, severe acute respiratory syndrome |
| Changes in life cycle of vectors or pathogens | Deforestation causes increased ambient temperature in homes and breeding sites, which shortens gonotrophic cycles, reduces development time, and increases survivalship of anopheline mosquitoes in Kenya. | Malaria |
| Changes in species composition of communities of organisms | Biodiversity loss in northeastern forests of the United States increases exposure to Lyme disease.<br>Altered species composition of wetlands in Belize in response to nutrient loading creates favorable habitat for a more effective malaria vector. | Lyme disease, West Nile virus, malaria, Hantavirus, Guanarito virus, Junin virus, Machupo virus, bartonellosis, Nipah virus, St. Louis encephalitis |

Finally, climate change is likely to alter the pattern of malaria and other vector-borne diseases. Although there is debate about the net impact of climate change on the global distribution of malaria (45, 46), there are several well-documented instances where malaria incidence is dependent on climate phenomena. In the highlands of East Africa, a warming trend from 1950 to 2002 coincided with increases in malaria incidence (47). Nor does this relationship appear to be linear. Just a half degree centigrade increase in temperature can translate into a 30% to 100% increase in mosquito abundance as a biological threshold appears to be crossed, allowing successful breeding and survival of the vector (48). In the Punjab region of India, malaria epidemics are strongly associated with precipitation (49). They have been shown to increase approximately fivefold during the year following an El Niño event when monsoons are particularly extreme. Similar associations have been shown between malaria outbreaks and El Niño–related climate variability in Botswana (50). Clear effects of changing climate have also been established for cutaneous leishmaniasis (51), cholera (52), plague (53, 54), and dengue fever (55).

Schistosomiasis provides another example of the numerous ways that a common infectious disease may be sensitive to a wide variety of climate or land-use changes. Schistosomiasis is caused by parasitic worms (*Schisotoma* spp.) that spend part of their life cycle in freshwater snails and then leave the snails to penetrate the skin of people who enter contaminated water. The disease can damage liver, lungs, intestines, and bladder and infects roughly 200 million people. Deforestation changes the ecology of freshwater snail populations by increasing sunlight penetration, encouraging growth of vegetation, and changing water levels and flow rates. Many snail species do not survive these changes, but those which do tend to be better hosts for the parasitic worms (schistosomes) that cause this disease (38). In Cameroon, for example, deforestation led to an upsurge in schistosomiasis. One type of freshwater snail, *Bulinus forskalii*, was displaced by another, *Bulinus truncatus*, better suited to cleared habitats. Although *B. forskalii* hosted a nonpathogenic schistosome, *B. truncatus* is an effective host for *Schistosoma hematobium*, a primary cause of urinary tract schistosomiasis (56).

Dams and irrigation systems have also caused surges in schistosomiasis cases. The construction of the Aswan dam in the Nile Delta of Egypt in 1965 created extensive new habitat for *B. truncatus*. As a result, prevalence of *S. hematobium* infection in Upper and Middle Egypt rose from about 6% before construction of the dam to nearly 20% in the 1980s. In Lower Egypt, intestinal schistosomiasis rose to an even greater extent (38, 57, 58). In the Tana River region of Kenya, the Hola irrigation project led to the introduction of snail vectors where they had never been before. Between 1956, when the project began, and 1966, the prevalence of urinary schistosomiasis in children in the region went from 0% to 70%. By 1982, it was 90% (59). Around the world, the rapid proliferation of dams and irrigation projects has generated new habitat for freshwater snails well adapted to these environments and to hosting schistosomes. A surge in global schistosomiasis has resulted. Schistosomiasis and malaria are not the only diseases strongly associated with dams and irrigation projects. Rift Valley fever, filariasis, leishmaniasis, dracunculosis, onchocerciasis, and Japanese encephalitis are also associated with these projects (22, 60–63). Trade-offs exist between these negative health ramifications and agricultural and/or power benefits from water projects. Even though economic and even environmental assessments are generally required for such projects, health impact assessments (HIAs) have generally been either insufficient or nonexistent.

**Health impact assessment (HIA):** is a rigorous approach to identifying and quantifying health impacts of proposed projects or activities. It includes benefits as well as risks

In Lake Malawi, there is suggestive evidence that overfishing has contributed to the recent surge of schistosomiasis around the Nankumba Peninsula. Investigators studying the biology of this lake have noted that, coincident with a very dramatic decline in molluscivorous fish, there has been a proliferation of the intermediate host, *Bulinus globosus*, in areas which used to be free of this snail. This relatively sudden surge in host density has been associated with a spike in schistosomiasis cases in an area that was historically free of this disease (64).

A final example of land-use change driving new exposure to schistosomiasis comes from the mountainous regions of Yunnan Province, China. There, an economic development project attempted to raise local incomes by giving villagers cows. Cattle are an important reservoir of *Schistosoma japonicum*, the agent responsible for schistosomiasis in this region. As cows spread throughout the region, they shed schistosome eggs into waterways where they could infect local snails. As a result, schistosomiasis rates surged, infecting up to 30% of some villages and correlating directly with cattle ownership (65).

Marine systems are also affected by global environmental change. A surge in the number of harmful algal blooms (HABs) has resulted from rising sea surface temperatures and increased application (and runoff) of fertilizers, which cause nutrient enrichment of freshwater and coastal systems (66). HABs can lead to massive fish kills, shellfish poisonings, disease and death of marine mammals and human morbidity and mortality. Worldwide, roughly 60,000 individual cases and clusters of human intoxication occur annually (67). Health impacts range from acute neurotoxic disorders and death to subacute and chronic disease.

Cholera outbreaks in Asia and South America have been associated with sea surface temperature, rainfall patterns, and nutrient loading from agricultural runoff. Copepods, a type of zooplankton, are a reservoir of *Vibrio cholerae*. High nutrient loads and warm water temperatures cause blooms of these zooplankton and can lead to the transformation of *V. cholerae* from a quiescent to a virulent form (52, 68–70).

Although the examples listed above are not exhaustive, they illustrate the variety of mechanisms by which changes in climate or land use can increase the density of disease-related organisms.

## Changes in Exposure Pathways

Changes in the density or presence of disease-related organisms are not the only mechanism by which global environmental change can impact infectious disease transmission. Global change is also altering routes of infectious disease exposure. Some of these new exposure pathways have little to do with changes in the natural world. For example, increases in global trade and transportation facilitate the rapid transport of disease-related organisms around the globe. However, many types of anthropogenic environmental change also lead to new exposure pathways. Land-use changes are often associated with nonimmune populations of workers moving into endemic areas where they are exposed to infectious diseases with which they have little experience. The creation of forest fringe in the Amazon is an example. By clearing forest, farmers, road-building crews, and other workers create forest fringe, which is ideal habitat for *A. darlingi*. This tight coupling of improved vector habitat with an influx of nonimmune human populations drives the phenomenon known as "frontier malaria" (28). A similar mechanism is responsible for increased transmission of African sleeping sickness (trypanosomiasis) in Cote d'Ivoire. The cultivation of coffee and cacao plantations creates excellent habitat for the tsetse fly, and nonimmune agricultural workers rapidly become infected by this vector (71).

A second exposure route results from direct incursions of people into wildlife habitat. Bushmeat hunting—which leads to handling, slaughtering, and consuming wild animal species—is such an incursion. In Central Africa alone, 1–3.4 million tons of bushmeat are harvested annually (72). Bushmeat hunters who reported direct contact with blood or body fluid of nonhuman primates have contracted simian foamy virus, a retrovirus that is endemic in most Old World primates (73). This finding provides further support for the already compelling hypothesis that the retrovirus causing human immunodeficiency virus (HIV)/acquired immunodeficiency syndrome (AIDS) was likely a mutated simian virus contracted through bushmeat hunting (74). It is likely that human infection with Ebola virus also had its origin in bushmeat hunting. Bushmeat hunting itself appears to be driven by the need of growing populations to supplement their protein intake. There are strong correlations between poor fish supply in Ghana and increased bushmeat hunting. Reductions in the fish supply in Ghana coincided with a 20-fold increase in European Union (EU) fish harvests off the coast of West Africa. Overfishing by heavily subsidized EU fleets, then, appears to be one of the driving forces behind increased bushmeat hunting and exposure to infectious disease (75).

Not all incursions into wildlife habitat are the result of hunting. There is growing evidence that settlement and extension of agricultural land into wildlife habitat may also increase exposure to zoonotic disease. Research done around Kibale National Park in Uganda has documented the transmission of pathogens between humans and nonhuman primates in areas where bushmeat hunting is not a factor. The transmission appears to be related to other factors including population growth, forest fragmentation, crop raiding, interaction with domesticated animals, and direct interaction of people and wildlife through farming, land clearing, scientific research, ecotourism, or conservation activities (76).

Urbanization, an important land-use trend and the dominant demographic trend of the twenty-first century, also provides new pathways for infectious disease exposure. Much of the rapid urbanization occurring today is taking place in urban or periurban slums with few services for clean water provision, sewage disposal, solid waste management, or quality housing (77). In these settings, piles of municipal waste, pools of contaminated water, and refuse, like old tires capable of holding water, create excellent habitat for a variety of rodent hosts and arthropod vectors, particularly those which transmit dengue, malaria, filariasis, Chagas disease, plague, leptospirosis, and typhus (78–80). In addition, rural-to-urban migration brings people from different disease-endemic regions together in high density, providing a source for new infection as well as nonimmune hosts. It can also erode social capital, which creates an obstacle to building infrastructure to prevent disease transmission, and can change disease-related behaviors as well (81, 82). Poor quality housing, which does not provide an effective barrier to mosquitoes, rodents, or fleas, further contributes to the spread of vector-borne disease in slums. Finally, increased human population density and size can both increase the likelihood of infectious disease becoming established in an urban population (83).

One example is dengue fever, which has rapidly spread out of Southeast Asia and the Pacific and has become endemic throughout the tropics. With roughly 50 million cases in over 100 countries each year, dengue is the most common mosquito-borne viral disease in the world (78). It is transmitted by the bite of infected *Aedes* mosquitoes, which selectively feed on humans and breed in man-made containers: earthenware jugs, tires, metal drums, discarded plastic food containers, and other items that collect rainwater. These characteristics make them well adapted to urban areas, and dengue is primarily a disease of urban communities (80).

A final way in which global change can affect routes of exposure to infectious disease is by altering the fate or transport of disease pathogens. Warmer temperatures in Europe, for example, correlate with increased incidence of food poisoning. The relationship is strongest for the period one week prior to illness, is linear, and has been reproduced in multiple European cities. Presumably, warmer temperatures allow the pathogen (the strongest relationship was seen for *Salmonella enteritidis*) to survive and multiply in higher numbers (84, 85).

The fate and transport of pathogens associated with waterborne disease are impacted by both climate and land-use change. Agricultural and livestock practices lead to waterborne disease exposure through direct contamination of water supplies. Protozoan parasites including *Cryptosporidium parvum* and *Giardia lamblia* are shed in the feces of domesticated livestock. During periods of heavy precipitation they are washed into waterways and then into drinking water supplies. Sixty-four percent of farms studied in Pennsylvania had at least one cow infected with *Cryptosporidium*. On 44% of the farms, all bovine stool samples were positive. On these farms, the cattle had full access to waterways that could be contaminated by their feces (86). This combination of land clearing and grazing ruminants with no buffer zones to protect waterways provides a widespread ecological setup for human infection. In Milwaukee in 1993, despite a new water filtration system, over 400,000 were estimated to become symptomatic from cryptosporidiosis, and 54 died following a period of heavy rainfall and runoff (87). A study of all-cause waterborne disease outbreaks in the United States found a strong association with heavy precipitation. Two-thirds of outbreaks occurred following exceptionally heavy rainfall months (88). The combination of more extreme precipitation patterns associated with climate change and the continued expansion of animal husbandry may be a setup for growing numbers of waterborne disease outbreaks, particularly in parts of the world where there is little water filtration infrastructure to insulate populations from this risk.

## Genetic Alterations

A variety of other livestock management practices are also affecting infectious diseases worldwide. The intensification of livestock management with larger numbers of animals held in higher densities in closer proximity to other species has allowed pathogens to proliferate and to develop genetic modifications more rapidly. These modifications can affect both their infectiousness and their virulence. Exposure of livestock to large quantities and varieties of antibiotics has driven the proliferation of antibiotic-resistant pathogens. Resistant strains of *Campylobacter*, *Salmonella*, and *Escherichia coli*, which can cause serious human infections, have all been traced to the use of antibiotics in intensive livestock management (22). Industrialization of pig farming in Malaysia with large numbers of pigs kept in confinement in high density proved to be the critical factor in allowing Nipah virus to jump from bats to pigs and then to humans, ultimately causing over 100 fatalities (89).

Smaller-scale backyard livestock management systems can also lead to genetic exchange and alteration of pathogens. Influenza A viruses are highly infectious respiratory pathogens that infect a wide variety of species. Because swine are susceptible to both avian and human influenza viruses, they can serve as genetic "mixing vessels," leading to novel reassortment viruses. These reassortment events have the potential to cause pandemic influenza as novel strains are generated with which human populations have little experience and, therefore, little immunity (90). Close confinement of pigs and fowl, for example in Asian "wet markets" and in pig-duck farms in China, fosters this type of genetic exchange (82). The severe acute respiratory syndrome (SARS) epidemic is likely to have resulted from similar crowding of animals in live-animal markets in China. In this case, the species at the center of the epidemic were horseshoe bats and palm civet cats as amplifying hosts, with possible roles for raccoon dogs and Chinese ferret badgers as well. Most of the early cases of SARS were among people who worked with the sale or handling of these animals (91). Such practices combined with the incursion of people into wildlife habitat (discussed above) may help to explain why roughly 75% of emerging infectious diseases are zoonoses (92).

## Changes in Life Cycle of Vectors or Pathogens

Environmental change can directly alter the life cycle of disease-related organisms. In experiments performed in the western Kenyan highlands, investigators showed that, by reducing shading, deforestation raises the average temperature in homes by 1.8°C and in nearby aquatic habitats by 4.8° to 6.1°C. In addition, these ambient temperature changes are associated, in anopheline mosquitoes, with much shorter gonotrophic cycles (nearly 60% shorter), reduced larva-to-adult developmental time, and increased larval and adult survivorship, all of which improve the vectorial capacity of the mosquitoes and increase exposure to malaria (93, 94).

Local deforestation has also been shown to increase the geographic range of less abundant vectors—in this case *Anopheles arabiensis*—into higher altitudes. As a result of warmer ambient temperatures in deforested areas, *A. arabiensis* has a 49% to 55% longer adult life span and a reproductive rate about twice that in forested areas. It has been suggested that a combination of deforestation and climate change may facilitate the establishment of *A. arabiensis* as an important malaria vector in the Kenyan highlands (95).

## Disease Ecology: Changes in the Species Composition of Communities of Organisms

We have discussed how environmentally mediated changes in the presence, abundance, exposure pathways, genetics, or life cycles of vectors, hosts, or pathogens will alter infectious disease transmission. Although these may all be considered aspects of disease ecology, there is a growing body of research shedding light on the complex ways in which changes in the species composition of whole communities of organisms can impact disease exposure.

In Belize, for example, the application of fertilizer to agricultural lands causes increased malaria exposure well downstream. Addition of nutrients, particularly phosphorus, to wetlands downstream of agricultural lands causes a transition from short, sparse vegetation to denser vegetation dominated by cattails (*Typha* spp.). This alteration in habitat creates breeding sites favored by females of the species *Anopheles vestitipennis* over *Anopheles albimanus* (96). The result is a higher density of *A. vestitipennis*, which is a significantly more effective malaria vector (97). Nor is Belize an isolated example. In a recent survey of 41 different pathogens on six continents, nutrient enrichment led to ecological changes, which resulted in increased disease exposure 95% of the time (98).

Lyme disease exposure in the northeastern United States also has a complex ecology. Lyme disease is caused by infection with the bacterium *Borrelia burgdorferi*. In the northeastern United States, it is transmitted by the bite of the blacklegged tick (*Ixodes scapularis*). The most competent reservoir of Lyme disease is the white-footed mouse (*Peromyscus leucopus*). The abundance of these mice is a good predictor of the number of infected ticks. Because acorns are this mouse's most important food source, the density of mice is strongly associated with the abundance of acorns in the prior fall. Not surprisingly, the abundance of infected ticks is also tightly associated with acorn abundance, although there is a two-year lag as a result of the long life cycle of the tick (99).

But Lyme disease exposure depends on more than the number of acorns available. It also depends on the species composition of the entire mammalian community in northeastern forests. Because most other mammals are much less competent reservoirs of Lyme disease, the presence of more nonmouse mammals, on which ticks may feed, reduces the likelihood of a tick becoming infected (100). This effect of biological diversity reducing disease transmission, known as the "dilution effect," has been described in a variety of other diseases, including West Nile virus encephalitis, hantavirus pulmonary syndrome, and bartonellosis (101–104).

In a final example, human outbreaks of St. Louis encephalitis (SLE) have been shown to follow wet summers after dry springs. In order to cause mosquito infection rates sufficient to drive human epidemics, SLE must be amplified in avian hosts. In South Florida, drought conditions in the spring cause *Culex nigripalpus*, the mosquito vector, to restrict their activity to densely vegetated, wet, "hammock" habitats. Nesting wild birds also make use of these habitats in the spring, and it appears that drought drives the mosquitoes and birds into close contact with one another. This forced contact provides for rapid epizootic amplification of the SLE virus. Subsequent wet conditions cause both birds and mosquitoes to disperse and favor breeding and feeding by *C. nigripalpus*. With a critical mass of wild birds already infected, newly hatched *C. nigripalpus* can be infected by feeding on birds that are still viremic, thus maintaining the transmission cycle. The epidemic of SLE among human residents of Indian River County in Florida in 1990 appeared to depend on this complex ecology of land cover-climate-wild bird-mosquito interaction (105).

One theme emerging from these types of studies is the complexity of relationships between land use, climate phenomenon, species diversity, and disease transmission. As a result of this complexity, a second theme is the unpredictability of some of these relationships. On the face of it, it is not obvious that a disease, which prevented oak trees from masting, might reduce exposure to Lyme disease or that more efficient use of fertilizers on the mountain slopes of Belize might reduce malaria exposure hundreds of miles away.

A third theme, recently emerging, is the extent to which ecological disturbance appears to favor disease transmission. Although there are certainly exceptions, more often than not, disruption of historical land cover through deforestation, dams and irrigation, agricultural practices, or livestock management practices seems to lead to increased disease exposure. As has been described, nutrient enrichment and reductions in species diversity also appear to increase disease exposure in most of the systems that have been studied. One explanation for this apparent trend is the possibility that pathogens have adapted to favor generalists, which are, in turn, well adapted to thrive during periods of ecological disruption (106). Another is that ecologically resilient generalist species have more "permissive" immune systems, either because of the variety of different environments in which they live or because there is some other advantage for them in dedicating less metabolic energy to fighting infection. Even though this is quite speculative, and it is possible that some of these apparent trends might be the result of reporting bias, it remains an interesting question and the subject of active research (106).

## Food and Nutrition

Although the relationships between environmental change and infectious diseases are the best studied, it is quite possible that, with respect to global human health, they are not the most important. It may be that scarcity of food and water combined with greater vulnerability to natural disasters and forced migration will lead to much higher morbidity and mortality than increased exposure to infectious disease.

One ecosystem service critical to human health is, of course, food production. Adequate nutrition—protein, calories, and micronutrients—is vital to cognitive development and learning, metabolic and endocrine functioning, reproductive health, preventing and fighting infectious disease, and overall vigor. It has been estimated that at least one-third of the burden of disease in poor countries is due to malnutrition (107), and roughly 16% of the global burden of disease is attributable to childhood malnutrition (108). As of 2008, an estimated 923 million people suffered chronic hunger (109).

As the human population grows by roughly another 3.3 billion people by 2050, and more prosperous people across the globe strive to add more meat to their diets, world agricultural production will need to roughly double over the next 50 years to keep up (110). One of the central public health questions of this century is whether we can meet this demand or whether we will be stymied by a series of ecological constraints.

This question must be answered at two scales, local and global. Because most of the chronically hungry people in the world are also among the over one billion people who live in absolute poverty, global food production is only partly relevant. Most of these people are too poor to access global food markets and depend on local production. For them, local ecological constraints can drive hunger, disease, and death, even while global food production exceeds demand.

In certain parts of the world, particularly sub-Saharan Africa and parts of South Asia, rapidly growing populations are already encountering ecological constraints to local food production. Soil degradation and water scarcity have prevented yields from rising over the past 35 years, and in some areas, they have been falling. In 37 African countries, for example, severe soil nutrient depletion over the past 30 years has led to significant soil impoverishment and reduced output (111). Water scarcity is necessitating grain imports in all but 2 of the 34 countries in Africa, Asia, and the Middle East that have annual per capita runoff levels below 1700 $m^3$ (defined as water stress). With the number of people living in water-stressed countries in Africa, Asia, and the Middle East projected to rise from 470 million to more than 3 billion by 2025, regional water scarcity is likely to affect local food production quite significantly (112).

Increasing agricultural output at the global scale may also be limited by ecological constraints. Some analysts are optimistic that the combination of a 10% to 20% increase in land under cultivation with more widespread use of irrigation, fertilizer, and new crop strains will allow a doubling of global output (113, 114). However, each aspect of this equation may be ecologically constrained. It is not clear how much additional arable land is really available. Widely used estimates lack sufficient ground truthing and may be unreliable (115, 116). Existing arable land is suffering degradation from erosion, salinization, desertification, and conversion to other uses, including rapid urbanization. The rates of many of these types of arable-land loss are not well quantified, but recent work on erosion rates indicates that tillage agriculture is causing erosion at rates that exceed soil formation by one to two orders of magnitude. Widespread agricultural approaches are essentially "mining" soils unsustainably with dramatic net reductions in fertile soil as a result (117, 118).

Increasing per hectare yields may be challenging in many parts of the world as well. In many of the largest grain producing areas of the world, yields are approaching biological limits, leaving little room for significant gains. [For an excellent discussion of the challenges associated with increasing crop yields, see Lobell et al.'s article (119) in this issue.] In sub-Saharan Africa, where there are still big yield gaps, the heterogeneity of agroclimatic conditions makes the dissemination of high-yielding seed varieties particularly challenging. Although new crop strains may provide greater stress resistance, there is little evidence to date that they are providing significant gains in yield potential (115).

Another critical element in doubling grain production will be increasing irrigation. Doubling agricultural output will require roughly an additional 2000–3000 $km^3$ of irrigation water—the equivalent of over 110 to 160 Colorado Rivers and more than a tripling of current irrigation demand (112, 120). Persistent industrial growth and urbanization will place yet further demands on global water supplies. These new demands will be placed on water resources that are already seriously constrained. Water tables below many agricultural lands, including the three largest grain producers, are falling as countries mine their aquifers faster than they can be recharged. In the North China Plain where 50% of China's wheat is grown, water tables are falling at over 1 meter/year (121). In India, 15% of grain production depends on water mined unsustainably from fossil aquifers, and electrical blackouts are becoming frequent in states where half of all electricity is used to pump water from depths of up to one kilometer. In the United States, the water table below parts of Texas, Oklahoma, and Kansas—three leading grain-producing states—has dropped more than 100 feet (122). [For an excellent discussion of water constraints to increasing agricultural production, see Rosegrant et al. (120) in this issue.]

A further concern is the dramatic increase in fertilizer needed to double agricultural productivity through intensification. Human beings already release more nitrogen and phosphorus to terrestrial ecosystems than all natural systems combined (7). Extrapolating from current trends, a doubling of food production by 2050 will require increasing the application of

**IPCC:** Intergovernmental Panel on Climate Change

both nitrogen and phosphorus by roughly two-and-a-half times, exacerbating already serious impacts including eutrophication of marine ecosystems (123), biodiversity loss, groundwater and air pollution, and acidification of soils and freshwater (124). [For a comprehensive discussion of fertilizers and nutrient balances see Robertson & Vitousek (125) in this issue.]

Two other global trends are likely to impact food supplies. On the demand side, the acceleration of the biofuel industry has stimulated a new nonfood market for cereals that consumed nearly 5% of global cereal production in 2007 and is growing rapidly. It has also pegged the price of food to the price of liquid fuel more directly than ever before, with ominous consequences to the hungry poor.

The second trend, on the supply side, is climate change. Many of the biophysical conditions anticipated under global climate change are likely to impact food production. Climate change is expected to worsen water scarcity. It will almost certainly alter hydrological cycles causing precipitation to fall in more intense storms with more runoff and also to cause more droughts (126). There is high confidence that many semiarid areas (e.g., Mediterranean basin, western United States, southern Africa, and northeast Brazil) will suffer a decrease in water resources owing to climate change (127). It is already causing rapid melting of many of the glacial systems that supply dry-season flow to many of the world's great rivers. Current Intergovernmental Panel on Climate Change (IPCC) projections are that for glaciers on the Tibetan plateau, which supply over a billion people with water in the dry season, the likelihood of them melting completely by 2035 is "very high" (128). Sea level rise, weakened coastal barriers, and more intense storms will lead to more coastal flooding and inundation of coastal freshwater aquifers and fertile soils with saltwater. Winter snowpack is expected to melt earlier in the year, disconnecting water supply from the height of growing season in some areas. Warmer temperatures will also lead to greater evapotranspiration and increase irrigation requirements for crops. All of these dynamics will further restrict already constrained access to freshwater for irrigation.

In addition, temperature rise has direct impacts on crop yields. Having been developed to maximize yields under current climate conditions, most cultivars now in use are grown at or near their thermal optima. A rule of thumb among crop ecologists is that a 1-degree Celsius rise in the minimum temperature during growing season leads to a 10% reduction in yields of rice, wheat, or corn (129). This was recently confirmed by a time series analysis from 1979 to 2003 at the International Rice Research Institute (130). Numerous modeling studies have projected similar sensitivities (albeit with a range of +3% to −17% yield changes depending on region and crop) of the major grains to a 1-degree Celsius rise in temperature (131). The implications of such extreme temperature sensitivity above a threshold could be major reductions in crop yields in many of the most important food-producing regions of the world, including the North China Plain, the Gangetic Plain of India, and the U.S. Corn Belt (129). Although the net impact of climate change on global agricultural productivity is still debated, there is agreement that, at a minimum, certain agricultural regions are likely to see significant overall reductions in food production, particularly in sub-Saharan Africa and South Asia (131, 132).

## Water

A second ecosystem service critical to human health is the provision of clean water. Apart from food production, humans depend on water for drinking, sanitation, hygiene, and food preparation. Each person needs roughly 50 liters of uncontaminated freshwater per day to meet these needs (133). Inadequate access to water, sanitation, and hygiene is already estimated to cause 1.7 million deaths annually and the loss of at least 50 million healthy life years. Half of the urban population of Africa, Asia, Latin America, and the Caribbean suffers from one or more diseases associated with inadequate water and sanitation (134).

As discussed in the section on food and nutrition, water is already scarce and getting scarcer. Roughly 40% to 50% of renewable, accessible freshwater supplies are already being used (3, 134). Rates of increase in water use relative to accessible supply from 1960 to the present have been nearly 20% per decade globally, with values of 15% to more than 30% per decade for individual continents. In many parts of the world, water is being mined unsustainably from fossil aquifers or withdrawn faster than the rates of replenishment. In the Middle East and North Africa, for example, current rates of freshwater use are equivalent to 115% of total renewable runoff (134).

As with food needs, our ability to meet future water needs will be further constrained by trends in both supply and demand. On the supply side, further intensification of agriculture and livestock management will generate additional runoff of excess nutrients and wastes, causing groundwater contamination and pollution of freshwater systems (124). Urbanization and the growth of manufacturing continue to drive both biological and chemical contamination. And, as discussed above, climate change is already leading to a series of physical changes—glacial melting, sea level rise, changes in the hydrological cycle, and warming temperatures—which are likely to further reduce access to freshwater. On the demand side, population growth, continued economic development, and rapidly growing manufacturing and agricultural sectors will continue to place additional demands on global freshwater supplies.

The health impacts of reduced access to uncontaminated freshwater depend on a wide variety of mediating factors as illustrated by **Figure 1**. Populations in wealthy countries, such as Israel, have developed highly efficient irrigation technologies, sanitation systems that require little water, and the economic capacity to import water in the form of grain (about 1000 tons of water are used to grow 1 ton of grain). Populations in poor countries, though, are less capable of insulating themselves with technology and infrastructure and lack the purchasing power to replace locally constrained resources on the international market. Lacking such resources, they are, therefore, vulnerable to local water scarcity just as they are vulnerable to local food scarcity. Such vulnerability differs not only as a result of socioeconomic status but by gender and age. For example, women suffer disproportionately as a result of water shortages (135).

## Protection from Natural Disasters

Increasing vulnerability to natural disasters is a further area where changing environmental conditions may impact human health and well-being. Human vulnerability to natural disasters is mediated by a wide variety of factors, including where people live, the quality of their housing, disaster preparedness, early warning systems, and environmental conditions (136). Annual economic losses from extreme events increased 10-fold over the past four decades (137). Annual average losses for all disasters over the 1990s were 62,000 deaths, 200 million affected, and $69 billion in economic losses. Twice as many people were affected by natural disasters in the 1990s as in the 1980s (137). There are limited data available to evaluate the contribution that environmental change has played in increasing vulnerability to fires, floods, storms, tidal waves, landslides, or other natural disasters. Model simulations and empirical observations indicate that damage from the Asian tsunami of 2004 was exacerbated by earlier destruction of coral reefs (138, 139). Additional studies have shown that areas where mangrove forests had been destroyed suffered disproportionate damage (140, 141).

Coincident with these changes in land use and cover are current and anticipated changes resulting from climate change. The IPCC fourth assessment (142) expressed high confidence that a warming of up to 2°C above 1900 to 2000 levels (on the lower end of most projections for 2100) would increase the risk of many extreme events, including severe tropical cyclones, floods, droughts, heat waves, and fires. Coastal areas may be particularly vulnerable. More than a third of the human population lives in coastal areas and small islands (within 100 km of the shore and less than 50 m above sea level) (143). The rapid destruction of mangrove forests, coral reefs, vegetated dunes, and wetlands increases coastal vulnerability to storm surge and flooding. Loss of these barriers combined with sea level rise and increasingly intense storms, particularly tropical cyclones, is likely to cause significant morbidity, mortality, and population displacement.

In addition to acute morbidity and mortality from heat waves, injuries, or drowning, there is considerable additional morbidity and mortality resulting from natural disasters. Severe storms can result in pollution or biological contamination of water supplies. Air quality may suffer as a result of fires or of mildew in homes following flooding. Loss of homes and the resulting displacement have numerous health impacts, discussed below. And we are only just beginning to understand the significant mental health impacts experienced by survivors of natural disasters. Survivors of Hurricane Katrina, for example, suffered twice the rate of mental illness as a similar population in New Orleans prior to that hurricane (144).

## Clean Air

There is extensive research documenting the negative health impacts of indoor and outdoor air pollution (145). Most of this work falls into the realm of traditional environmental health, which addresses the local impacts of exposure to toxic pollutants. However, air pollution in certain regions has become so extensive that it is literally blotting out the sun, impacting regional weather patterns, affecting agriculture production, and accelerating glacial melting (146). Composed primarily of the combustion products of biomass and fossil fuels, atmospheric brown clouds (ABCs) are estimated to cause 337,000 excess deaths from cardiorespiratory disease each year in China and India. In addition to these direct health effects, ABCs are also preventing sunlight from reaching Earth's surface, thereby reducing agricultural yields. ABCs are contributing to reductions in the Indian summer monsoon rainfall and in shifting rainfall patterns in eastern China from the dry North to the relatively wet South (146, 147). Soot deposition from ABCs onto glaciers, particularly the Hindu Kush-Himalayan Tibetan glaciers and snowpacks, is further accelerating melting with worrisome consequences for the water security of South and East Asia. The combination of increased ground-level ozone (which can significantly reduce crop yields), decreased solar radiation, reduced or altered precipitation, and accelerated glacial melting all pose challenges to agricultural production. These trends may be part of the explanation for falling rates of annual growth in the harvests of rice, wheat, maize, and sorghum throughout Asia from 3.5% (1961–1984) to 1.3% (1985–1998) (146, 147).

Global environmental change is impacting air quality in other ways as well, by worsening ambient air pollution and altering regional pollen production. Tropospheric ozone is an air pollutant strongly associated with increased morbidity and mortality from cardiorespiratory disease (148). The application of nitrogen-containing fertilizers to agricultural lands produces $NO_x$ (as does fossil fuel combustion), which is an important precursor to ozone formation. Perhaps of even greater concern, tropospheric ozone formation rises with temperature, with a particularly strong association found at temperatures above 90°F (32°C). Modeling studies project increased concentrations of ground-level ozone with consequent increases in respiratory morbidity and mortality resulting from higher temperatures associated with climate change (149, 150). In addition, warmer temperatures and higher $CO_2$ concentrations are associated with longer pollen seasons and increased pollen production for many allergenic plants. This trend will cause additional allergic respiratory disease, particularly asthma, which is already associated with a quarter of a million deaths annually (151).

## Population Displacement

Population displacement and violent conflict may represent the final common pathways as large, vulnerable populations suffer amplified exposure to water scarcity, hunger, and natural disasters. Sea level rise and more extreme storms will make some low-lying coastal areas untenable for habitation. A recent analysis reveals that, although coastal areas less than 10 meters above sea level only represent two percent of the world's land area, they house 10% of the world's population (152). Degraded lands and altered precipitation patterns are likely to turn marginal agricultural lands into deserts, which cannot support local populations. Local scarcities of food and water may drive populations out of resource-poor regions. These forces, working in concert, may drive hundreds of millions of people with few resources and many needs to seek new homes (153). In 2008, the UN Commissioner for Refugees estimated that between 250 million and one billion people would be displaced by climate change alone between now and 2050 (154).

Population displacement is associated with increased morbidity and mortality for a variety of reasons. Nonimmune populations migrating into endemic areas are more susceptible to a variety of infectious diseases (155). Poor housing, sanitation, and waste management infrastructure combined with inadequate safe drinking water and poor nutrition lead to epidemics of infectious disease, particularly diarrheal diseases, measles, and acute respiratory infections. Protein energy malnutrition increases mortality from these communicable diseases and contributes independently to morbidity and mortality. Prevalence rates of acute malnutrition have reached up to 50% in refugee populations in Africa (156). In addition to malnutrition and communicable disease, displaced people suffer high levels of violence, sexual abuse, and mental illness. One study found symptoms and signs of post-traumatic stress disorder in 30% to 75% of resettled refugee children and adolescents (157). Overall, crude mortality rates as high as 30 times baseline are not unusual following an acute movement of refugees, with much of the mortality occurring in children under the age of five (158).

In addition to the burden of suffering and disease associated with population displacement itself is the risk of violent conflict. Already, resource scarcity has played an important role in generating such conflict, and the prospect of significantly larger numbers of resource-constrained people seeking new homes in already settled lands must raise concern for greater conflict in the future (159).

## OPPORTUNITIES AND CHALLENGES

We have seen that accelerating changes to the planet's climate, its land surface, and the functioning of its ecosystems are acting synergistically to generate emerging threats to human health at a scale that threatens the health and well-being of hundreds of millions of people. Responding to these threats effectively will require new research efforts as well as new approaches to policy and decision making.

From a research standpoint, we need to improve our understanding of the dynamics of each of these threats. How do different types of anthropogenic change interact with local conditions to generate each of these emerging threats? What are the characteristics of populations that make them particularly vulnerable or resilient in the face of such threats? Which populations around the globe are at greatest risk for each type of threat? To answer these questions, we need to do a much better job of integrating information across sectors and scientific disciplines. There is tremendous potential to advance our understanding by tapping large existing sets of environmental and social science data and identifying relationships with human health. For example, a wealth of data is available from near real-time environmental monitoring satellite platforms. This data could be analyzed with historical data on local and regional land use, climate, and sociodemographic conditions to help us identify health/environment relationships.

In addition to integration at the research level, we need better integration in the training of research scientists (160). Researchers in health, natural, and social sciences need training across each other's disciplines so that they can work together collaboratively. Agencies and academic institutions should augment awards and promotion by developing criteria for scholarship in interdisciplinary pursuits, rather than the current incentives for reductionism in research endeavors. Government agencies, such as the National Science Foundation and the National Institutes of Health, could work together to support more collaborative research efforts, including funding for postdoctoral fellowships that emphasize work across these disciplines.

Although better integration and collaboration across disciplines is a critical step to improving our understanding of health/environment relationships, we also need to fill several important data gaps. We have an astonishing lack of reliable, fine-scaled, georeferenced data about population health, environmental conditions, or the host of factors that determine vulnerability. We know little about the incidence or prevalence of most infectious diseases, water-related diseases, and different types of malnutrition at subnational scales. We lack fine-scaled population data on key components of vulnerability: resource availability, socioeconomic status, quality of infrastructure, human behavior, and governance. Nor do we have good data on some of the most basic and critical questions pertaining to environmental conditions that have very significant health consequences: There is disagreement within the scientific community on how much additional arable land is available for cultivation and on how much additional freshwater is available for sustainable use; global rates of deforestation are not well established; we do not know how much arable land is becoming degraded by salinization, erosion, desertification, or nutrient loss; and we do not know how fast many of these processes are occurring or how reversible they are. Without such basic information, we are steering in the dark and have little chance of making good decisions about policy or resource management.

But it would be misleading to imply that our only constraints are related to data availability. One of the major factors curtailing our understanding of the health impacts of global change is the subject's sheer complexity. As we have discussed, these health impacts are mediated by numerous different factors (**Figure 1**). In response to new threats imposed by altered environmental conditions, people adapt. They move, they find alternative resources, they externalize their resource use, they trade, they alter behaviors, and they seek assistance from national and international organizations. Although filling data gaps is critically important, it is also important to acknowledge that the complexity of some of these relationships will always make exact impacts of changing environmental conditions on human well-being difficult to quantify. In this context, stepped-up efforts at surveillance so that we are able to detect changing patterns of infectious disease, malnutrition, cardiorespiratory disease, morbidity from natural disasters, and environmental migration will also be critical.

In addition to increased research efforts, the emerging threats associated with globally changing environmental conditions also require a reorientation of policy and decision making. Public health practitioners cannot effectively protect public health without moving outside of the traditional health sector. Schools of public health and public health professionals need to expand their focus to include health impacts from global environmental change. Public health professionals need to join their colleagues in sectors that have traditionally been considered unrelated to health to discuss the health impacts of different approaches to energy generation, food production, land-use management, urban design, transportation, and water resource management, and these topics should be integral components of public health research and training.

In addition to their more traditional metrics, decision makers in nonhealth sectors need to evaluate the impacts of their decisions through a public health lens. Decision making should be fully integrated with coordination across agencies and with policy makers involved in all aspects of economic development and societal well-being. For example, every development project will have trade-offs and should require an HIA in addition to current requirements for environmental impact assessments. Beyond specific development projects, treaty negotiations and large-scale policy decisions should also include health impact evaluations. One of the important advantages of more widespread use of HIAs would be the identification of cobenefits whereby actions taken to address one problem can significantly improve public health at the same time. For example, replacing coal-fired power plants with solar or wind generation would help reduce carbon emissions and would also significantly improve air quality and cardiorespiratory health (161). What would be the health impacts of different approaches to reducing global $CO_2$ emissions versus continuing business as usual? How would widespread adoption of improved agricultural techniques or altered management of coastal zones impact human health? How can ecosystems be managed to maximize their services while allowing for other uses?

A final important element is to bring these emerging public health threats to the attention of political leaders around the world in order to encourage them to take strong action both to reduce the pace of global environmental change and to help the populations at highest risk. Modeling the dynamics of each of the major public health threats associated with large-scale anthropogenic change and mapping out which populations are at greatest risk for each of these threats would provide such leaders with the information they need to convince their political constituencies of the importance of such actions and to target their resources in the most effective way possible.

## CONCLUSION

How much suffering will result from infectious disease exposure, constrained agricultural production, water scarcity, poor air quality, natural disasters, displacement, and civil strife is impossible to project without knowing the effectiveness of mitigating factors that protect populations from these threats. Will economic development occur in patterns that increase the capacity of the world's poorest people to access international food markets? What degree of responsibility will the wealthy countries and international community take for helping the poor reduce their vulnerability? How rapidly will technology and infrastructure proliferate to make more efficient use of water, soil, and fertilizers; produce energy more cleanly; break transmission cycles of infectious disease; or a host of other interventions? To a large extent, our global society will decide how much suffering results from large-scale environmental change by the way it answers these questions.

Our inability to exactly quantify current or projected health impacts resulting from altered environmental conditions should not be an excuse for complacency. Even without exact estimates, we have ample cause for concern. Numerous infectious diseases, including vector-borne diseases that affect roughly half the world's population, are changing their distribution, exposure pathways, virulence, and infectiousness in response to environmental changes that we only partially understand. New infectious diseases are emerging at an accelerating rate, frequently as a result of altered environmental conditions. Huge segments of the world's population live without adequate access to food or water, and many large-scale environmental trends appear likely to further constrain access to these resources. Climate change represents an additional destabilization of this already tenuous relationship between human populations and their resource base.

At present, all of the major types of anthropogenic environmental change—climate change, changes in land use and cover, and ecosystem service degradation—are accelerating. In concert, these trends are producing significant and growing vulnerabilities for large segments of a growing human population. Many of the threats people face from changing environmental conditions can be addressed with technology, infrastructure, policy, and economic development. However, with nearly half the world's population living on less than $2.00 per day (162), such development will require a level of international assistance and cooperation that is not currently evident. In order to reduce avoidable human suffering, vigorous efforts at slowing the pace of environmental change, humanely reducing the rate of population growth, and helping to reduce vulnerabilities of those in harm's way are necessary.

## SUMMARY POINTS

1. Large-scale anthropogenic changes to the natural environment including land-use change, climate change, and the deterioration of ecosystem services are all accelerating. These changes are combining synergistically to endanger the health and well-being of hundreds of millions of people through emerging threats in five main areas: increasing exposure to infectious disease, water scarcity, food scarcity, natural disasters, and population displacement.
2. Although the relationships between environmental change and infectious diseases are the best studied, it is quite possible that, with respect to global human health, they are not the most important. It may be that scarcity of food and water combined with greater vulnerability to natural disasters and forced migration will lead to much higher morbidity and mortality than increased exposure to infectious disease.
3. One reason that direct causal links between ecological degradation and human health are difficult to quantify is because human populations tend to be insulated from direct impacts of ecosystem service degradation by a variety of mitigating factors, such as local public health infrastructure and the ability to procure natural resources from elsewhere.
4. The causal chain between global environmental change and health impacts can be quite complex and may be lagged in time. Land use and climate change can directly threaten human health or can produce vulnerability by degrading ecosystem services relevant to health. For diminishing resources to threaten a population, it must be largely reliant on local resources and must be at a critical threshold of resource consumption. The population must lack the infrastructure, adaptive behaviors, governance, and access to international philanthropy that might otherwise protect it from the impacts of environmental degradation.
5. Global land use and climate change drive new patterns of infectious disease exposure through a variety of mechanisms. These mechanisms include the altering of (*a*) the biophysical conditions of habitats that can affect the density or presence of disease-related organisms; (*b*) exposure pathways, or the way organisms (including humans) interact with each other; (*c*) the genetics of pathogens; (*d*) the life cycles of pathogens and vectors; and (*e*) species composition within a community of organisms.
6. Decisions made in sectors that are not traditionally associated with health—agriculture, energy, natural resource management, urban design, and others—will have important health impacts mediated by their effects on the environment. Health practitioners need to move outside of the traditional health sector to consider these types of impacts and inform decision making, just as nonhealth decision makers need to reach out to the public health community for assistance in evaluating these health impacts. Health impact assessments (HIAs) should be integral to the planning of new projects and activities in these sectors.

7. A final important element is to bring these emerging public health threats to the attention of political leaders around the world in order to encourage them to take strong action both to reduce the pace of global environmental change and to help the populations at highest risk. Modeling the dynamics of each of the major public health threats associated with large-scale anthropogenic change and mapping out which populations are at greatest risk for each of these threats would provide such leaders with the information they need to convince their political constituencies of the importance of such actions and to target their resources in the most effective way possible.

## FUTURE ISSUES

1. Far more integration of information across sectors and scientific disciplines is greatly needed to best understand the web of interconnected health challenges arising from global environmental change. This integration is required in research, training, and decision making.
2. There is an astonishing lack of reliable, fine-scaled, geo-referenced data about population health, environmental conditions, and the host of factors that determine vulnerability. We know little about the incidence or prevalence of most infectious diseases, water-related diseases, and different types of malnutrition at subnational scales. We lack reliable, fine-scaled population data on key components of vulnerability: resource availability, socioeconomic status, quality of infrastructure, human behavior, and governance. Nor do we have reliable, comprehensive data on some of the most basic and critical questions pertaining to environmental conditions, such as the availability of arable land and freshwater supplies as well as accurate measures of current rates of deforestation.
3. Given the complexity of health impacts from global environmental change, improved efforts at surveillance of environmentally sensitive conditions—environmentally mediated infectious diseases, all types of malnutrition, food- and water-borne disease, natural disasters, and environmentally driven migration—are particularly important.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

## ACKNOWLEDGMENTS

We are grateful to Katie Arkema, Gretchen Daily, Jenna Davis, Paul Ehrlich, Dris Ennaanay, Rachelle Gould, Karen Levy, Amy Luers, Hal Mooney, and Gary Schoolnik at Stanford University and Felicia Keesing at Bard University for constructive comments on our conceptual model. We would like to thank Paul Ehrlich, Rosamond Naylor, David Lobell, and Gretchen Daily at Stanford University, James McCarthy and Daniel Schrag at Harvard University, Richard Ostfeld at the Cary Institute of Ecosystem Studies, and Timothy Wirth at the United Nations Foundation for helpful comments on an earlier draft of this manuscript. We also thank Mary Sternitzky at the University of Wisconsin's Center for Sustainability and the Global Environment for help creating the figures.

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**Annual Review of Environment and Resources**

Volume 34, 2009

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