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Introduction

Human beings are rapidly and profoundly changing Earth’s landscape. With continuing population growth and pervasive economic development, human consumption of food, water, fiber, building materials, and other products is growing exponentially. To meet these demands, Earth’s terrestrial surface is being transformed in many different ways. The most pervasive changes to the landscape include deforestation, agricultural intensification and animal husbandry, dams and irrigation projects, road building, and urbanization.

Each of these types of change has important health implications, not all of which are fully characterized. An understanding of the relationships between land use change and human health helps in anticipating possible health consequences of new land use projects and potentially mitigating the health effects of land use changes already under way. Such an understanding also highlights the need for further research in this area (Table 1).

Deforestation

The world’s forests are rapidly dwindling, particularly in the tropics. Over the past 300 years, between 7 and 11 million km² of forest have been cut down – an area the size of the continental United States. An additional 2 million km² of forest are highly managed plantations with significantly reduced biological diversity.

Cutting down forest dramatically alters the biophysical environment. It alters biological composition and complexity, soil dynamics, biogeochemical cycles, surface water chemistry, ambient temperature, exposure to sunlight, and hydrological cycles. It also creates forest fringe – areas where intact forest abut cleared, open land. Fringe represents new habitat for a variety of disease vectors that like to feed in open areas but dwell or breed in forested habitat. Fringe created by deforestation also creates an active interface between human populations clearing the forest or inhabiting these clearings and forest-dwelling vectors and host species.

All of these types of change can promote infectious disease exposure, particularly to vector-borne and zoonotic diseases. Vector-borne diseases are caused by pathogens – viruses, bacteria, parasites – which are transmitted from one individual to another by an intermediary organism – usually an arthropod like a tick or mosquito. Common examples include Lyme disease and malaria. Zoonoses are diseases that exist in both human and nonhuman hosts and, therefore, have natural reservoirs in the nonhuman animal community. Yellow fever (monkeys) and rabies (dogs, raccoons, foxes, skunks, etc.) are common examples.

The case of malaria provides an excellent example of the many ways in which deforestation can impact exposure to disease. Of an estimated 3 billion people living in malaria-prone areas, approximately 500 million contract the disease annually, and roughly 1 million people die each year, mostly in Africa. Malaria is transmitted by a number of different species of Anopheles mosquito. To understand the effect of deforestation on malaria, it is necessary to know which species of mosquito are responsible for transmission in a given location and what its breeding habitat and feeding preferences are. Land use change dramatically changes habitat, breeding sites, and availability of food, thereby favoring some species over others.

In the Americas, four out of five cases of malaria occur in Amazonia. Although there are over 50 different Anopheles mosquitoes in this region, only one has been shown to be an important vector of malaria: Anopheles darlingi. A. darlingi breeds in partly shaded pools. Slash and burn land clearing and road building change the chemical composition of the soil, reduce shading, and often create small pools of water. As a result, deforestation favors breeding of this vector and has been shown to increase malaria exposure in the Amazon. In the Peruvian Amazon, investigators found that biting rates of A. darlingi in deforested areas were 278 times higher than biting rates in forested areas. These findings supported earlier work showing strong associations between deforestation and malaria and epidemiological evidence of malaria surges following periods of deforestation (Figure 1).
| Disease                                  | Cases per year | DALYs (000) | (Proximate) Emergence mechanism | (Ultimate) Emergence driver                                                                 | Geographical distribution                          | Expected variation from ecological change | Confidence level |
|-----------------------------------------|----------------|-------------|---------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------|-------------------------------------------|------------------|
| Malaria                                 | 350 m          | 46 486      | Niche invasion; vector expansion | Deforestation, water projects                                                                | Tropical (America, Asia, and Africa)               | ++ + + +                             | + + + +          |
| Dengue fever                            | 80 m           | 616         | Vector expansion                | Urbanization, poor housing conditions                                                         | Tropical                                          | ++ + + +                             | + +               |
| HIV                                     | 42 m           | 84 458      | Host transfer                   | Forest encroachment, bushmeat hunting, human behavior                                       | Global                                            | + + + + +                         | + +               |
| Leishmaniasis                           | 12 m           | 2090        | Host transfer, habitat alteration | Deforestation, agricultural development                                                      | Tropical Americas, Europe, and Middle East       | ++ + + + +                         | + + + +          |
| Lyme disease                            | 23 763 (US 2002)|            | Depletion of predators, biodiversity loss, reservoir expansion | Habitat fragmentation                                                                      | North America and Europe                           | ++ + + + +             | + +               |
| Chagas disease                          | 16–18 m        | 667         | Habitat alteration              | Deforestation, urban sprawl, and encroachment                                               | Americas                                          | + + + + +                         | + +               |
| Japanese encephalitis                   | 30–50 000      | 709         | Vector expansion                | Irrigated rice fields                                                                       | SE Asia                                           | ++ + + + +                         | + +               |
| West Nile virus and other encephalitides| –              | –           |                                 |                                                                                             | Americas, Eurasia                                 | + + + + +                         | + +               |
| Guanarito, Junin, Machupo               | –              | –           | Biodiversity loss, reservoir expansion | Monoculture in agriculture after deforestation                                             | South America                                      | + + + + +                         | + +               |
| Oropouche/Mayaro virus in Brazil       | –              | –           | Vector expansion                | Forest encroachment, urbanization                                                           | South America                                      | + + + + +                         | + +               |
| Hantavirus                              | –              | –           | Variations in population density of natural food sources | Climate variability                                                                        | South America                                      | + + + + +                         | + +               |
| Rabies                                  | –              | –           | Biodiversity loss, altered host selection | Deforestation and mining                                                                   | Tropical                                          | + + + + +                         | + +               |
| Schistosomiasis                         | 120 m          | 1702        | Intermediate host expansion     | Dam building, irrigation                                                                   | America, Africa, Asia                              | ++ + + + +                         | + + + +          |
| Leptospirosis                           | –              | –           |                                 |                                                                                             | Global (Tropical)                                  | ++ + + + +                         | + +               |
| Cholera                                 | †              | ¥           | Sea surface temperature rising  | Climate variability and change                                                               | Global (Tropical)                                  | ++ + + + +                         | + +               |
| Cryptosporidiosis                       | †              | ¥           | Contamination by oocytes        | Poor watershed management where livestock exist                                            | Global                                            | ++ + + + +                         | + +               |
| Meningitis                              | –              | 6192        | Dust storms                     | Desertification                                                                             | Saharan Africa                                     | + + + + + +                        | + +               |
| Coccidioidomycosis                     | –              | –           | Disturbing soils                | Climate variability                                                                         | Global                                            | + + + + + +                        | + +               |
| Lymphatic filariasis                    | 120 m          | 5777        |                                 |                                                                                             | Tropical America and Africa                        | + + + + + +                        | + +               |

(Continued)
| Disease                  | Cases per year\(^a\) | DALYs\(^b\) (000) | (Proximate) Emergence mechanism | (Ultimate) Emergence driver                                                                 | Geographical distribution | Expected variation from ecological change | Confidence level |
|-------------------------|-----------------------|-------------------|---------------------------------|---------------------------------------------------------------------------------------------|---------------------------|-------------------------------------------|------------------|
| Trypanosomiasis         | 30–500 000            | 1525              |                                 |                                               | Africa                     |                                           |                  |
| Onchocerciasis          | 18 m                  | 484               |                                 |                                               | Africa, Tropical America   |                                           | + +              |
| Rift Valley fever       |                       |                   | Heavy rains                      | Climate variability and change                 | Africa                     |                                           | + +              |
| Nipah/Hendra viruses   |                       |                   | Niche invasion                   | Industrial food production, deforestation, climate abnormalities | Australia, SE Asia         |                                           | + +              |
| Salmonellosis           |                       |                   | Niche invasion                   | Antibiotic resistance from using antibiotics in animal feed |                                           |                                           |                  |
| Ebola                   |                       |                   | Forest encroachment, bushmeat hunting |                                             |                           |                                           |                  |
| BSE                     |                       |                   | Host transfer                    | Intensive livestock farming                   |                           |                                           |                  |
| SARS                    |                       |                   | Host transfer                    | Intensive livestock operations mixing wild and domestic animals |                           |                                           |                  |

\(^a\)m = millions.

\(^b\)Disability-adjusted life year: years of healthy life lost, a measure of disease burden for the gap between actual health of a population compared to an ideal situation where everyone lives in full health into old age.

HIV, human immunodeficiency virus; BSE, bovine spongiform encephalopathy; SARS, severe acute respiratory syndrome.

Note: + low; ++ moderate; +++ high; and ++++ very high; † and ‡ Diarrheal diseases (aggregated) deaths and DALYs, respectively: 1798 × 1000 cases and 61 966 × 1000 DALYs.

Source: The World Health Report (2004).
Deforestation and forestation may affect the life cycle of Kenya highlands, these investigators evaluated how deforested areas. In experiments performed in the western density of anopheline vectors in forested versus deforested areas, Afrane and colleagues has gone beyond counting the primary malaria vectors and thereby increases human exposure to malaria. Essentially, forest clearing increases the habitat and range of the primary vectors and thereby increases human exposure to malaria.

Changing habitat or breeding sites for mosquito species is not the only way that deforestation can increase malaria exposure. An elegant series of investigations by Afrane and colleagues has gone beyond counting the density of anopheline vectors in forested versus deforested areas. In experiments performed in the western Kenya highlands, these investigators evaluated how deforestation may affect the life cycle of Anopheles species through microclimatic change. They showed that, by reducing shading, deforestation raises the temperature in homes by 1.8 °C and in aquatic habitats by 4.8–6.1 °C. In addition, these ambient temperature changes are associated with shorter gonotrophic cycles, 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. In short, warmer microclimate means more rapid development of adult mosquitoes, which then live longer lives. This dramatically increases their ability to transmit malaria to human hosts.

Deforestation, through these microclimatic effects, can also increase the geographic range of marginal vectors – in this case, *A. arabiensis* – into higher altitudes. As a result of increased ambient temperatures in deforested areas, *A. arabiensis* lives 50% longer and reproduces nearly twice as fast as it does in forested areas. Afrane and colleagues argue that a combination of deforestation and climate change may facilitate the establishment of *A. arabiensis* in the Kenya highlands.

In Asia, the relationship between deforestation and malaria is more complex. In part, this is because there are a wider variety of *Anopheles* species that are effective malaria vectors and have more variable habitat preferences. Unlike the Americas and Africa, much of the malaria transmission in Asia has occurred in forested areas. Almost all of the malaria transmission in Bangladesh in 1989 occurred in forests. In India, 7% of the population living in forested areas contributed 30% of the malaria in 1987. Deforestation in Asia has driven down the density of important malaria vectors including *A. dirus*, *A. minimus*, and *A. barbirostris* in Thailand, Nepal, India, and Sri Lanka. However, it has also caused an increase in the density of alternative vectors including *A. fluviatilis*, *A. annularis*, *A. jamesii*, *A. niggerrimus*, *A. subpictus*, and *A. peditaeniatus*. In an excellent review of over 60 studies of land use change and malaria, Yasuoka and Levins described the unpredictable nature of the impacts of these complex changes. In Kanchanaburi, Thailand, widespread deforestation from 1986 to 1995 eliminated breeding sites for *A. dirus* and decreased malaria incidence. However, in northeast India, deforestation increased malaria transmission by replacing the historical vector *A. minimus* with a more abundant vector: *A. fluviatilis*. In Sri Lanka, deforestation has led to major malaria epidemics. Given the complexity of malaria transmission in Asia, it is particularly hard to generalize the effects of deforestation on malaria exposure. However, what is clear from the research is that local changes in forest cover have had profound impacts on malaria exposure. Forest clearing has been credited with strong reductions in exposure and has also been implicated as a primary driver of major epidemics.

The effects of deforestation on other vector-borne diseases have been less well characterized. For example, there is some evidence that deforestation increases the incidence of cutaneous leishmaniasis (transmitted by the bite of the sandfly) in Latin America. However, further research is necessary to understand these relationships adequately.

The impact of deforestation on exposure to infectious disease is a rich field for further research. Nearly half the
human population suffers from one or more vector-borne diseases. Deforestation is one of the most pervasive features of global change. In most instances, the dramatic biological, geochemical, and hydrological changes associated with deforestation will strongly impact the dynamics of these insect-transmitted diseases. In the majority of diseases that have been studied, forest clearing has increased disease exposure. However, regardless of whether deforestation has a positive or negative impact on disease exposure, understanding the relationships is important in guiding disease surveillance and mitigation efforts. The importance of understanding these relationships between environmental change and vector-borne disease has been recently emphasized by the World Health Organization (WHO) as part of its emphasis on integrated vector management.

Not all health consequences of deforestation are related to infectious disease. Over the past decade, investigators have uncovered an important association between deforestation in the Amazon basin and ‘natural’ mercury contamination, particularly of rivers. Deforestation, particularly ‘slash and burn’ clearing releases mercury that is naturally found in trees and soils. As a result, areas disturbed by deforestation have significantly higher mercury loads than upstream areas that remain intact. This is not a result of adding exogenous mercury to the environment through gold mining or other activities. The effect can be seen in watersheds that are hundreds of kilometers removed from the nearest gold mining operations. This ‘natural’ contamination has led to elevated mercury levels in fish and in the local people who eat them. Other investigators have demonstrated neurotoxicity in Amazonian forest dwellers even at very low levels of mercury contamination.

There are other, less direct, effects of deforestation on human health. Deforestation makes a significant contribution to climate change. By releasing carbon from soils and forest biomass and by decreasing carbon uptake from growing trees, deforestation has contributed roughly one quarter to the total rise in greenhouse gases. Climate change, itself, has significant public health impacts that are discussed in a different article of this encyclopedia. In addition to climate regulation, forests play an important role in maintaining a reliable supply of clean fresh water. Forest litter absorbs water, filters it, and releases it slowly over time. Deforestation causes more rapid runoff, increased sediment loads, and poorer water quality. It can lead to flooding and landslides as well as increased incidence of waterborne disease. In 1998, upstream deforestation played an important role in the Yellow River flood disaster that killed more than 3500 people, damaged over 7 million houses, submerged 25 million hectares of farmlands, and caused US$30 billion of damage. In the same year, Hurricane Mitch killed nearly 10,000 people in Central America and left roughly a million people homeless. Areas with deforested hillsides and floodplains suffered disproportionate morbidity and mortality.

Agriculture and Animal Husbandry

Although deforestation has dramatically altered the planet’s land surface, perhaps the most profound changes to the terrestrial landscape have been driven by agriculture. Rapid human population growth coupled with economic development and adoption of a western-style diet has required dramatic increases in global grain and meat production. Since 1960, global food production has risen by roughly two and a half times. To achieve these increases has required bringing more land into cultivation and pasture – roughly 40% of the planet’s ice-free land surface has been converted into croplands or pasture (Figure 2). The area of cultivated land is expected to continue increasing dramatically across the tropics due to unprecedented increases in global demand for food, feed, and fuel. In addition to bringing more land under cultivation, much of the world is intensifying the way it grows crops – relying on industrial fertilizers and pesticides, widespread irrigation, new crop varieties, and mechanization.

The conversion of new land into cropland or pasture and the practices associated with agricultural intensification have a wide variety of health impacts. As with deforestation, all of these impacts have not been well described, but the research that has been done is highly illustrative.

One way that agriculture and animal husbandry impact health is by creating new ecological niches that favor organisms (mosquitoes, ticks, rodents, etc.) that play an important role in disease transmission. In South America, conversion of forest into grain cultivation combined with pesticide spraying and grain storage practices led to a boom in grain-eating rodent populations. These rodents were prime hosts for a group of hemorrhagic viruses (viruses that cause internal bleeding), and their explosion in numbers and anthropophilic behavior (living in and around human dwellings) led to serious outbreaks of fatal hemorrhagic disease. In Trinidad, in the 1940s, the development of cacao plantations caused a major malaria epidemic. The cacao was planted beneath nurse trees. The nurse trees provided ideal habitat for a type of plant (epiphytic bromeliads). These bromeliads, in turn, created excellent breeding sites for the mosquito: A. bellator, the principal local malaria vector. The epidemic wasn’t controlled until the nurse trees were reduced and plantation techniques were changed. Both cassava and sugarcane cultivation in Thailand led to reductions in the density of A. dirus but created
widespread breeding grounds for a more effective malaria vector, *A. minimus*, with a resulting surge in malaria. In Côte d’Ivoire, cultivation of coffee and cacao plantations has been associated with exposure to African trypanosomiasis (sleeping sickness). The plantations create habitat for the tsetse fly vector and cause exposure by bringing agricultural workers into contact with the vector. In a final example, the drainage and cultivation of papyrus swamps in highland Uganda appear to have increased the risk of malaria. Households located near drained and cultivated swamps had higher ambient temperatures and more *A. gambiae* mosquitoes (the principle vector of malaria in this area) per household than households in villages surrounding undisturbed papyrus swamps.

In addition to creating favorable niches for infectious disease hosts or vectors, agricultural practices can impact health through contamination of waterways with pathogens and excess nutrients. In 1993, the largest waterborne disease outbreak ever recorded occurred in Milwaukee. Over 400,000 people were infected with *Cryptosporidium parvum*, a protozoan that can cause severe diarrhea. The outbreak followed a period of heavy rainfall and runoff that contaminated Milwaukee’s water supply despite new filtration and disinfection facilities. Fifty-four people died in the outbreak. Heavy rainfall and runoff has been associated with other cryptosporidiosis outbreaks. The protozoan is shed in the feces of many animals including ruminants like cows and sheep. Clearing of land for grazing, and the absence of forested buffer zones along river ways can increase runoff and lead to this type of contamination from animal manure. A second protozoan parasite, *Giardia lamblia*, is also shed by a variety of animals and can cause similar surface water contamination after periods of heavy precipitation.

In addition to pathogens, agricultural runoff contains high concentrations of nutrients, particularly phosphorus and nitrogen. Agricultural activity adds a tremendous amount of fixed nitrogen to the terrestrial environment. In fact, human activity overall adds at least as much fixed N to the terrestrial environment as all natural sources combined. Because fixed nitrogen is a critical and rate-limiting nutrient in many ecosystems, its widespread addition can have profound impacts on these systems. In marine and freshwater environments, nutrient enrichment is responsible for a rapidly increasing number of harmful algal blooms (HABs). Caused by a wide variety of algae, these blooms can cause massive fish kills, shellfish poisonings, disease and death of marine mammals, and human morbidity and mortality. In the United States alone, roughly 60,000 individual cases and clusters of human intoxication occur annually. Health impacts range from acute neurotoxic disorders and death to subacute and chronic disease. The cost of HABs in the United States over a 15-year period was estimated to exceed $400,000,000. Nutrient enrichment of coastal waters is also likely to play a role in cholera outbreaks. Plankton blooms stimulated by warm temperatures and increased nutrient levels help to transform the cholera bacteria from a quiescent to an infectious state.

Nutrient enrichment from agricultural runoff can lead to increased risk of parasitic and infectious diseases through other types of ecological change as well. A recent review of the literature included 34 studies involving 41 different species of pathogens on 6 continents. Some of the studies contained multiple observations of pathogen/nutrient relationships. The authors concluded that in 95% of observations (51 of 55), nutrient enrichment increased exposure to pathogens. An example of this type of process has been documented by researchers in Belize. Addition of nutrients from agricultural runoff has been shown to change the plant community in wetland areas, promoting the growth of dense cattail marshes (e.g., *Typha* spp.). This type of vegetation is favored by the mosquito, *A. vestitipennis*, which is a more efficient malaria vector than the mosquitoes it displaces. In this ecotype, agricultural runoff leads directly to increased malaria exposure. Understanding how nutrient loading changes
exposure to infectious disease is a rich field for future research, given the pervasiveness of nutrient loading, the importance of the diseases likely to be impacted, and the fact that most of these relationships have not yet been described.

A final human health impact of nutrient loading is direct exposure to nitrogenous compounds in air and water. Nitrogen from synthetic fertilizers contributes to the formation of nitrogen oxides that, in turn, lead to the production of tropospheric ozone (O₃). Nitrogen oxides in the atmosphere are also an important driver of particulate air pollution. Both O₃ and nitrogen oxides contribute to respiratory disease (both chronic and acute) and cardiovascular disease. In addition, agricultural application of nitrogen to land surfaces leads to contamination of groundwater with nitrates. The World Health Organization (WHO) maximum standard of nitrate in safe drinking water is 10 ppm. Globally, this standard is often exceeded. Even in the United States where strict drinking water legislation applies, 10–20% of groundwater sources may exceed 10 ppm. The potential health effects of excess nitrate in drinking water include reproductive problems, methemoglobinemia (blue baby syndrome), and cancer.

Animal husbandry practices also have a series of important health consequences. The widespread use of antibiotics for livestock has contributed to rapidly increasing microbial resistance to these antibiotics. A variety of emerging or resurging infectious diseases are associated with animal husbandry practices as well. Pandemic influenza in humans is thought to result from genetic exchange among the strains of influenza virus in wild and domestic birds, and pigs. Keeping these animals in close proximity to each other, for example, in Asian ‘wet markets,’ fosters this type of genetic exchange. The 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 a possible role for raccoon dogs and ferret badgers. Most of the early cases of SARS were among people who worked with the sale or handling of these animals. More complete understanding of the ecology of this type of zoonotic disease transmission could lead to less risky animal husbandry practices. Most of the infectious diseases that are now endemic in human populations originated in nonhuman populations. This includes the major killers of humanity – smallpox, tuberculosis, influenza, malaria, measles, cholera, and plague. Practices that bring new populations of wild or domestic animals into close proximity with each other or human populations are likely to be the source of new emerging diseases in the future.

A final example of animal husbandry practices leading to resurgence of infectious disease comes from the mountainous regions of Yunnan Province, China. There, an economic development project tried to raise local incomes by giving villagers cows. Cattle are an important reservoir of Schistosoma japonicum, the agent responsible for schistosomiasis. As cows spread throughout the region, they shed schistosome eggs into waterways where they could infect snails – the intermediate host. As a result, schistosomiasis rates surged, infecting up to 30% of some villages and correlating directly with cattle ownership.

Dams and Irrigation Projects

Large dams and irrigation projects have become another pervasive feature of the human-dominated landscape. By the end of the twentieth century, there were over 45 000 dams in over 150 countries. About half of these were built exclusively or primarily for irrigation, and about one-third of the world’s irrigated cropland relies on dams.

The health impacts of dams and irrigation are far reaching. On the upside is the tremendous contribution to global food production, reliable water supply, and clean power generation. Representing only one-fifth of total agricultural lands, irrigated cropland produces roughly 40% of total agricultural yield. Dams are estimated to contribute 12–16% of world food production.

Dams and irrigation projects also change local ecology and create new favorable habitat for the transmission of a variety of vector-borne diseases. As it is with deforestation, the association with malaria is one of the best documented. A study in northern Ethiopia has shown a sevenfold increase in malaria in villages within 3 km of microdams compared with control villages 8–10 km distant. In general, dams and irrigation projects constructed in endemic areas tend to increase breeding habitat and transmission of malaria. Agricultural projects that combine deforestation with dams and irrigation can be a particularly potent combination for increasing malaria exposure, given their combined effects on breeding habitat and microclimate.

In the Nile delta area of Egypt, prevalence of lymphatic filariasis (elephantiasis) rose from <1% in 1965 to >20% after construction of the Aswan High Dam and subsequent irrigation projects. This surge resulted from increased surface and subsurface moisture that created improved breeding sites for Culex pipiens, the mosquito vector of this disease. The widespread proliferation of schistosomiasis beyond lakes and river deltas has also been attributed to the proliferation of dams and irrigation projects. This parasitic disease is spread by fresh water snails that breed in still or slow-moving waters. Roughly 200 million people are estimated to suffer from schistosomiasis. Propagation of Rift Valley
Fever, leishmaniasis, and Japanese encephalitis has also been associated with dams and irrigation projects.

**Roads**

Construction of roads can provide fringe habitat for disease vectors as well as create pools of water that can be excellent breeding sites for mosquitoes. Roads built for other purposes (e.g., transport, mining, and pipelines) can become an entry point for settlers. In these situations, the combination of deforestation and exposure of a non-immune population to local vector-borne or zoonotic disease can lead to new epidemics. With malaria, this phenomenon is referred to as ‘frontier malaria.’

Road building has also been implicated as an important factor in the penetration of human populations into previously undisturbed wildlife habitat. This mixing of previously isolated human and nonhuman populations can lead to exposure to new zoonoses. Consumption of wild animal species, through bushmeat hunting, further increases the risk for exposure to new pathogens.

Invasion into the jungle for bushmeat has afforded easier exchange of pathogens between humans and nonhuman primates. In Central Africa, 1–3.4 million tons of bushmeat are harvested annually. In West Africa, a large share of protein in the diet comes from bushmeat. The bushmeat harvest in West Africa includes a large numbers of primates, so the opportunity for interspecies disease transfer is significant. Therefore, there is opportunity for cross-species transmission and the emergence of novel microbes into the human population.

Recently, infection with simian foamy virus, a retrovirus that is endemic in most Old World primates, was demonstrated in hunters who reported direct contact with blood or body fluid of nonhuman primates. This finding provides additional support for the hypothesis that the retrovirus causing human immunodeficiency virus/acquired immunodeficiency syndrome (HIV/AIDS) was likely a mutated simian virus contracted through bushmeat hunting. It is likely that bushmeat hunting was also the origin of Ebola virus infection in human populations.

**Urbanization**

A final pervasive form of land use change has been the rapid, global development and expansion of cities. Over the past two centuries, the proportion of people living in cities or large towns has grown from approximately 5% to 50% and continues to climb. Between 1960 and 1980, the urban population in developing countries more than doubled. By 2025, urban population in developing countries is expected to account for well over half the global population. Urbanization is associated with a large variety of health impacts. Some of these impacts are likely to be positive. Some urban environments provide improved access to water and sanitation, a more reliable food supply, better security, and new employment opportunities that lead to improved income. Although the net effect of urbanization on global health is difficult to characterize, certain patterns of urbanization are clearly associated with higher risk of disease exposure. Some of these exposures fall within the realm of classic environmental health since they are not mediated by changes in the natural environment so much as by direct, toxic exposures. Urban air pollution, lead exposure, traffic accidents, and diseases associated with a more sedentary lifestyle are examples of classic environmental health problems that are only indirectly related to land use change.

However, there are also direct ecological consequences of widespread urbanization. As with deforestation, agriculture, and dams and irrigation systems, urbanization creates new habitat for disease hosts and vectors while changing human exposure patterns. 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. Pools of contaminated water, water containers kept in homes, tires, and other refuse capable of holding water, and piles of municipal waste all create excellent habitat for a variety of arthropod vectors, particularly those that transmit dengue, malaria, filariasis, Chagas disease, plague, and typhus. 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. A final contributing factor to the spread of vector-borne disease in slums is the poor quality housing that does not provide an effective barrier to mosquitoes, rodents, or fleas.

Dengue fever provides a good example. Over recent decades there has been a tremendous surge in dengue cases as it has spread out of Southeast Asia and the Pacific and become endemic throughout the tropics. Dengue is the most common mosquito-borne viral disease in the world with roughly 50 million cases in over 100 countries each year. It is transmitted by the bite of infected Aedes mosquitoes, primarily Aedes aegypti. These mosquitoes prefer to feed on humans over animals and usually live close to human dwellings. They breed in man-made containers like earthenware jugs, tires, metal drums, discarded plastic food containers, and other items that collect rainwater. These characteristics make them highly effective at adapting to urban areas.

A second consequence of rapid urbanization in slums and squatter settlements is lack of access to safe drinking water or sanitation. Current projections are that if efforts to provide water and sanitation to the underserved continue at the current rate, more than 692 million people
will live without basic sanitation and 240 million without improved sources of drinking water in urban areas in 2015. Particularly in crowded urban conditions, the exposure to infectious disease resulting from both contaminated drinking water and inadequate sanitation is significant. Diarrhea alone, caused primarily by contaminated drinking water and poor sanitation, causes around 2.2 million deaths each year, approximately 4% of all global mortality.

A more subtle effect of urban land use may be found around cities in the northeastern United States. Settlement patterns that have favored suburbanization with small woodlots and low biodiversity favor Lyme disease transmission. Lyme disease is transmitted by deer ticks infected with the bacteria, *Borrelia burgdorfi*. Most tick vectors feed on a variety of host species that differ dramatically in their efficiency as a reservoir for these bacteria – that is, the probability of a tick picking up the bacteria from different reservoir hosts varies substantially. Increasing species richness has been found to reduce disease risk, and the involvement of a diverse collection of vertebrates (squirrels, raccoons, skunks, etc.) in this case may dilute the impact of the main reservoir, the white-footed mouse.

Predators also tend to be absent in small woodlots, and probable competitors occur at lower densities in these areas than in more continuous habitat. Therefore, habitat fragmentation causes a reduction in biodiversity within the host communities, increasing disease risk though the increase in both the absolute and relative density of the primary reservoir.

Finally, rapidly growing urban areas cast a footprint far beyond their local boundaries. Wastewater from cities is often poorly treated and can expose downstream communities to infectious disease. It can also lead to outbreaks of harmful algal blooms and shellfish poisoning as it contaminates coastal marine environments. Urban emissions not only contribute to local air pollution but also have impacts regionally (acid rain, for example) and globally (climate change). Urban demand for food, building materials, fiber, and other ecosystem services drives many of the land use trends discussed earlier. Whether these demands are reduced by concentrating people in urban environments and creating efficiencies of large scale or increased because of transportation requirements, waste, etc. has not been well studied.

**Conclusion**

Human activity has dramatically changed the global landscape. These changes in land use and cover have, in turn, altered the dynamics of infectious disease transmission in numerous ways. They have created new habitat and breeding sites for disease vectors that, in many cases, favor disease transmission. They have led to direct exposure to pathogens by changing water quality and runoff patterns. They have altered the nature of human–wildlife interactions and created new exposure routes. Not surprisingly, these changes have occurred coincident with a rise in new or reemerging infectious diseases. These are not merely academic concerns. The diseases impacted by these changes represent a large percentage of the total global burden of disease.

Understanding how large-scale changes in the landscape can create new dynamics in disease transmission is important. Identifying potential synergistic effects of land use change alongside concomitant global climate change and globalization trends is a daunting yet critical challenge. This type of understanding can help in anticipating that there may be significant health effects from dam building, irrigation projects, clearing of forests, etc. – an understanding that can guide preparedness and prevention efforts.

**Further Reading**

Aguirre AA, Ostfeld RS, Tabor GM, House C, and Pearl MC (2002) Conservation Medicine: Ecological Health in Practice. Oxford, UK: Oxford University Press.

Aron JL and Patz JA (2001) Ecosystem Change and Public Health: A Global Perspective. Baltimore, MD: Johns Hopkins University Press.

Chivian E and Bernstein A (2008) Sustaining Life: How Human Health Depends on Biodiversity. Oxford, UK: Oxford University Press.

Collinge SK and Ray C (2006) Disease Ecology: Community Structure and Pathogen Dynamics. Oxford, UK: Oxford University Press.

Corvalan C, Hales S, and McMichael A (2005) Ecosystems and human well-being: Health synthesis. A Report of the Millennium Ecosystem Assessment. Geneva: World Health Organization Press.

Harb M, Faris R, Gad AM, Hafez ON, Ramzy R, and Buck AA (1993) The resurgence of lymphatic filariasis in the Nile delta. Bulletin of the World Health Organization 71: 49–54.

McMichael AJ (2001) Human Frontiers, Environments and Disease: Past Patterns, Uncertain Futures. Cambridge, UK: Cambridge University Press.

Myers SS and Patz J (2000) Emerging threats to human health from global environmental change. Annual Review of Environment & Resources 34: 223–252.

Ostfeld RS, Keeling F, and Evrinner VT (2008) Infectious Disease Ecology: Effects of Ecosystems on Disease and of Disease on Ecosystems. Princeton, NJ: Princeton University Press.

Patz JA, Daszak P, Tabor GM, et al. (2004) Unhealthy landscapes: policy recommendations on land use change and infectious disease emergence. Environmental Health Perspectives 112: 1092–1098.

Yasuoka J and Levine R (2007) Impact of deforestation and agricultural development on anopheline ecology and malaria epidemiology. *American Journal of Tropical Medicine and Hygiene* 76: 450–460.

** Relevant Websites**

http://www.sage.wisc.edu

Center for Sustainability and the Global Environment at the University of Wisconsin, Madison.

http://www.millenniumassessment.org

Millennium Ecosystem Assessment.

http://www.ecohealth.net

The International Association for Ecology and Health (and its flagship journal *EcoHealth*).