Forests and emerging infectious diseases of humans

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With the interweaving of forests, pathogens and the development of human civilization, deforestation and other land use changes have an important part in the emergence of disease.

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Infectious diseases have always been an important part of human life. They have significantly influenced human biology and society, even determining the course of major historical events.

Infectious diseases can be viewed ecologically as an extension of host–parasite relationships. They are as much a part of any ecosystem as predator–prey or plant–herbivore relationships. In fact, disease-causing viruses, bacteria and protozoans are commonly and collectively referred to as "microparasites" in infectious disease epidemiology. Moreover, infection by a microparasite is not inevitably a disease-causing event. Most often, host and microparasite coexist peacefully, because highly pathogenic genotypes that eliminate the host are selected against, as are susceptible hosts lacking acquired or native immunity (inherited resistance). Thus disease emergence is a transient phenomenon in a human population, and in its most severe form is typically a consequence of rapid social and environmental change or instability.

The first plague-causing pathogens such as smallpox are believed to have originated in tropical Asia early in the history of animal husbandry and large-scale forest clearing for permanent cropland and human settlements (McNeil, 1976). Crowding and the mixing of people, domestic animals and wildlife, along with a warm humid climate, were as ideal for pathogen evolution, survival and transmission several millennia ago as they are now.

The concept of emerging infectious diseases (EIDs) was prompted by the appearance of novel pathogens such as human immunodeficiency virus (HIV) and Ebola virus; the evolution of more virulent or drug-resistant pathogenic variants of known microbes; and the geographic expansion and increasing epidemic outbreaks of the diseases caused by these pathogens as well as older diseases such as malaria and dengue. More recently, the concept was reinforced by the dramatic outbreak of severe acute respiratory syndrome (SARS) virus.

The recent upsurge in infectious diseases, which began to attract the attention of the World Health Organization (WHO) and leading national health agencies in the 1980s, is often attributed to the dramatic increase in human population size and mobility, as well as social and environmental changes since the Second World War. Actually, such transitions have caused major upsurges in infectious diseases at the regional level since antiquity. The most notable difference today is the speed, scale and global dimension of the transition, and its occurrence in the era of modern biomedicine and public health programmes. Overconfidence in the former and inadequate deployment of the latter are major contributors to the EID problem, especially in the tropical developing regions.

An increasing number of studies on EIDs point to changes in land cover and land use, including forest cover change (particularly deforestation and forest fragmentation) along with urbanization and agricultural intensification, as major factors contributing to the surge in infectious diseases. Indeed the current increase coincides with accelerating rates of tropical deforestation in the past

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Expansion into the forest, involving more frequent contact with wildlife, exposes humans to pathogens that are foreign to them and is a frequent cause of disease outbreaks – for example yellow fever in the case of this forest-adjacent settlement in Kenya

several decades. Today, both deforestation and emerging infectious diseases remain largely associated with tropical regions but have impacts that extend globally. Both are similarly intertwined with issues of economic development, land use and governance, requiring cross-sectoral solutions.

This article provides an overview of the role of forests and deforestation in EIDs. It highlights the most prominent forest-associated diseases and briefly describes the current state of understanding of the mechanisms by which forest conversion and alteration contribute to EIDs. Finally, it identifies forest resource management measures required to mitigate the EID problem.

ASSOCIATION OF EMERGING INFECTIOUS DISEASES WITH FORESTS

In all, about three-fourths of recognized EIDs either once were, or currently are, zoonotic, i.e. transmitted between animals and humans (Taylor, Latham and Woolhouse, 2001). Not surprisingly, the ancestry of the pathogens causing these diseases can usually be traced to wildlife. Pathogens whose current emergence patterns show a direct association with forests (see Table for examples) represent about 15 percent of the approximately 250 EIDs (Despommier, Ellis and Wilcox, 2006). Some EIDs not currently associated with forests originated from a sylvatic cycle but have since "escaped" and are now solely maintained by human–human transmission or a human–vector–human cycle independent of forests. The two most prominent EIDs in this category are HIV and dengue, which broke free from their primate transmission cycles in African forests and eventually spread globally, two decades ago in the case of HIV and several centuries ago for dengue. Still other EIDs such as tuberculosis, hepatitis A/B/C/E/G, most sexually transmitted diseases, opportunistic infections of individuals who are immunocompromised (as a result of HIV, for example), and a growing number of infections caused by bacteria resistant to antimicrobial drugs are mainly attributable to dramatic social and ecological changes associated with the explosive rates of urban growth in recent decades.

For those EIDs currently associated with forests, the proximate causal factors in their emergence include a combination of deforestation and other land use changes, increased human contact with forest pathogens among populations lacking previous exposure, and pathogen adaptation. Many may be transmitted among non-human primate hosts or insect vectors, and involve a variety of potential intermediate hosts including domestic animals. Of most concern, following initial local emergence a number of these diseases have demonstrated the potential to spread regionally or globally and become a significant threat to humans, domestic animals and wildlife populations.

Although relatively few plant parasites or pathogens are known to infect

Examples of forest-associated emerging infectious diseases

Agent/disease	Distribution	Hosts and/or reservoirs	Exposure	Possible emergence mechanisms
Viruses				
Yellow fever	Africa South America	Non-human primates	Vector	Deforestation and expansion of settlements along forest edges Hunting Water and wood collection Domestication of vectors and pathogen
Dengue	Pantropical	Non-human primates	Vector	Mosquito vector and pathogen adaptation Urbanization and ineffective vector control programmes
Chikungunya	Africa Indian Ocean Southeast Asia	Non-human primates	Vector	Pathogen and vector
Oropouche	South America	Non-human primates Others	Vector	Forest travel Vector composition changes
SIV	Pantropical	Non-human primates	Direct	Deforestation and human expansion into forest Hunting and butchering of forest wildlife Pathogen adaptation
Ebola	Africa	Non-human primates Bats	Direct	Hunting and butchering Logging Outbreaks along forest fringes Agriculture Alteration of natural fauna
Nipah virus	South Asia	Bats Pigs	Direct	Pig and fruit production on forest border
SARS	Southeast Asia	Bats Civets	Direct	Harvesting, marketing and mixing of bats and civet cats Wildlife trade for human consumption
Rabies	Worldwide	Canines Bats Other wildlife	Direct	Human expansion into forest
Rocky Mountain spotted fever	North America	Invertebrate ticks	Vector	Human expansion into forest Forest recreation
Protozoa				
Malaria	Africa Southeast Asia South America	Non-human primates	Vector	Deforestation, habitat alteration beneficial for mosquito breeding Human expansion into forest, non-human primate malaria among humans
Leishmaniasis	South America	Numerous mammals	Vector	Human expansion into forest Domestication of zoophilic vectors Habitat alteration, habitation building near forest edge Deforestation Domestication of zoonotic cycles by non-immune workers
Sleeping sickness	West and Central Africa	Humans	Vector	Human expansion into forest, disease incidence associated with forest edge
Bacteria				
Babesiosis	North America Europe	Humans Wildlife	Vector	Disease often found among ticks in forested areas
Lyme disease	Worldwide	Humans Deer Mice	Vector	Possible association with deforestation and habitat fragmentation Forest workers at increased risk of disease
Leptospirosis	Worldwide	Rodents	Indirect	Watershed alteration and flooding
Helminth				
Eccinococcus multiocularis	Northern Hemisphere	Foxes Rodents Small mammals	Direct	Deforestation Increase in rodent and fox hosts Pathogen spillover to dogs Human expansion into forest, exposure of susceptible population

animals, including humans, the impact of emerging plant diseases on plant populations is also an increasing concern. The problem of EIDs includes not only the impacts of diseases from forests, but also the impacts of disease on forests, including forest wildlife as well as vegetation (Ostfeld, Keesing and Eviner, 2006).

Forests or deforestation *per se* are not the cause of either forest-associated infectious disease emergence or the globally increasing EID trend overall; EID causality is more complex than this. The main driver is the exponential growth in population, consumption and waste generation of the past several decades, which has driven the combination of urbanization, agricultural expansion and intensification, and forest habitat alteration that results in regional environmental change (see Box). The disease emergence process typically appears to be associated with a combination of these environmental factors. But the common factor is change – relatively abrupt or episodic social and ecological change. Most often this is reflected in changes in land cover and land use (unplanned urbanization and land use conversion), agricultural intensification (dams, irrigation projects, factory farms, etc.) and displacement and migration of people.

Episodic population migration and resettlement, associated with road building and the opening up of new transportation routes along with forest clearing and fragmentation, can be described as local or regional drivers of disease emergence. Such changes, particularly when unplanned and a result of political or economic instability or even military conflict in some cases, can have catastrophic consequences. The prime example is AIDS, which originated in tropical forest (Sharp *et al*., 2001) and expanded throughout a region that was undergoing such changes and lacked public health infrastructure, including systems of disease surveillance and control.

Like AIDS, most forest-originating EIDs are caused by viruses, although others are caused by bacteria, protozoans, helminths (worms) and fungi. These diseases are frequently not research priorities until they have become a threat to affluent populations, so knowledge about their distribution and biology is very limited in most cases. The historical orientation of tropical medicine towards understanding disease natural history and ecology was, unfortunately, abandoned with the advent of modern biomedicine and the mistaken belief that infectious diseases had been conquered by science (Gubler, 2001). Today's biggest research challenge is posed by the disciplinary gaps between infectious disease researchers, wildlife experts, ecologists and social scientists. The problems are of course compounded by the increasing numbers and densities of poor people living without potable water, sanitation and adequate public health infrastructure in developing countries.

Forest zoonotic and vector-transmitted diseases

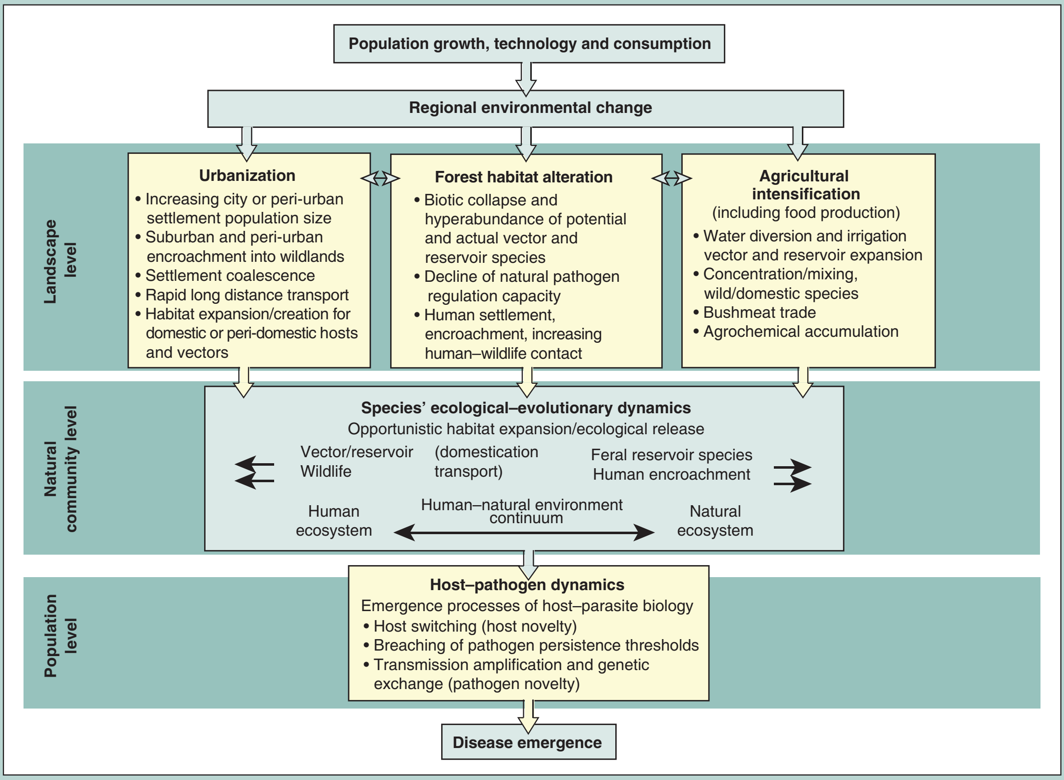
Yellow fever is the most well-studied disease from the standpoint of its association with forests (Monath, 1994). The virus that causes yellow fever is maintained in a transmission cycle of arboreal monkeys and sylvatic mosquitoes. Expansion into the forest by human settlements is a frequent cause of outbreaks. For example, the first outbreak of yellow fever in Kenya (1992 to 1993) involved a settlement where cases were limited to people collecting fuelwood and water, or possibly hunting in the forest. Much larger outbreaks occur when the transmission cycle leaves the forest canopy and extends to peri-urban and urban areas where the much higher density of humans and mosquitoes can fuel large epidemics (Sang and Dunster, 2001). This occurred in the Sudan in 2005, probably exacerbated by people fleeing areas of armed conflict and soldiers returning from forested areas. Environmental factors including abnormal rainfall may also have contributed to spreading the disease. The evolutionary capacity for rapid adaptation enables viruses to be transmitted efficiently in domestic or peri-domestic cycles.

Dengue haemorrhagic fever, caused by a type of dengue virus, is very similar to yellow fever in its ecology, at least historically (Monath, 1994). Originating as a sylvatic disease with a similar set of primate hosts, mosquito vectors and niche, it acquired a domestic cycle at least several centuries ago. It has recently developed into one of the world's most rapidly emerging diseases, infecting as many as 50 million to 100 million people annually (Holmes and Twiddy, 2003). The key to dengue's success as a pathogen is believed to be its adaptation to the domestic mosquito *Aedes aegypti*, which has allowed it to become endemic in an increasing number of cities and surrounding peri-urban areas, particularly in Asia and Latin America (Moncayo *et al*., 2004).

Malaria, a much older disease which contributes by far to the greatest number of deaths and disability of any infectious disease (300 million to 500 million cases annually, with a death toll as high as 2.7 million), has less definitive zoonotic origins (Mu *et al*., 2005). It is nonetheless transmitted in many areas by forest-associated mosquitoes. Recent research suggests that increased disease incidence in some areas of Africa, South America and Southeast Asia is linked to deforestation (Vittor *et al*., 2006; Walsh, Molyneux and Birley, 1993). Road building, tree felling, reduced shade and increased pooling of water have been shown to promote breeding and more rapid development of mosquito larvae (Afrane *et al*., 2005; de Castro *et al*., 2006). Of additional concern, a form of malaria previously found in non-human primates has recently been found in humans in Southeast Asia (Jongwutiwes *et al*., 2004; Singh *et al*., 2004).

A number of other noteworthy forest-associated zoonotic EIDs do not

Causal schema of infectious disease ecology



The combination of increasing population and resource consumption, along with waste generation, drives the regional environmental change typically indicated by trends in land use and land cover change. Although the pattern of change varies from region to region, three characteristic processes occur in relation to land use: urbanization, agricultural intensification (including food production and distribution) and alteration of forest habitat.

The three categories of land use – urban, agricultural and natural habitat – represent an ecosystem continuum along a gradient from domestic to natural (left to right in the diagram). Three ecological trends are associated with these changes: vector and reservoir domestication (or peri-domestication); invasion of domestic habitat by opportunistic wildlife such as some rodents and blood-sucking arthropods (mosquitoes, ticks, midges and others); and invasion of the natural habitat by feral species such as domestic pigs, goats, rats, mice, dogs and cats. These species become pathogen reservoirs particularly in disturbed and fragmented forest adjacent to settlements. The convergence of human and animal hosts and reservoir and vector species within ecosystems, and the movement, shifting and mixing across the ecosystem continuum affects host–pathogen dynamics in a manner that facilitates disease emergence, as follows:

- pathogens have increased opportunities for host switching (including adaptation to a new host);
- transmission is amplified and the opportunity for more rapid evolution is increased with multiple, interacting transmission cycles;
- pathogens' rate of infection exceeds the threshold required to produce an epidemic or an endemic disease owing to unprecedented population densities of the vector, the reservoir and susceptible human populations;
- pathogens evolve increased pathogenicity, infectivity and ability to avoid immune system detection, owing to increased opportunities for interaction of endemic infection cycles and pathogen strains, and greater density and genetic variability of pathogen populations.

Sources: Wilcox and Colwell, 2005; Wilcox and Gubler, 2005.

appear to involve mosquitoes as vectors although their transmission cycles are not yet entirely certain. These include chikungunya, Oropouche virus, Ebola and simian immunodeficiency virus (SIV). The dramatic consequences of Ebola and SIV emergence have been evidenced over recent decades. HIV is a zoonotic SIV. SIVs have recently been found to be common in Old World monkeys (Galat and Galat-Luong, 1997). The hunting, butchering or illegal procurement of these animals not only is a major concern for conservation but also increases the risk of disease emergence (Wolfe *et al.*, 2005).

Many of the Ebola outbreaks have occurred in forest fringe areas, where expansion of human populations is bringing them into contact with pathogens that are foreign to them, particularly through more frequent contact with wildlife. This has led to a hypothesis that mechanisms associated with agricultural land use changes bordering forests and changes in the natural fauna may be involved in emergence (Morvan *et al.*, 2000; Patz *et al.*, 2004). Recently, it has also been suggested that bats may serve as the reservoir for Ebola and that monkeys may contract the disease much as humans do (Leroy *et al.*, 2005). Fruit bats are also important hosts of additional EIDs including Nipah and SARS viruses (Field *et al.*, 2001; Lau *et al.*, 2005).

Water-borne diseases

Another category of infectious diseases – indirectly associated with forests or forest land management – is water-borne. Their natural cycles may or may not involve forest wildlife, but their transmission (both among their animal hosts and to humans) is facilitated by altered surface water quality and regimes, which may be influenced by upland deforestation and poor watershed management (including overgrazing, removal of riparian vegetation and stream channellization). Water-borne pathogens include the enteric viruses rotavirus and norovirus and the bacteria *Campylobacter* spp. and Vibrio cholerae, which collectively cause millions of deaths annually, particularly among infants. *Vibrio cholerae*, which lives symbiotically (in mutually beneficial relationship) with marine and estuarine crustaceans, is responsible for an estimated 1 to 2 million cholera cases annually (WHO, 2006). All these pathogens are found in inland as well as coastal surface waters, especially (but not only) water contaminated with human or animal excrement. Other widespread water-borne EIDs include protozoans of the genera *Cryptosporidium* and *Giardia*, which along with *Campylobacter* spp. are maintained by wild and feral ungulates. These pathogens, along with leptospirosis, one of the world's most widespread zoonotic EIDs for which virtually all mammal species are natural or accidental hosts, are often associated with ecologically disturbed forested watersheds supporting high densities of pigs and rats. Epidemics of leptospirosis have been occurring with increased frequency globally in flood-prone rural and urban areas with poor drainage and sanitation, conditions commonly found in impoverished urban, peri-urban and rural environments throughout the developed and developing world (Vinetz *et al.*, 2005; Wilcox and Colwell, 2005).

MECHANISMS OF HUMAN PATHOGEN EMERGENCE

The role of forests and forest management in the emergence of infectious diseases of humans appears to involve three separate but interacting dynamics:

- land use change and expansion of human populations into forest areas, resulting in exposure of immunologically naïve human and domestic animal populations (i.e. those lacking previous experience with the microparasite fauna) to pathogens occurring naturally in wildlife;
- forest clearing and alteration producing an increase in the abundance or dispersal of pathogens by influencing host and vector abundance and distribution;
- alteration of ecohydrological functions such as infiltration, peak discharge and runoff which facilitate the survival and transport of water-borne pathogens in watersheds and catchment basins.

These changes are often linked to forest clearing and increased edge habitat, with fragmentation of the forest landscape and disturbance of the vertical structure and diversity within the forest stands. The increase in the density of some pathogens' hosts and vectors effectively expands the pathogens' habitat and increases their infection prevalence in hosts. The increased number of hosts or vectors or both and their increased rate of infection not only increase the frequency of their contact with humans, but also the likelihood of the host or vector being infectious. Most importantly, it allows the pathogen to persist indefinitely and the disease to become endemic.

One of the best documented cases of this process concerns Lyme disease, an EID caused by a pan-temperate tick-borne spirochete bacteria of the genus *Borrellia*. The ecology of its emergence in the northeastern United States, studied in great detail, has implications regarding the role of forest management in disease generally (Allan, Keesing and Ostfeld, 2003). Lyme disease involves a complex sylvatic cycle in which the vector prefers different animal host species during different stages of its life cycle. The most important factor determining pathogen abundance appears to be the abundance of two animal species that proliferate in fragmented forest landscapes: white-footed mice, which act as pathogen "superspreaders", and white-tailed deer, the optimal adult tick host. These species are adapted to forest edges, and they have fewer predators in these landscapes than in unfragmented forest blocks. Moreover, the less diverse community of vertebrates in fragmented forests results in higher overall pathogen

Forest fragmentation affects disease dynamics by influencing host and vector abundance and distribution and thus the abundance or dispersal of pathogens

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transmission rates, since white-footed mice are among the most successful vertebrate hosts for this microparasite.

The finding that intact forest vertebrate communities provide a pathogen dilution effect, together with the well-known role of predators in regulating rodents and ungulate populations in healthy ecosystems, has prompted some ecologists to categorize regulation of pathogen emergence as a forest ecosystem service. The ecohydrological functions of healthy upland forests and watersheds can be said to have a similar role, regulating water-borne pathogen emergence by "capturing" and filtering pathogen-laden runoff and modulating the amplitude of peak flows during seasonal storms. The loss of these functions facilitates pathogen transmission and maintenance in host populations, increasing the amount of human pathogens contained in animal excreta. Epidemics of cholera and leptospirosis frequently occur following exposure of large numbers of people to the pathogens mobilized from soil and sediments and suspended in the flood waters (Wilcox and Colwell, 2005).

CONCLUSION

Emerging infectious diseases are considered to be among today's major challenges to science, global health and human development. Rapid changes associated with globalization, especially the rapidly increasing ease of transport, are mixing people, domestic animals, wildlife and plants, along with their parasites and pathogens, at a frequency and in combinations that are unprecedented.

The role of and potential effects on forests and implications for forest resource management are significant. Forest land use changes and practices, particularly when unregulated and unplanned, frequently lead to increased prevalence of zoonotic and vector-borne diseases, and occasionally boost the prevalence of diseases capable of producing catastrophic pandemics. This should be a consideration in forest land use and forest resource planning and management.

In view of the enormous impact EIDs have on humans and economic development, including the economic impacts of diseases on agriculture and forestry, collaboration between the agricultural, forest and public health sectors is required to develop policies and practices for the prevention and control of EIDs. This will require substantial increases in the regulation, surveillance and screening of pathogens in transportation systems.

Research on EIDs, particularly that involving the ecological epidemiology of zoonotic and vector-borne diseases associated with forests, needs to be integrated with forest resource management and planning. Greater emphasis is needed on integrating research and practice, for example through the development of forest management guidelines that can contribute to the control and prevention of EIDs. This will require increased interdisciplinary and collaborative research among foresters, forest ecologists, and wildlife and human infectious disease experts for better understanding of the role and impact of forests and forest land use and management on EIDs. ◆

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