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ARTICLES

# Primates and the Ecology of Their Infectious Diseases: How will Anthropogenic Change Affect Host-Parasite Interactions?

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The sudden appearance of diseases like SARS (severe acute respiratory syndrome[1]), the devastating impacts of diseases like Ebola on both human and wildlife communities,[2,3] and the immense social and economic costs created by viruses like HIV[4] underscore our need to understand the ecology of infectious diseases. Given that monkeys and apes often share parasites with humans, understanding the ecology of infectious diseases in nonhuman primates is of paramount importance. This is well illustrated by the HIV viruses, the causative agents of human AIDS, which evolved recently from related viruses of chimpanzees (*Pan troglodytes*) and sooty mangabeys (*Cercocebus atys*[5]), as well as by the outbreaks of Ebola virus, which trace their origins to zoonotic transmissions from local apes.[6] A consideration of how environmental change may promote contact between humans and nonhuman primates and thus increase the possibility of sharing infectious diseases detrimental to humans or nonhuman primates is now paramount in conservation and human health planning.

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Although humans have always shared habitats with nonhuman primates, the dynamics of human-primate interactions are changing radically.[7–9] Within the last several decades, humans have been responsible for massive, irrevocable changes to primate habitats. Most primates today live in anthropogenically disturbed habitat mosaics of farmland, human settlements, forest fragments, and isolated protected areas.[7] As anthropogenic habitat change forces humans and primates into closer and more frequent contact, the risks of interspecific disease transmission increase.[10,11]

The importance of these issues is readily apparent from the many diseases that nonhuman primates and humans presently share (Table 1). For example, monkeys are reservoirs for the yellow fever virus, an arbovirus of critical importance to human health in Africa and South America.[12] Other important human viruses stemming from nonhuman primates include herpesvirus B, SV40 polyomavirus, and various simian retroviruses.[13] Among bacterial parasites, *Mycobacterium tuberculosis,* the causal agent of tuberculosis, can be transmitted zoonotically, both in captivity and in the wild.[14] *Mycobacterium leprae,*[15] *Shigella* sp., *E. coli, Campylobacter* sp., and *Salmonella* sp.[16] have also caused human disease traceable to nonhuman primates. Parasitic agents shared with nonhuman primates include malarias (*Plasmodium* sp.[17]), *Trypanosoma cruzi* (the causative agent of Chagas disease[18]), *Giardia, Cryptosporidium,*[19,20] and a variety of gastrointestinal helminths.[21] Malaria is one of the best examples of the importance of human-primate interactions with

TABLE 1. PARASITES EXCHANGED BETWEEN HUMANS AND NONHUMAN PRIMATES: THE ROUTE AND DIRECTION OF EXCHANGE[a]

| Parasite | Route of Exchange | Direction of Exchange |
|---|---|---|
| Herpes B | Animal bite | Nonhuman primate to human |
| Monkey pox | Animal bite | Nonhuman primate to human |
| Polio virus | Fecal, oral | Humans to nonhuman primate |
| Ebola | Hunting & butchering | Nonhuman primate to human |
| *Mycobaterium leprae* | Nasal secretion | Among primates |
| Tuberculosis | Respiratory droplet | Humans to nonhuman primate |
| Malaria | Vector | Both directions |
| Filaria | Vector | Both directions |
| Yellow Fever | Vector | Both directions |
| Dracunculiasis | Water-mediated | Human to nonhuman primate |
| Schistosomiasis | Water-mediated | Nonhuman primate to human |
| SV40 | Vaccinations | Nonhuman primate to human |
| Gastrointestinal parasites | Fecal | Both directions |

[a] Also see Wolfe and coworkers.[90]

respect to current or emerging infectious diseases (Box 1).

Such parasites pose significant conservation risks to nonhuman primate populations, many of which are already threatened or endangered by habitat loss and hunting.[7,22] For example, evidence indicates that between 1983 and 2000 Ebola virus outbreaks contributed to the reduction of ape population densities by more than 50% over a broad geographic scale.[2,3] Polio epidemics have caused widespread mortality in wild chimpanzee communities.[23] Gastrointestinal and respiratory parasites shared between mountain gorillas, trackers, and ecotourists threaten the long-term viability of gorilla populations, as well as the economic sustainability of associated ecotourism ventures.[24,25] Such risks will surely increase as humans continue to encroach upon nonhuman primate habitats, and as rates of forest fragmentation and degradation in the tropics continue to accelerate.

In this paper, we first discuss the potential importance of disease as a fundamental factor determining nonhuman primate abundance and suggest ways in which population regulation can be demonstrated empirically. Second, we review what is known about how anthropogenic change can affect host-pathogen interactions. We consider anthropogenic effects on disease emergence at different spatial scales, from local effects, such as hunting, to regional effects, such as logging and fragmentation, to multiregional effects, such as climate change. Our goal is to provide a framework for understanding the potential importance of infectious disease to the ecology and conservation of primates, and to suggest ways in which the scientific community might approach the issue (Fig. 1).

## DISEASE AND PRIMATE POPULATION DYNAMICS

A fundamental issue in ecology is determining the factors that regulate the density of animal populations.

TABLE 2. HOST RANGE, MORBIDITY, AND MORTALITY ASSOCIATED WITH GASTROINTESTINAL PARASITES INFECTING WILD PRIMATES AND HUMANS IN KIBALE NATIONAL PARK, UGANDA.[21,70]

| Parasite Species (Taxon) | Primate Species[f] | Morbidity and Mortality |
|---|---|---|
| *Trichuris* sp.[a] | RC, BW, RT, Hu | Typically asymptomatic |
| *Strongyloides fulleborni*[a] | RC, BW, RT, Hu | Mucosal inflammation, death |
| *Strongyloides stericalis*[a] | RC, Hu | Mucosal inflammation, death |
| *Oesophagostomum stephanostomum*[a] | RC, BW, RT, Hu | Severe diarrhea, weight loss, death |
| *Colobenterobius* sp.[a,e] | RC, BW | Dysentery, enteritis, ulceration, death |
| *Enterobius* sp.[a,e] | RT, Hu | Dysentery, enteritis, ulceration, death |
| *Streptopharagus* sp.[a] | RT | Typically asymptomatic |
| *Ascaris* sp.[a] | RC, BW, Hu | Intestinal obstruction, death |
| *Dicrocoeliidae* sp.[b] | BW, RT | Typically asymptomatic |
| *Bertiella* sp.[c] | BW, RT, Hu | Typically asymptomatic |
| *Chilomastix mesnili*[d] | RT, Hu | Diarrhea |
| *Iodameoba buetschli*[d] | RT, Hu | Typically asymptomatic |
| *Giardia lamblia*[d] | RT, Hu | Enteritis, diarrhea |
| *Entamoeba coli*[d] | RC, BW, RT, Hu | Typically asymptomatic |
| *Entamoeba histolytica*[d] | RC, BW, RT, Hu | Hepatic and gastric amoebiasis, death |

[a] Nematoda.
[b] Trematoda.
[c] Cestoda.
[d] Protozoa.
[e] Known to be host specific.
[f] RC = Red colobus; BW = Black-and-white colobus; RT = Redtail guenon; Hu = Human.

## Box 1. MALARIA

One of the best examples of the close interactions between a group of parasites and primates is malaria, a parasite that dramatically affects humans and that potentially can affect nonhuman primate populations. It is estimated that there are 300 to 500 million clinical cases of malaria every year[88] and that it causes 0.7 to 2.7 million deaths per year.[89] Converting this to a more comprehensive statistic, a child dies of malaria every 40 seconds.[88] However, the actual figures are likely to be substantially higher owing to under-reporting and difficulties of diagnosis.[89] If no new control measures are developed, the death toll is predicted to double in the next 20 years.[89]

The close interactions among a variety of primate species and the *Plasmodium* parasite are illustrated by the fact that there has been frequent transmission between humans and nonhuman primates. More than 26 species of *Plasmodium* infect primates. Moreover, morphological and molecular data demonstrate that human and nonhuman primate malarias are spread throughout the phylogenetic trees,[90] suggesting extensive exchange. There are four major human malaria parasites, *Plasmodium falciparum, P. vivax, P. ovale,* and *P. malariae. P. falciparium* can infect owl and squirrel monkeys; *P. vivax* infects chimpanzees, *P. malaria* is thought to have come from chimpanzees originally and, in South America, has gone from humans back into nonhuman primates, where it is now called *P. brasilianum.* Little is known about the impact of *P. brasilianum* on primate populations, but it was found in all five monkey species captured in a rescue operation associated with the filling of a hydroelectric dam in French Guiana.[17] *P. vivax* is thought to have been derived from a monkey malaria strain between 40,000 and 60,000 years ago in Southeast Asia. There is even the possibility that a new strain having a global impact will soon emerge. Singh and coworkers[91] used PCR assays to demonstrate that 58% of the people with malaria in Kapit division of Malaysian Borneo tested positive for *P. knowlesi,* but had been misdiagnosed as having *P. malaria.* The natural hosts of *P. knowlesi* are long-tailed (*M. fascicularis*) and pig-tailed (*M. nemestrina*) macaques. If this new strain of malaria becomes more widespread, it could have serious consequences. *P. malaria* infections are almost never severe, but *P. knowlesi* multiplies more rapidly and infections can be more serious.[92]

This is central to the formulation of conservation plans; that is, if a factor that limits a population is known, attempts can be made to manage that particular factor. Given this, it is surprising that so little is known about determinants of primate abundance. Various potential factors have been proposed and disease-related mortality is often discussed. However, the importance of disease either as an independent determinant or as one working in conjunction with other factors has proven difficult to quantify.

Disease and parasites can clearly cause short-term reductions in population size.[26–28] For example, a 50% decline in the howler monkey (*Alouatta palliata*) population on Barro Colorado Island, Panama, between 1933 and 1951 was attributed to yellow fever.[26] Cheney and coworkers[29] found that illness accounted for more deaths than predation did in one troop of vervet monkeys (*Chlorocebus aethiops*) and that lower-ranking individuals were more likely to experience the effect of parasites. Chacma baboons (*Papio ursinus*) living in the Namib desert have been found to be heavily infected by ticks (*Rhipicephalus*); these infections were speculated to be responsible for more than half ($n = 18$) of recorded infant deaths.[30] Some infants were not able to nurse because of the number of ticks attached to their muzzles. As a final example, Rudran and Fernandez-Duque[31] have quantified the demographic changes that occurred in a population of red howler monkeys (*Alouatta seniculus*) over thirty years and reported a population decline of 74% that was likely due to disease. They found that new groups died out more rapidly than did established groups and speculated that food shortages occurring in the regenerating areas occupied by these new groups contributed to the population crash.

Given that disease and parasites can clearly cause mortality, the question of interest is: Can disease operate as an independent agent or in conjunction with other factors to regulate primate populations? Based on a 68-month study of howler monkeys (*Alouatta palliata*) and a parasitic bot fly (*Alouattamyia baeri*), Milton[32] concluded that the annual pattern of howler mortality on Barro Colorado Island, Panama, resulted from a combination of effects, including age, physical condition, and larval burden of the parasitized individual, which becomes critical when the population experiences dietary stress. She concluded that the lack of growth of this closed population over the past 20 years apparently resulted, in large part, from the primary and secondary effects of bot-fly parasitism. She called for further study of potential synergistic interactions among nutritional factors, larval burdens, and howler monkey physiology. However, observational studies such as this provide only indirect evidence that primate diseases regulate populations. Scott and Dobson[33] argued that it is important to conduct manipulative experiments to determine the intensity with which parasites or other factors operate at different population densities. They argued that if populations of hosts and pathogen (a pathogenic parasite is one that is the causative agent of a disease) are relatively constant, then a lack of statistical correlation between the density of a host and its parasite tells little about what is structuring the system. For pri-

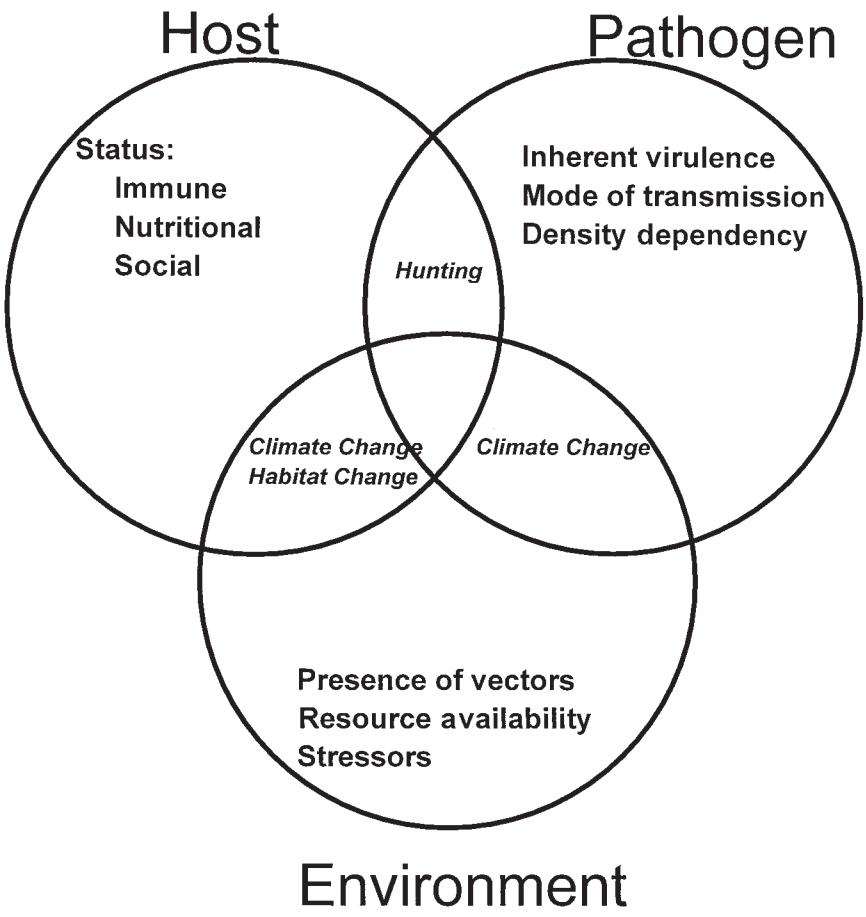


Figure 1. Clinical disease is the result of factors operating on the level of the host, the pathogen, and the environment. Human cultural practices and primate life history modify these factors. For example, the sociality, mating practices, and ranging patterns of nonhuman primates are known to affect the richness and diversity of their parasitic worm and viruses.[87] With respect to how anthropogenic change will effect these interactions, we suggest that hunting, habitat disturbance (for example, logging and fragmentation), and climate change (indicated in italics) are the factors that have the greatest potential to result in change in host-pathogen interactions.

mates, such experiments are logistically difficult, but they may be necessary to shed light on this issue.[34] Gulland[35] provided an instructive example of how to use such experimental approaches on mammals. He studied the interactions of Soay sheep and nematode parasites, demonstrating that at times of population crashes sheep were emaciated, had high nematode burdens, and showed signs of protein-energy malnutrition. In the field, sheep treated with antihelminthics had lower mortality rates, while experimentally infected sheep with high parasite loads, but fed nutritious diets, showed no sign of malnutrition.

Quantifying patterns of disease prevalence in nonhuman primate populations is difficult since, for many parasites, it is necessary to obtain clinical samples from animals to determine their infection status. Enteric parasites are notable exceptions, in that it is possible to diagnose animals by analyzing fecal samples.[36] Among enteric parasites, helminths and protozoans are most easily characterized in wild nonhuman primates. These parasites can affect host survival and reproduction directly through pathological effects and indirectly by reducing host condition.[37,38] Severe parasitosis can lead to blood loss, tissue damage, spontaneous abortion, congenital malformations, and death.[39] However, less severe infections, which are more common, may damage nutrition, increase energy expenditure, and impair travel, feeding, predator escape, and competition for resources or mates.[37,38] Even upregulation of host immunity can reduce breeding success.[40] Some parasites extract significant amounts of nutrients from hosts, resulting in marked reduction in energy uptake,[41] but others appear to have little or no effect on host energetics.[42,43] Animal body condition and reproductive status can be compromised when parasites inflict substantial energetic costs.[44] However, parasites do not necessarily induce negative effects if hosts have adequate energy reserves or nutrient supplies concurrent with infection,[32,35,42] suggesting that the outcome of host-parasite associations may be contingent on host nutritional status and infection severity.

Dietary stress may exacerbate the clinical consequences of parasitic infection through immunosuppression.[32,45,46] If so, food shortages could result in higher parasite burden, which in turn could increase nutritional demands on the host and exacerbate the effects of food shortages. If this occurred, nutritional status and parasitism could have synergistic effects on the host; that is, the individual effects of each factor would be amplified when they co-occur. The interactions between nutritional stress and parasitism have been examined in many laboratory studies[42,47] and a handful of field studies,[35,48,49] and have led to speculation that vertebrate populations may be influenced by the interactive effects of food shortage and parasitism.[45,50,51] The interactive effects of parasitism and nutritional status have rarely been examined in nonhuman primates (but see Milton[32]).

Studies of the interactions of nonhuman primate nutritional status with infectious diseases have been limited to eukaryotic parasites largely because of the methodological ease of diagnosing parasitic infections. However, modern molecular diagnostic tools should expand the ability to assess primate health noninvasively. Extracting DNA from animal feces is now commonplace, as is the selective amplification of parasite-specific DNA sequences from fecal DNA by polymerase chain reaction (PCR).[52] Methods such as real-time quantitative

PCR[53] now obviate the need for electrophoretic gels, significantly speeding the diagnostic process. Furthermore, such assays provide quantitative information on the concentration of target DNA in the original sample, yielding not only presence or absence data, but also information on infection intensity, which can be useful for analyses of the temporal course of infection.[54] These assays can also be "multiplexed," allowing noninvasive screening of animals for multiple parasites simultaneously.[55] In addition, thermocyclers with optical capabilities, which are necessary for real-time PCR applications, are shrinking in size and weight, while lyophilized reagents have become available that are stable at room temperature for extended periods, making it possible to transport these new diagnostic tools to remote field sites.[56] Although such technologies are primarily being developed for military and agricultural applications, only minor adaptations would be required for the rapid diagnosis of primate infectious disease in field settings. It should soon be possible to screen large numbers of primates for a series of parasites in "real time" at remote field sites, and to generate accurate and precise measurements of seasonal variation in infectious disease prevalence and intensity.

## HOW ANTHROPOGENIC CHANGE CAN AFFECT HOST-PARASITE INTERACTION

As recently as the 1980s, the dominant perspective on the treatment and prevention of infectious diseases was one of optimism.[57] Immunization and antibiotics were considered adequate for combating infectious diseases. This optimism was shaken by the increased prevalence of antibiotic-resistant bacteria and the emergence and reemergence of diseases such as Ebola, HIV, multi-drug-resistant tuberculosis, malaria, and enterohemorrhagic *E. coli*. Infectious diseases are now viewed as emerging at an accelerated rate in human and animal populations worldwide.[58,59]

In 1992 the Institute of Medicine[60] recognized this increased rate of disease emergence and identified six factors influencing disease emergence: changes in human demographics and behavior; changes in technology and industry; international travel and commerce; microbial adaptation; breakdown of public health measures; and environmental change and land use. With respect to primates, the last factor is critical. However, the other factors contribute to the rate of spread of diseases once they emerge. Disease emergence most frequently results from a change in the ecology of host, parasite, or both.[61] As anthropogenic habitat change forces humans and animals into closer and more frequent contact, risks of zoonotic disease transmission will increase.[10] Dobson and Foufopoulos[11] conducted a survey of emerging pathogens of wildlife in North America and found that human involvement facilitated 55% of pathogen outbreaks. In only 19% of the cases was there no evidence of human influence. We are not aware of a similar survey for tropical regions, and the data for most regions with endemic primate populations are limited.

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We suggest that changes in the ecology of hosts and parasites can be viewed as occurring on three scales: local, regional, and multiregional. Processes occurring on the local scale are those that act on individual populations of monkeys, apes, and humans to affect the rates with which they come into close contact and include, for example, hunting, crop raiding, research, and ecotourism. Processes occurring on the regional scale are those that alter primate habitats to affect direct and indirect contact rates and disease transmission patterns (for example, when forests are logged and fragmented). Finally, processes occurring on the multiregional scale are those that act indirectly on an ecosystem-wide level to modify disease transmission patterns. Multiregional effects would occur, for example, if climate change altered forest ecology throughout the tropics in ways that affected rates of disease transmission among primate populations and species. We should not assume that the magnitude of effect on primate populations is proportional to the scale of effect. For example, disease-associated local processes, such as hunting, might cause the extinction of a highly endemic primate species more quickly than might multiregional processes such as climate change. Although research at all three levels are important, we know the least about processes occurring at the larger spatial scales.

### Changes at the Local Scale: Hunting

There is little doubt that when monkeys, apes, and humans come into physical contact, the risk of disease transmission increases. The hunting and butchering of wild nonhuman primates leads to extremely close contact and will cause humans to come into contact with the body fluids of living or recently dead nonhuman primates (Fig. 2).

Subsistence and commercial hunting of tropical wildlife are occurring at extremely high, unsustainable levels; however, obtaining comprehensive data on the extent of harvest is difficult. Case studies at particular locations indicate that wildlife harvest provides a major source of food for many local communities. For example, a market survey in two cities in Equatorial Guinea, West Africa, having a combined population size of 107,000, recorded 4,222 primate carcasses on sale over 424 days.[61] Peres[62] documented that a single family of

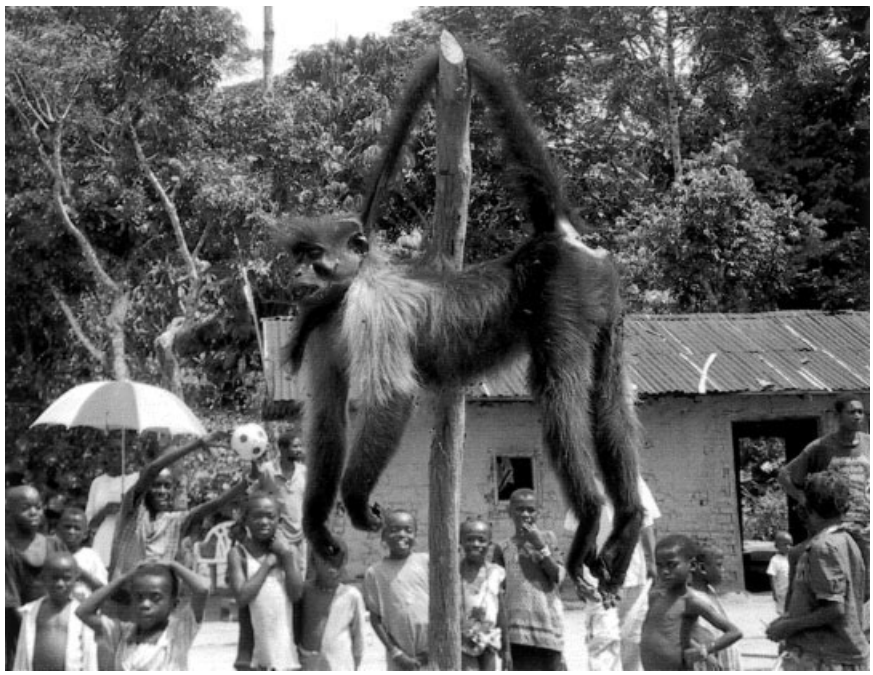

Figure 2. Hunted mangabey (*Lophocebus albigina*) for sale along a roadside in Cuvette West region of the Republic of Congo. Hunting and butchering of non-human primates is thought to have led to the origin of two significant emerging diseases with non-human primate zoonotic origins: AIDS and Ebola. Photo by A. M. Kilbourn, WCS.

rubber tappers in a remote forest site of western Brazilian Amazonia killed more than 200 woolly monkeys (*Lagothrix lagotricha*), 100 spider monkeys (*Ateles paniscus*), and 80 howlers (*Alouatta seniculus*) over 18 months. The market for bushmeat is not restricted to tropical countries where these animals originate. For example, 25 tons of turtles are exported every week from Sumatra.[63] Individuals that hunt or butcher these animals risk contracting zoonotic infections.

Hunting and butchering of nonhuman primates is thought to have led to the origin of two significant emerging diseases with nonhuman primate zoonotic origins, AIDS and Ebola (Box 2). Peeters and colleagues[64] tested 788 monkeys hunted in Cameroon for simian immunodeficiency virus (SIV), the precursor to HIV. Evidence of SIV infection was found in 13 of the 16 species tested and in 16% of the animals. Wolfe and coworkers[8] tested people living in Central African forests who reported having had contact with blood and body fluids of wild nonhuman primates for simian foamy virus. They found that 1% of these people had antibodies to the virus. In some regions, a large proportion of rural communities have contact with nonhuman primates. In remote villages in Cameroon, more than 60% of the community reported having butchered nonhuman primates, 30% hunted primates, and 11% reported keeping primates as pets.[9] Monkeypox was associated with the hunting of red colobus monkeys (*Procolobus badius*) after a localized epidemic emerged in humans.[65]

As conservation agencies increasingly turn to ecotourism as a strategy to provide local communities with benefits from protected areas, and as the number of primate research sites increases, so does the possibility of transmission via these activities. Already, cases have been documented of primates in eco-tourist and research sites contracting infections with likely human origins. For example, in 1966 six chimpanzees at Gombe National Park, Tanzania, died from a polio-like virus and six others were paralyzed for life.[25] Also, in 1996, a severe skin disease was documented in gorillas in Bwindi Impenetrable National Park, Uganda, and skin biopsy confirmed the presence of scabies (*Sarcoptes scabiei*).[25] Of five troops of baboons studied at Gombe, three were infected with schistosomiasis (*Schistosoma mansoni*); the troop having the most contact with people showed the highest prevalence of infection.[25] Such risks will surely increase as humans continue to encroach upon nonhuman primate habitats.

### Changes at the Regional Scale: Logging and Forest Fragmentation

Only a handful of studies have provided evidence that habitat disturbance occurring at the regional scale alters primate-parasite interactions.[66–69] If changes at this scale are important, this lack of data is unfortunate, since this is the scale at which management practices could be most easily implemented.

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We have recently completed a series of investigations demonstrating that various forms of anthropogenic disturbance, specifically selective logging and forest fragmentation, alter the dynamics of gastrointestinal parasite infection in the human and nonhuman primate populations in the region of Kibale National Park, Uganda.[69–72] We have determined that the prevalence and richness of gastrointestinal parasite infections were greater for

## Box 2. Ebola: A crisis and wake-up call for better understanding of reservoirs and transmission routes

W. Karesh and C.A. Chapman

Ebola has been known to the scientific community since it was first identified in 1976.[93,94] Since that time it has entered into human populations at least a dozen times in six different countries in Equatorial Africa and killed hundreds of people. But it has also had significant impacts on non-human primate populations. The worst-case scenario in great apes may have been demonstrated in the Minkebe forest region of northeastern Gabon where lowland gorilla and chimpanzee populations have come close to disappearing during the period of the human Ebola outbreaks in 1994 and 1996.[95] Up to tens of thousands of gorillas and chimpanzees may have died due to Ebola. Unfortunately, no one was working in the region during the human outbreaks to collect either samples or observations on wildlife to determine conclusively if or how Ebola affected the ape populations. "No one was in the region" is an unfortunate recurrent theme in Ebola research that has limited our understanding of the ecology of the pathogen.

Initial fears of catastrophic declines[2] led to calls for dramatic action, such as creating barriers to divide infected populations.[96] Further study, however, yielded more information the type of conservation action that would be appropriate to curb an Ebola outbreak. While the need to anticipate Ebola outbreaks, establish appropriate wildlife monitoring teams, and educate people of the potential dangers of bushmeat have remained constant,[97] some initial actions plans have been illustrated to potentially be ineffective.

Three findings deserve special mention. First, Eric Leroy and colleagues[3] sampled humans and wildlife in five outbreaks and found eight distinct strains of the virus. The authors conclude that these distinct strains probably diverged over decades or even centuries, and potentially came from different sources, suggesting a wide distribution of the virus. The spread of the disease within and between groups of great apes is still poorly understood. Second, Leroy et al.[98] found the servo-prevalence of Ebola antibody in wild chimpanzees was 12.9%, indicating both that wild apes can survive exposure, that the Ebola virus is distributed over a large region of central Africa, and that the virus was present in certain regions before the observed outbreaks. Third, research is starting to explore non-primate natural reservoirs of the virus. For example, laboratory experiments have shown that some species of fruit bats and insectivorous bats can survive infection with the Ebola virus and shed the organism in their excrement.[99] Field work in the Central African Republic has found at least fragments of Ebola viral particles using PCR genetic techniques in rodents,[100] and similar work in the Republic of Congo has found the same in bats (E. Leroy, personal communication).

These studies imply a very complex picture for Ebola virus transmission, and one that must be understood quickly if we are to respond in an appropriate timeframe. Clearly there is a need to take conservation action, such as establishing systems to anticipate Ebola outbreaks, monitor, and reduce impacts on wildlife, but this situation also highlights the importance understanding potential reservoirs and modes of transmission.[97] Furthermore, the situation also points to the need to understand how humans could be altering the ecology of host-virus interactions. For example, Morvan and colleagues[100] suggest that rather than being a virus of deep forest, Ebola is actually more common in forest peripheries and fragments. Humans are currently creating forest fragments in Central Africa at a rapid rate. Similarly, Pinzon et al.[101] suggest outbreaks of Ebola hemorrhagic fever are associated with dry conditions, raising the question of how anthropogenically driven climate change will effect transmission of this virus to non-human primates and humans alike.

red-tail monkeys (*Cercopithecus ascanius*) in logged than in undisturbed forest. Infective-stage primate parasites were found at higher densities in canopy and ground vegetation plots from logged compared to undisturbed forest, demonstrating a greater infection risk for humans and nonhuman primates in logged forest.[69]

In degraded forest fragments, humans and nonhuman primates overlap a great deal, and we found tentative evidence that parasites may be shared between Kibale nonhuman primates and resident humans (Table 1). Two parasite genera in particular, *Ascaris* and *Giardia,* were found to occur in red colobus monkeys in forest fragments and to have a high prevalence in the human populations near these fragments. These parasites were never found in more than 2,000 samples from "pristine" areas where people and primates interact with much less frequency.[68]

Most recently, we have documented that certain disturbance-related features of forest fragments are excellent predictors of infection prevalence in primates.[72] In a five-year study, we compared patterns of gastrointestinal parasite infection and infection risk among populations of black-and-white (*Colobus guereza*) and red colobus (*Piliocolobus tephrosceles*) inhabiting undisturbed habitats and forest fragments. Our results demonstrate that forest fragmentation alters prevalence and infection risk and that these factors are influenced by host density. We also examined the relationships between forest-fragment attributes and infection patterns. Interfragment comparisons examining nine potential factors demonstrated that tree-stump density, an index of degradation, had a strongly positive influence on the prevalence of parasitic nematodes. Both fragment size (negative relationship) and primate population density (positive relationship) also predicted prevalence of some parasites.[72] These results demonstrate that the transmission dynamics of gastrointestinal parasites are affected by the degree and nature of anthropogenic disturbance of forest fragments.

The exact mechanism leading to altered transmission dynamics remains an area for future study. Perhaps animals in these disturbed habitats are nutritionally stressed, lowering their immune status and making them more susceptible to gastrointestinal parasites. Alternatively, their restricted ranging and increased time spent in any one tree may increase the chances of infection for direct life-cycle parasites. Habitat fragmentation may have led to reduced genetic diversity and thus potentially increased susceptibility to infectious disease. Likewise, smaller population size in forest fragments may support less genetic diversity, reducing the potential scope of the response to parasites (Charles Nunn, personal communication). Identifying plausible mechanisms is a priority, because only once a mechanism is identified is it possible to construct an informed management plan that includes disease as an integral component.

**. . . studies suggest that the geographic distribution and prevalence of many parasites will increase with global warming. Human medical professionals have recently become concerned as to whether global warming will cause increased rates of infectious diseases and, with their wealth of clinical data, are well ahead of primate ecologists at documenting trends.**

The effects that we have documented likely apply to systems other than primate gastrointestinal parasites. Habitat disturbance associated with the creation of the Panama Canal, for example, is thought to have catalyzed the yellow fever outbreak that occurred at that time in howler monkeys.[73] The use of human crops and rubbish has been shown to alter gastrointestinal parasite communities in primates.[66,74]

## Changes at the Multiregional Scale: Climate Change

The larger the geographic scale over which host-parasite interactions change, the greater the number of populations that can potentially be affected. Climate is the factor that has the greatest potential to influence host-parasite interaction at this spatial scale. Connections between weather and disease are well established. Many diseases occur during certain seasons or erupt in association with unseasonable conditions. For example, meningococcal meningitis epidemics in sub-Saharan Africa erupt during the hot dry season and subside soon after the onset of the rains.[75] Recently, Guernier, Hochberg, and Guegan[76] documented that climatic factors are the most important determinant of the global distribution of human pathogens and that climate, rather than socioeconomic conditions, is responsible for the number of pathogens increasing toward the equator. Nunn and coworkers[77] used a data set encompassing 330 parasite species and 119 primate hosts to illustrate the importance of latitude in predicting vector-borne parasite species richness, with higher diversity being found in the tropics. Both of these studies suggest that the geographic distribution and prevalence of many parasites will increase with global warming. Human medical professionals have recently become concerned as to whether global warming will cause increased rates of infectious diseases and, with their wealth of clinical data, are well ahead of primate ecologists at documenting trends.

The earth's climate has warmed by approximately 0.6°C over the past 100 years, with two main periods of warming (1910–1945 and 1976–present). The 1990s were the warmest decade on record.[78] Recently the scientific community has begun to quantify ecological responses to climate change and has realized that some communities experience marked

changes with slight shifts in temperature.[78,79] We have recent data demonstrating that climate change is having an impact on primate populations. Chapman and coworkers[80] analyzed a 30-year phenology data set from Kibale National Park, Uganda, and documented that currently a number of the most common species rarely fruit, and that when they do typically <4% of the individuals take part in fruiting events. Presently, the Kibale region is receiving approximately 300 mm more rain than it did at the start of the century, droughts are less frequent, the onset of the rainy season is earlier, and the average maximum monthly temperature is 3.5°C hotter than it was 25 years ago. Contrasting changes in fruiting patterns over the 30 years with differences among four sites with varying rainfall suggests that the changes observed in fruiting may be due to climate change. If climate change does alter fruiting patterns and cause a reduction in food availability, the susceptibility of nonhuman primates to infectious diseases might be compounded by nutritional stress.

Climate change could affect disease transmission by facilitating conditions for transmission (for example, increased rainfall will promote transmission of waterborne disease); influencing the ecology of hosts and vectors; or causing resource shifts that stress primates physiologically.[81] With respect to climate change directly affecting disease transmission rates, heavy rain events have been associated with outbreaks of waterborne diseases in humans. In the United States, 68% of waterborne disease outbreaks were preceded by precipitation events above the 80% percentile.[82] Many waterborne pathogens of humans, among them *Giardia* spp., *Entamoeba histolytica,* and *E. coli,* can also infect nonhuman primates. The danger of such outbreaks will be particularly high for primates that frequently interact with water sources affected by humans. Given that protected areas rarely protect watersheds,[83] even populations well away from the edges of parks are at risk.

Heavy precipitation associated with climate change may indirectly affect disease transmission by providing new breeding sites for vectors such as mosquitoes. Mosquito-borne diseases are among the most sensitive to climate shifts, with increased rain and temperature resulting in increased reproduction, increased biting rates, and shortened incubation time. For example, with increased rains between 1984 and 1988 in Rwanda there was a 266% increase in reported malaria.[75] Malaria incidence is exponentially related to temperature, indicating that global climate change could result in dramatic increases in malaria rates.[84] Global warming is likely to increase the altitudinal range of malaria, having an impact on both human and nonhuman primate populations. In Kenya, Shanks and colleagues[85] documented increased malaria incidence in high-altitude areas of East Africa and attributed it at least in part to global warming.

How climate change may stress populations will likely be species- and situation-dependent. However, some effects are likely to be generalized. Increased ultraviolet light, which accompanies atmospheric ozone depletion, has been shown to cause immunosuppression in animals and humans.[75] Heat stress has also been associated with an increase in the number of human patients admitted for pulmonary and cardiovascular disease-related problems[86] and could negatively affect primate populations in many arid regions. As our studies have documented, local climate change in Kibale National Park, Uganda, may disrupt fruiting or flowering patterns and place nutritional stresses on primate populations.[80] We predict that the overall effect of climate change will be to increase the prevalence and severity of infectious disease in most primates.

## FUTURE DIRECTIONS

Given the history of the effects of disease on nonhuman primate populations, and given a future that will undoubtedly be characterized by increasing rates of local and global anthropogenic habitat change, we see two research priorities. First, it will be important to understand the relationships between infectious disease and primate demography in relatively undisturbed systems. Only then will we be able to assess the importance of parasites as moderators of primate population size and structure under "natural" conditions. Healthy ecosystems will consist of the natural complement of predators, prey, and parasites, and only by monitoring healthy populations can we discover what that complement will be. The unique feature that studies of primates offer over studies of many other animals is the ease of relating the attributes of individuals, such as dominance, nutritional stress, and individual parasite burden, to outcomes such as fitness, survival probability, and reproductive success. Second, once we have quantified the effects of specific parasites on primate populations in undisturbed habitats, the next step will be to conduct comparative studies of primate populations living in different types of anthropogenically altered habitats. If anthropogenic habitat disturbance does interact with infectious disease, then relationships between individual attributes of primates and health or fitness outcomes should differ between disturbed and undisturbed habitats. Between-site comparisons should be chosen carefully to explore the modifying effects of specific anthropogenic disturbances, (such as forest fragmentation with or without elevated rates of human contact), because the focus will then have shifted from *whether* anthropogenic habitat change alters primate-disease interactions to *how* anthropogenic change alters primate-disease interactions. This, of course, will require granting agencies to prioritize long-term studies of primates that include health assessment and funding for veterinarians to accompany primatologists into the wild.

As new diseases emerge, we can either react to them and understand the reasons for their emergence after the fact or take a proactive approach and try to understand the principles that govern the emergence of novel primate diseases in general. We argue that the latter approach is preferable and has the greatest potential to benefit human health, primate health and conservation, and ecosystem sustainability in the long term.

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