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Applied Cases of Ecological Health

Edited by A. Alonso Aguirre,
Richard S. Ostfeld,
and Peter Daszak

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THE KIBALE ECOHEALTH PROJECT

Exploring Connections Among Human Health, Animal Health, and Landscape Dynamics in Western Uganda

Tony L. Goldberg, Sarah B. Paige, and Colin A. Chapman

"EcoHealth" is a nebulous concept. In the broadest sense, it is a medical reiteration of the age-old philosophy that people and animals are inherently connected to each other and the physical environment. The term "EcoHealth" therefore usually needs little definition beyond the meaning it naturally evokes through the juxtaposition of its word roots. The idea of ecology segueing into health is self-evident.

In another sense, EcoHealth is a biological and ethical goal. Properly functioning ecosystems and the well-being of their constituent parts are ends to which we should all aspire. One might trace the origins of this meaning to Aldo Leopold's concept of "land health," one of the formative ideas of the modern conservation movement (Rapport 1998). The EcoHealth concept in this context exploits the health metaphor to argue that our present-day ecosystems are sick and must be healed.

Paradoxically, even its practitioners rarely treat EcoHealth as a testable scientific hypothesis. Although scientists often cite case studies showing how ecological damage has led to unhealthy people and animals, few formally acknowledge that the general trend could swing in either direction. Indeed, some of the most "successful" historical improvements to human public health have come from planned ecosystem degradations, such as the draining of wetlands to control the mosquito vectors of malaria (Keiser et al. 2005).

The Kibale EcoHealth Project is an attempt to subject the "EcoHealth paradigm" to the scientific rigor demanded by the ideal of evidence-based medicine. Founded in 2004, the Kibale EcoHealth Project is an ecological study of animal and human health in the region of Kibale National Park, western Uganda (http://svmweb.vetmed.wisc.edu/KibaleEcoHealth/). This region's volatile ecological and political history make it a particularly useful backdrop for exploring connections among human health, animal health, and landscape dynamics (Fig. 31.1). Importantly, the Kibale EcoHealth Project treats the EcoHealth paradigm itself as a fundamentally falsifiable hypothesis. We believe that this objective approach is the right one, since acknowledging the falsifiability of any hypothesis, no matter how palatable, is the most efficient means towards scientific progress.

This chapter describes some of the insights that the Kibale EcoHealth Project has generated concerning health, disease, land use change, and their interdependency in western Uganda. We review some of our findings that support the EcoHealth paradigm, as well some that go against it. The overall picture is complex, which is not surprising. It illustrates, among other

Figure 31.1:
The Kibale EcoHealth Project logo. The logo was designed to convey the interdependency of human health, domestic animal health, and the health of forests, here represented by a black-and-white colobus, one of the well-studied wild non-human primates of Kibale. (Logo designed by K. Helms)

things, the importance of spatial and temporal scale to the study of health ecology, and the ways in which quantitative and qualitative approaches sometimes complement each other and other times collide. We hope that the Kibale EcoHealth Project will inspire similar efforts elsewhere in the world aimed at objectively evaluating how human health, animal health, and landscape dynamics interact.

THE SETTING

Western Uganda is a nearly ideal place to examine the interconnections between ecology and health. Uganda is exceptionally biodiverse while at the same time having a high human and animal disease burden and a high rate of human population growth (Hartter and Southworth 2009). As a result, Uganda is an acknowledged "hotspot" for emerging zoonoses (Jones et al. 2008; Pedersen and Davies 2010). Kibale National Park is a mid-altitude, moist-evergreen forest in central-western Uganda (0 13′–0 41′ N and 30 19′–30 32′ E) near the foothills of the Ruwenzori Mountains (Struhsaker 1997). Kibale was designated a forest reserve in 1932 and became a national park in 1993. Its conservation history predates the colonial era, however; it may have served as the traditional hunting grounds for leaders of the local Batooro tribe, perhaps explaining why it persisted as a forest until the arrival of colonial powers (Naughton-Treves 1999).

Certain locations within Kibale National Park contain a remarkable diversity and biomass of non-human primates and have been the focus of primatology research for over 40 years (Chapman et al. 2005). The "core" areas of Kibale are home to 13 species of primates, from nocturnal prosimians to chimpanzees (*Pan troglodytes*), as well as an impressive variety of plants, insects, fishes, amphibians, reptiles, birds, mammals, and various other taxa that together form a diverse and "healthy" African montane forest community (Howard 1991; Struhsaker 1997).

Kibale has had a long and complex history of conservation successes and failures. On the one hand, Kibale's national park status has enhanced its protection and led to the establishment of a lucrative ecotourism industry, focused mainly on chimpanzees and birds (Archabald and Naughton-Treves 2001). However, darker episodes in Kibale's history have also occurred, including a series of forced government evictions of local people living illegally inside the park boundary in 1992 (van Orsdol 1986; Baranga 1991). Issues of park–people conflict continue to arise in Kibale, ranging from economic disparities created by tourism to the raiding of crops by now-protected wildlife (Naughton-Treves 1998; Rode et al. 2006).

Outside Kibale, and not subject to the protections afforded by the park, exist a series of community-owned forest fragments, representing what has been left after agricultural clearing (Fig. 31.2). These fragments

Figure 31.2:
Forest fragment outside of Kibale National Park, with Rwenzori Mountains in the background. Note the abrupt boundary between the forest fragment and the surrounding tea crop. (Photograph by Tony Goldberg)

tend to persist in areas unfavorable for agriculture, such as wet valley bottoms and steep hillsides, and they contain remnant populations of species found in the park, including primates (Onderdonk and Chapman 2000). Local people use these forest fragments for activities ranging from forest product extraction (e.g., timber, charcoal, forest plants) to slash-and-burn agriculture.

Superimposed on this spatial variation are more insidious temporal trends. Western Uganda has one of the highest rates of human population growth in sub-Saharan Africa, which has notably accelerated the rate of forest clearing and human–park conflict over the past approximately 20 years (Naughton-Treves et al. 2006; Hartter and Southworth 2009). Within the park, areas where forests had been cleared in the early 1900s and converted to grasslands are now regenerating to forest (Fig. 31.3). Long-term data document substantial local climate change, characterized by a marked increase in local yearly rainfall and maximum temperature, which are notably steeper than global averages (Fig. 31.4). Indeed, those of us fortunate to have visited Kibale for longer than a decade have personally witnessed the receding of glaciers on the Rwenzori Mountains just to the west of the park (Taylor et al. 2006).

The Kibale EcoHealth Project has taken scientific advantage of the inherent ecological variation in this complex system. Specifically, we have treated the core protected areas of Kibale National Park as a type of "control," in which animals live more or less free of human impact (this is clearly not true, as evidenced by the presence of researchers and well-established "edge effects" that can permeate deep into forests; Murcia 1995). Comparing animals in these core areas to those in the forest fragments, which are highly degraded, thus serves as a "natural experiment," and a framework for testing our coarsest-scale hypothesis that land use change in the form of forest fragmentation affects health, defined broadly.

The Kibale EcoHealth Project strives to go beyond the level of coarse-scale statistical association and to gain more detailed insights into how disturbed landscapes alter animal and human health (or not, in

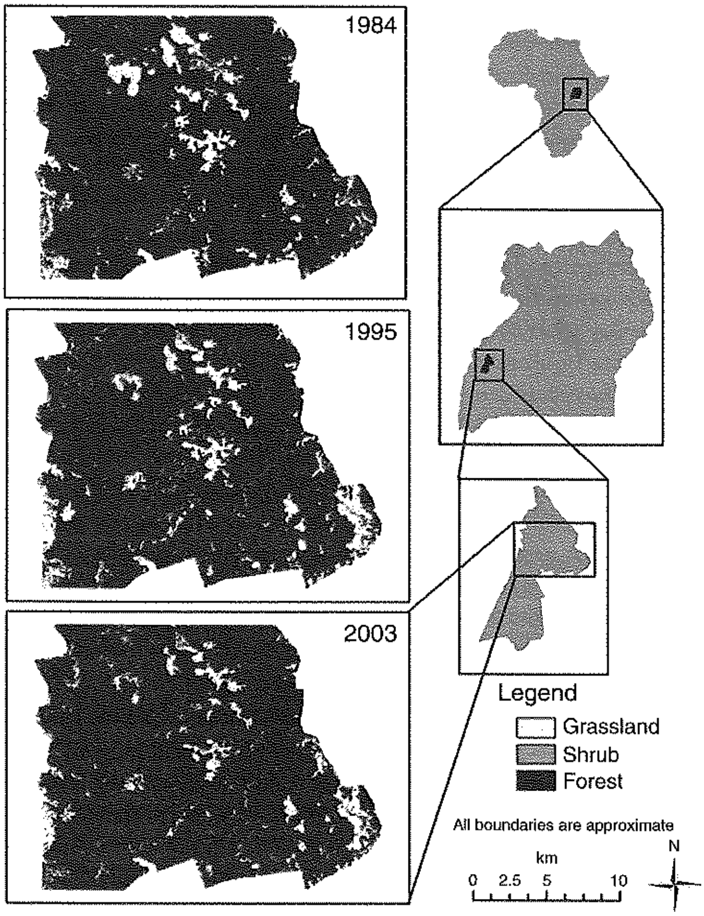

Figure 31.3.
Forest transition in Kibale National Park between 1984 and 2003. Note the increase in grassland from 1984 to 1995 but the reversion of grassland to forest from 1995 to 2003, when Kibale was a national park and under protection by the Uganda Wildlife Authority. The land cover assessment was based on five-class supervised classification (89% overall accuracy, kappa statistic 0.867) from three dry-season Landsat Images (May 26, 1984; January 17, 1995; January 31, 2003) at 30m spatial resolution. (Figure courtesy of J. Hartter)

the spirit of objective hypothesis testing). For this reason, we have attempted to make use of finer-scale natural ecological comparisons. The most basic of these are comparisons among forest fragments, which, for political, historical, and geographic reasons, differ widely in their nature and degree of disturbance (Chapman et al. 2006; Gillespie and Chapman 2006). Finer-scale still are contrasts among households and individuals, in the case of people and domestic animals, and social groups and individuals, in the case of primates.

The Kibale EcoHealth Project therefore operates on multiple, hierarchical spatial scales, from the forest to the social unit to the individual, framed against a background of changing human population, environment, and climate. At all levels, we make use of natural variation in the system to ask targeted questions about the relationship between environment and health. Our research methods are observational and typically non-invasive. However, these non-disruptive methodologies belie our decidedly "experimentalist" approach, in that we capitalize whenever

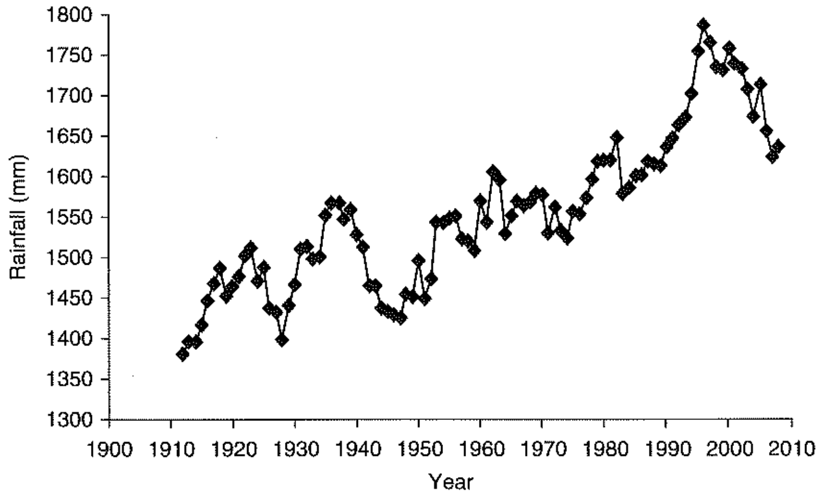

Figure 31.4:
Yearly rainfall (10-year running average) in Kibale National Park, Uganda, 1911–2010, showing a long-term trend of increasing precipitation. A similar trend exists for temperature, with local changes in both rainfall and temperature exceeding global averages (C. Chapman and L. Chapman, unpublished data).

we can on the experiments that politics and nature have already conducted.

ANIMAL HEALTH AND INFECTION

The Kibale EcoHealth Project's main research emphasis has been in the area of infectious disease, focusing on how the dynamic landscapes of Kibale affect microbial transmission. Infection is clearly important, as evidenced by the striking contribution of zoonotic disease transmission to the global emergence of human pathogens (Cleaveland et al. 2001). This does not, however, mean that infection is the most important determinant of health in our system. Indeed, our broader analyses reveal that disease transmission may be a consequence of higher-level ecological changes, such as the aforementioned forest fragmentation, rather than a primary cause of health declines.

One difficulty of prospective ecological studies of multi-species infection dynamics is finding an appropriate pathogen. In primates, deadly epidemics of Ebola virus (Leroy et al. 2004; Walsh et al. 2007) and human respiratory viruses (Kaur et al. 2008; Kondgen et al. 2008) have shed considerable light on the risks of human–primate disease transmission, but these events have been thankfully infrequent. Microscopic evaluations of gastrointestinal helminths, often the first target for primatologists venturing into the study of infection, are inadequate for understanding cross-species transmission. This is because many helminths are highly host-specific but morphologically cryptic, as illustrated by the case of the nodular worm *Oesophagostomum bifurcum* in West Africa. In this case, traditional parasitological analyses suggested a transmission link between humans and non-human primates, but subsequent molecular analyses demonstrated that the parasite in non-human primates was entirely distinct from that in humans (Gasser et al. 2006, 2009).

The ideal pathogen to serve as a "baseline" for studies of transmission ecology would be ubiquitous, biologically variable, non–species-specific, and benign. Such a pathogen would reflect transmission unbiased by non-uniform distributions, host specificity, or clinical disease. Although no pathogen meets these criteria perfectly, we initially chose to examine the common gastrointestinal bacterium *Escherichia coli*. *E. coli* inhabits the gastrointestinal tracts of all vertebrates but is highly variable genetically and clinically (Donnenberg 2002). Transmitted through food, water, and the physical environment, *E. coli* is a "generalist" microbe known for its ability to cross species barriers (Trabulsi et al. 2002). Because of the importance of certain *E. coli* serotypes to food safety (e.g., the infamous O157-H7 serotype), a suite of molecular methods is available for inferring the bacterium's movement over short time scales (i.e., "source tracking"; Foley et al. 2009).

E. coli appears to move easily between people and animals in Kibale, where ecological overlap is high. Unlike in industrialized nations, where food animals are relegated to farms, cattle, sheep, and goats (and the occasional pig) live in close proximity to households in western Uganda, often sharing an almost identical activity space with people. Not surprisingly, we found *E. coli* populations in people to be all but genetically indistinguishable from *E. coli* populations of their livestock (Rwego et al. 2008a), based on DNA fingerprinting methods optimized for this system (Goldberg et al. 2006b). Hygiene matters, since genetically inferred transmission rates between people and their livestock were twice as high when people did not regularly wash their hands before eating (Rwego et al. 2008a).

Ecological overlap between people and primates is more difficult to document, but it clearly occurs in the context of ecotourism. Uganda has developed a thriving ecotourism industry centered on apes, since the country contains the largest population of mountain gorillas (*Gorilla beringei beringei*) and a number of relatively accessible communities of Eastern chimpanzees (*P. t. schweinfurthii*). As a result, personnel employed by the Uganda Wildlife Authority as ranger-guides or as field assistants for various ape research projects spend considerable time in ape habitats as part of their daily duties. Intriguingly, this high degree of habitat overlap is reflected in genetic relationships among gastrointestinal bacterial populations: people in Kibale employed in chimpanzee-related ecotourism harbor *E. coli* more closely related genetically to the *E. coli* of the chimpanzees they track than do people from local villages (Goldberg et al. 2007). Parallel data from Bwindi Impenetrable National Park, Uganda's main site for gorilla tourism, about 150 km south of Kibale, indicate a strikingly similar pattern: gorillas interacting frequently with people and livestock at the edge of the park harbor *E. coli* genetically similar to those of people and livestock, whereas gorillas in the "core" areas of Bwindi harbor *E. coli* that are less genetically similar to those of people and their livestock (Rwego et al. 2008b).

The exact mechanisms explaining this type of microbial transmission remain elusive. We speculate a strong role of environmental contamination, perhaps of water, as a result of interacting human and ape populations living in the same watersheds and being exposed to the same water sources. However, such effects are difficult to document, partially due to small sample sizes of apes and ape-tracking personnel. Most of our recent efforts have therefore focused on more numerous primates, including the well-studied endangered red colobus monkey (*Procolobus* [*Piliocolobus*] *badius tephrosceles*), its common and widely distributed relative the black-and-white colobus monkey (*Colobus guereza*), and the red-tailed guenon (*Cercopithecus ascanius*), a notorious crop-raider. These three species inhabit both the protected areas of the national park and the disturbed forest fragments outside of the park, facilitating inter-population comparisons.

Our initial studies focused on three forest fragments near Kibale: Kiko-1 (most intensively used and now entirely gone), Rurama (relatively less encroached upon), and Bugembe (only moderately used). Satisfyingly, we found the "dose–response" effect predicted by this gradation of forest fragment disturbance: human–primate bacterial genetic similarity was highest in Kiko-1, followed by Rurama, followed by Bugembe (Goldberg et al. 2008c). Moreover, we were able to regress human–primate bacterial genetic similarity at the level of the individual against interview data on health and land use. These analyses indicate that people who tend livestock and experience gastrointestinal symptoms are also at elevated risk for harboring primate-like *E. coli* (Goldberg et al. 2008c). We note that we cannot definitively prove the direction of causality. For example, people who report gastrointestinal symptoms may have contracted primate-borne microbes, or sick people may be shedding microbes into the environment that primates subsequently encounter.

As we have come up against the limitations of our quantitative study design, we have begun to rely increasingly on observation and inference to refine our understanding of microbial transmission risk. Local human cultural practices in particular strike us as being important, one prime example being an intriguing practice that we call "maize daubing" (Goldberg et al. 2008b). In the course of our ground surveys, we have encountered ears of maize at the edges of fields abutting forest fragments that are pasted with a noxious mixture of cattle dung, sand, and hot pepper. People use this strategy to ward off wildlife intent on raiding their crops—primarily red-tailed guenons. Interestingly, red-tailed guenons harbor *E. coli* that are particularly closely related genetically to the *E. coli* of local people and their livestock (Goldberg et al. 2008c). We marvel at the likelihood that this unique human cultural practice, borne out of human–wildlife conflict, might inadvertently increase microbial transmission risk not only between people and primates, but also between people and livestock and primates and livestock.

It has been difficult to ascertain the direction of microbial transmission in our system. Although we initially thought to apply comparative phylogenetic methods to this problem (Goldberg 2003), these have been inconclusive. More informative has been our discovery of antibiotic resistance in *E. coli* in western Uganda's primates. In *E. coli* from chimpanzees, we find patterns of multiple antibiotic resistance matching the most common patterns in *E. coli* from local people (Goldberg et al. 2007). In the mountain gorillas of Bwindi Impenetrable National Park in southwest Uganda, we find carriage rates of antibiotic-resistant *E. coli* that increase with increasing contact rates between gorilla groups and people (Rwego et al. 2008b). Because wild primates only very rarely receive antibiotics (only in unusual cases where apes might be anesthetized to remove snares and treated with a single dose of antibiotics), the best explanation for these observations is transmission of bacteria or resistance-conferring bacterial genetic elements from people to primates. Indeed, our ongoing studies suggest a strong directional bias towards reverse zoonotic transmission of bacteria, perhaps indicating that, in matters of disease, non-human primates are once again disadvantaged.

Our results based on *E. coli* admittedly bias our understanding of disease transmission dynamics. *E. coli* may be a favorable "indicator system" for human–primate disease transmission, but the generality of findings based on this particular microbe should not be overstated. Although *E. coli* is benign, this is not true of other pathogens also present in Kibale's primates (Bonnell et al. 2010). For example, we have found that the pathogenic gastrointestinal protozoa *Giardia duodenalis* and *Cryptosporidium* spp. infect red colobus in forest fragments (Salzer et al. 2007). In the case of *G. duodenalis*, molecular analyses indicate that this is due to independent transmission cycles involving at least two parasite genotypes, one moving from people to red colobus and the other moving from livestock to red colobus (Johnston et al. 2010). More troublesome still are the novel pathogens in this system. We have found evidence of a previously uncharacterized *Orthopoxvirus* in Kibale red colobus, similar but not identical to cowpox, vaccinia, and monkeypox viruses (Goldberg et al. 2008a). We have documented three novel simian retroviruses in these same red colobus (Goldberg et al. 2009), related to viruses in West Africa that are known zoonoses (Wolfe et al. 2004; Wolfe et al. 2005b), as well as two novel and highly divergent variants of simian hemorrhagic fever virus, which is an animal pathogen of biodefense concern (Lauck et al. 2011). Primates in the forest fragments where we work have frequent, antagonistic interactions with people and are unusually aggressive (Goldberg et al. 2006a). On top of this, immune compromise due to such factors as HIV/AIDS and malnutrition already burdens people in Uganda, leaving the population especially susceptible to opportunistic infections. Such a "perfect storm" of conditions may explain Uganda's status as a country of concern from the standpoint of disease emergence.

Despite our growing collection of compelling stories about how people, primates, and livestock exchange pathogens across a dynamic landscape, we nevertheless believe that enhanced microbial transmission by itself does not imperil Kibale's animals or people. Rather, disease may be the "coup de grâce" for primates forced to live in marginal habitats near Kibale and for people already burdened with the health-related challenges of poverty (Farmer 1999). Many of Kibale's forest fragments have disappeared since they were first studied almost two decades ago (Onderdonk and Chapman 2000), along with their primates (Chapman et al. 2007). Now, we are becoming aware of synergies between the nutritional and physiological stresses experienced by primates forced to live in these marginal environments and the parasites they harbor (Chapman et al. 2006). Infection does not work alone, in other words, but rather synergizes with the far more dire threats of habitat loss and population compression.

The overall outlook is unfortunately grim. In Kibale, we estimate that most primates in unprotected forest fragments will perish within the next two decades as a result of the combined stressors of habitat loss, agonistic interactions with people, nutritional stress, and disease. Based on our observations to date about the relationship between habitat overlap and cross-species microbial transmission, we predict these local primate extinctions to be accompanied by "spikes" in infectious disease transmission to other species, including humans. This fine-scale effect mirrors coarser-scale processes. Perhaps it is no coincidence that the world today appears be facing a global extinction crisis at the same time that it faces a global infection crisis.

HUMAN DIMENSIONS OF ECOHEALTH

"Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmary" (World Health Organization 1948). This appealing definition reflects the relativity of health and shifts our focus from disease to wellness. Unfortunately, it also makes it difficult to identify, define, and model the physical, psychological, and social factors that interact to shape health. Nevertheless, this holistic view of health can complement more traditional quantitative and "disease-centric" approaches.

Our research into the human dimensions of health in Kibale adopts such an integrated theoretical framework, focusing simultaneously on the social and biological dimensions of health and layers of interactions across scales (Mayer 1996). This approach allows us to remain tuned to the physical context of health and its connections to tropical forest ecology while also allowing us to expand beyond the limits of the traditional quantitative epidemiological approach. In this section, we describe how our holistic approach has yielded unique insights into the drivers of ecosystem health in the Kibale region. The emerging picture reveals how structural and physical forces that change landscapes also mediate human–environment relationships and health-related outcomes.

Structural forces, like poverty and inequality, are intricately linked to health and infectious disease outcomes (Marmot and Wilson 1999; Farmer 2005). In rural Uganda, the area around Kibale is experiencing significant population growth as a result of both high birth rates and immigration (Hartter and Southworth 2009). A widespread lack of livelihood options forces people to practice subsistence agriculture even as the price of arable land increases and the amount of available land decreases. This situation pushes the poorest subsistence farmers, usually immigrants, to the least expensive areas, which are plots adjacent to Kibale National Park (Naughton-Treves 1997). These economic conditions (poverty and lack of options) trigger a cascade of interactions between people and wildlife that result in negative health outcomes through two separate pathways.

One pathway to poor health is a consequence of cross-species transmission of infectious agents. As much field-based research has shown, infectious agents are shared between primates and people living next to national parks (e.g., Graczyk et al. 2001; Nizeyi et al. 2001; Graczyk et al. 2002; Nizeyi et al. 2002; Goldberg et al. 2008c; Rwego et al. 2008b; Johnston et al. 2010), particularly as wild primates transgress park boundaries to raid crops planted along the park edges (Kalema-Zikusoka 2002; Rwego et al. 2009). This type of primate behavior enhances the risk of transferring a sylvatic infectious agent to people through indirect ecological exposure, thus resulting in a higher risk of zoonotic disease for the poorest people.

Another pathway to poor health is through crop-raiding, its exacerbation of malnutrition, and the interactions between infectious disease and malnutrition. For example, one response to raiding animals has been to limit the variety of food crops planted. However, homogeneous diets make it difficult to consume the variety of nutrients necessary for good health (Krebs-Smith et al. 1987; Oldewage-Theron and Kruger 2008), especially in a location where protein deficiencies are already common (Muller and Krawinkel 2005). Ugandan law prohibits the hunting or killing of most wildlife, so a second option is to guard crops. At harvest time, local people will "camp out" in fields for days or weeks, banging cans, yelling, and burning fires day and night to keep animals out of fields. Still, findings from a study in the late 1990s found that 4% to 7% of food crops were lost due to crop-raiding (Naughton-Treves 1998), and this problem is increasing yearly, primarily due to a growing elephant population (Wanyama et al. 2010).

Malnutrition and infectious disease operate synergistically to worsen morbidity. Malnutrition weakens immunity, and infection increases nutritional needs (Scrimshaw and SanGiovanni 1997). The interaction between poverty and infectious disease is therefore manifest through conservation conflicts that represent serious barriers to good health for the poorest people.

Moreover, the strong urban bias in healthcare systems services and delivery limits access to quality care by the rural poor (Farmer 1999; Pariyo et al. 2009). If, for example, a family member becomes seriously sick with an infectious disease, the ability to seek quality care is limited further by poor health systems infrastructure. If the household is able to marshal resources to travel to the hospital to seek care, the costs incurred (transportation, hospital fees, medications, meals) frequently require liquidation of household assets, like domestic animals or even land, leading to a downward spiral.

The dynamic relationship between poverty and poor health at the border of the national park is replicated in the forest fragments that persist beyond the park edges. Forest fragments are typically surrounded by household compounds, fields, and pastures, and they are also home to primates (Onderdonk and Chapman 2000). Because of their small size and high human and primate densities, these fragment locations are magnified examples of the intense human–primate interaction and conservation conflict found in households adjacent to the park (Goldberg et al. 2008b). However, fragments are different from the park in one key way: fragments, unlike the park, are unprotected, so interaction between people and primates occurs not only in the fields, but also inside the fragment. People use fragments as sources of fuel wood, timber, medicinal plants, and materials for household use, for making charcoal, and for collecting water. The ecological role of the fragment is thus similar to that of the park boundary, in that animals leave the park to raid crops, but different in that people commonly use the fragment to access natural resources. This situation enables a sustained overlap between human activity spaces and primate activity spaces, and as a result human–primate contact, accelerating the cross-species exchange of infectious agents (Goldberg et al. 2008c).

As mentioned above, we have noted cultural adaptations to crop-raiding that likely have negative health effects, such as "maize daubing." This practice puts people and primates in direct contact with potential enteric bovine pathogens, thereby exacerbating the likelihood of disease exchange across species. Another response is the active guarding of crops throughout the night. This task is usually the responsibility of both children and adults, and the resulting sleepless nights likely have an impact on school performance and overall health. Still another practice is hunting. Although local people do not hunt primates for food, numerous anecdotes across our study sites reference dogs hunting primates in nocturnal packs, and children hunting primates either for fun or to protect crops. Once a monkey has been killed, the head of household will usually butcher it, cook the meat, and feed it to dogs. In West Africa, the practice of butchering primates in the context of "bushmeat hunting" is known to transfer blood-borne primate pathogens to people (Wolfe et al. 2005a); this may be replicated here as a result of very different socioeconomic drivers.

The distinction between infectious disease and health emerges in a different light when people are asked to talk about their health explicitly. By asking people in communities near the park what are the most important health issues, few will respond with zoonoses as a top concern. Instead, our grounded public health/community-based health surveys suggest that the processes shaping health as physical, social, and mental well-being are profoundly rooted in the interaction between social and biological forces. Specifically, poverty and lack of access to food and healthcare are repeatedly named as the biggest barriers to good health. Moreover, local people define health in ways that more closely reflect the WHO construct and are less focused on infectious disease.

Overall, therefore, ecological interactions at the community and individual levels provide a sufficient explanation for pathogen exchange between people and animals, but they do not paint a complete picture. Rather, we believe that the knowledge, beliefs, and behaviors of individual people fundamentally shape the human–environment interactions that ultimately fuel zoonotic disease transmission as well as other health-related outcomes. The interdisciplinary approaches currently employed by the Kibale EcoHealth Project make possible the integration of inter-scalar structural and cultural factors. Going beyond traditional "disease ecology" and incorporating social science certainly complicates research questions and processes, but it also enables a more complete understanding of cross-species disease exchange and health in the broadest sense.

ECOHEALTH INTERVENTIONS

As we have continued to identify the root causes of health declines in the Kibale region (human health, animal health, and ecosystem health), we are often asked what concrete steps can be taken to improve the situation. Interventions based on managing wildlife populations and altering agricultural practices sometimes seem like the most obvious solutions, but they tend to be difficult given the scale of implementation that would be required. Therefore, we have recently initiated an intervention that focuses on human health but that is specifically designed to have positive external benefits for wildlife health and forest conservation.

The Kibale Health and Conservation Centre was established to improve access to healthcare for rural residents around Kibale National Park. The decision to establish a primary care health clinic near the park was based on health surveys of local people conducted in 2005 indicating limited local knowledge about health, limited practice of protective health behaviors, but a strong desire for accessible healthcare. The immediate goal of the new clinic is to serve human health needs through basic primary care and public health outreach activities; however, its long-term goal is also to reduce conservation conflicts around the park. By situating the clinic within the park and framing it as a service of conservation interests, we have endeavored to put the EcoHealth paradigm into practice. Our hope is that that improving human health and local attitudes towards the park will "spill over" into improved animal health and forest conservation (Kalema-Zikusoka 2004; Kalema-Zikusoka and Gaffikin 2008). The clinic works alongside local civic organizations such as women's groups, local councils, and primary schools to improve "physical, mental, and social well-being" within catchment communities.

The clinic staff includes two nurses and a number of volunteers from the local community. Nurses provide primary care services within the clinic, make house calls, and conduct regular public health outreach activities. An Employee Health Program was initiated in August 2009 with the goal of enhancing the health of park research and conservation staff working directly with primates to limit pathogen exchange. The clinic is distinct from typical non-governmental organizations. It is integrated into the existing district public health system of Uganda, accessing the majority of its pharmaceuticals from the Ugandan national supply chain. Integration of the clinic into the existing public health infrastructure is imperative for the clinic's sustainability, and collaboration between the international and local conservation and health professional communities exemplifies the EcoHealth spirit in action.

CONCLUSIONS

The paradigm of EcoHealth is often represented by a Venn diagram with intersecting circles of human health, animal health, and ecosystem health. Although heuristically useful, this representation is inadequate for capturing the complexity of EcoHealth in practice. In some cases the circles fail to intersect, as exemplified by our studies showing that perceptions of health in local communities do not generally include consideration of animals or the land. In other cases, the circles are of varying sizes and the interactions are decidedly lopsided or unidirectional, as exemplified by our studies showing extensive transmission of microbes from people to wild primates but limited evidence of the reverse. In other cases still, we find incompatibility with the fundamental concept of "balance" underlying the EcoHealth paradigm, as exemplified by crop-raiding: people living in environments denuded of primates are better off economically and likely have higher nutritional status than people living in biodiverse environments containing primates. Where the optimal balance between human interests, wildlife interests, and ecosystem conservation ultimately lies is context-dependent.

Despite these complexities, we can nevertheless make some generalizations. For example, our work to date supports our coarsest-scale hypothesis that landscape changes alter infectious disease transmission dynamics, and specifically that ecological overlap enhances microbial transmission between species. In the case of *E. coli*, we have documented a direct relationship between the degree of human–animal overlap and the rate of microbial transmission across species (Goldberg et al. 2008c; Rwego et al. 2008a). Infection in the Kibale system appears to flow readily from people and livestock to primates, as evidenced by our findings of antibiotic-resistant bacteria in wild primates and multiple human-associated and livestock-associated *G. duodenalis* genotypes in endangered red colobus (Goldberg et al. 2007; Rwego et al. 2008b; Johnston et al. 2010). Infection of wild primates with human and livestock pathogens may have additional negative consequences. Primates are important seed dispersers and are central to maintaining the diversity of tropical forests and the ecosystem services they provide (Chapman and Onderdonk 1998); forests without primates, or forests with sick primates, may be poorly functioning and "unhealthy" ecosystems.

Our findings also clarify the temporal scale on which EcoHealth operates, which is relevant to the idea of EcoHealth as a biological and ethical goal. The historical forces that have shaped Kibale's present-day landscape originated decades in the past (e.g., intensive logging, forest fragmentation); however, their effects on land health are strongly evident today, even nearly two decades after Kibale's designation as a national park. It is clear that factors such as logging exert long-term influences on forest communities (Chapman et al. 2000) and that recovery is slow. It is also clear that recovery will be equally slow in the arena of health. In the Kibale system, the relevant time scale for ecological improvements to health is likely to be the time scale of forest regeneration. Health interventions based on restoring forest integrity should therefore be expected to reap benefits only decades into the future—a sobering lesson for researchers and policy planners under pressure to show tangible results quickly.

Finally, we may draw some conclusions about the knowledge, beliefs, and behaviors of the people who inhabit and shape Kibale's dynamic landscapes. Most important, perhaps, is that the paradigm of EcoHealth does not figure prominently in the minds of these people. Although people in communities near Kibale are indeed aware of the relationship between the forest and their well-being, the connection to health is tenuous at best. Because of such forces as crop-raiding, "healthy" ecosystems containing biodiverse animal communities are associated with poverty and are perceived as undesirable. Is this a failure of education, a bias in perception, or a breakdown of the utility of EcoHealth thinking? Whatever the explanation, there is a notable gap between our quantitative results showing strong ecology and health connections in the case of microbial transmission and our qualitative results showing different perceptions in the minds of local people.

As a more nuanced picture emerges of environment–health linkages in the Kibale region, it is tempting to simplify the task ahead by focusing on a small topic or a particular question. Indeed, a progressive narrowing of focus defines success in many modern fields of science. We argue, however, that this approach is antithetical to the concept of EcoHealth. If the Kibale EcoHealth Project differs from the norm in any way, it is in its dogged determination not to succumb to the temptations of reductionism. Intellectually, this is because focusing on the diverse interactions that link human health, animal health, and the environment keeps us rooted to our ecological underpinnings. Philosophically, it is because we appreciate that new insights are most likely to emerge where disciplines intersect and when multiple approaches are applied to complex problems. Pragmatically, it is because interventions that target a single relationship within a complex ecological web will surely have unforeseen consequences and are likely to fail as a result.

The Kibale EcoHealth Project ultimately provides a concrete example of how holistic science can progress, and how a "bottom-up," place-based approach can inform fundamental questions at the interface of ecology and health. As we enter the phase of intervention with such efforts as the Kibale Health and Conservation Centre, the holistic approach becomes increasingly important, since the costs of allocating resources incorrectly or sub-optimally increases commensurately. We will continue to emphasize the evidence-based approach, now studying not only the "natural experiments" that nature and politics have already conducted in western Uganda, but also the "experiments" that we are conducting ourselves in the form of targeted public health interventions. The degree to which our focused efforts to improve human health will have positive, external benefits for animal health and conservation may in the end be the ultimate test of the real-world relevance of the EcoHealth paradigm to the complex and dynamic ecosystems of western Uganda and beyond.

REFERENCES

Archabald, K., and L. Naughton-Treves. 2001. Tourism revenue sharing around national parks in western Uganda: early efforts to identify and reward local communities. Environ Conserv 23:135–149.

Baranga, J. 1991. Kibale forest game corridor: man or wildlife? *In* D.A. Saunders and R.J. Hobbs, eds. Nature conservation: the role of corridors, pp. 371–375. Surrey Beatty and Sons, London.

Bonnell, T.R., R.R. Sengupta, C.A. Chapman, and T.L. Goldberg. 2010. An agent-based model of red colobus resources and disease dynamics implicates key resource sites as hot spots of disease transmission. Ecol Model 221:2491–2500.

Chapman, C.A., and D.A. Onderdonk. 1998. Forests without primates: primate/plant codependency. Am J Primatol 45:127–141.

Chapman, C.A., S.R. Balcomb, T.R. Gillespie, J. Skorupa, and T.T. Struhsaker. 2000. Long-term effects of logging on African primate communities: A 28-year comparison from Kibale National Park, Uganda. Conserv Biol 14:207–217.

Chapman, C.A., T.T. Struhsaker, and J.E. Lambert. 2005. Thirty years of research in Kibale National Park, Uganda, reveals a complex picture for conservation. Int J Primatol 26:539–555.

Chapman, C.A., M.D. Wasserman, T.R. Gillespie, M.L. Speirs, M.J. Lawes, T.L. Saj, and T.E. Ziegler. 2006. Do food availability, parasitism, and stress have synergistic effects on red colobus populations living in forest fragments? Am J Phys Anthropol 131:525–534.

Chapman, C.A., L. Naughton-Treves, M.J. Lawes, M.D. Wasserman, and T.R. Gillespie. 2007. The conservation value of forest fragments: explanations for population declines of the colobus of western Uganda. Int J Primatol 28:513–528.

Cleaveland, S., M.K. Laurenson, and L.H. Taylor. 2001. Diseases of humans and their domestic mammals: pathogen characteristics, host range and the risk of emergence. Philos Trans R Soc Lond B 356: 991–999.

Donnenberg, M., ed. 2002. Escherichia coli: Virulence mechanisms of a versatile pathogen. Academic Press, San Diego California.

Farmer, P. 1999. Infections and inequalities: the modern plagues. University of California Press, Berkeley, California,

Farmer, P. 2005. Pathologies of power: health, human rights, and the new war on the poor. University of California Press, Berkeley, California.

Foley, S.L., A.M. Lynne, and R. Nayak. 2009. Molecular typing methodologies for microbial source tracking and epidemiological investigations of Gram-negative bacterial foodborne pathogens. Infect Genet Evol 9:430–440.

Gasser, R.B., J.M. de Gruijter, and A.M. Polderman. 2006. Insights into the epidemiology and genetic make-up of *Oesophagostomum bifurcum* from human and non-human primates using molecular tools. Parasitology 132:453–460.

Gasser, R.B., J. M. de Gruijter, and A. M. Polderman. 2009. The utility of molecular methods for elucidating primate-pathogen relationships—the *Oesophagostomum bifurcum* example. *In* M.A. Huffman and C.A. Chapman, eds. Primate parasite ecology: the dynamics and study of host-parasite relationships, pp. 47–62. Cambridge University Press, Cambridge, UK.

Gillespie, T.R., and C.A. Chapman. 2006. Prediction of parasite infection dynamics in primate metapopulations based on attributes of forest fragmentation. Conserv Biol 20:441–448.

Goldberg, T.L. 2003. Application of phylogeny reconstruction and character-evolution analysis to inferring patterns of directional microbial transmission. Prev Vet Med 61:59–70.

Goldberg, T.L., T.R. Gillespie, I.B. Rwego, and C. Kaganzi. 2006a. Killing of a pearl-spotted owlet (*Glaucidium perlatum*) by male red colobus monkeys (*Procolobus tephrosceles*) in a forest fragment near Kibale National Park, Uganda. Am J Primatol 68:1007–1011.

Goldberg, T.L., T.R. Gillespie, and R.S. Singer. 2006b. Optimization of analytical parameters for inferring relationships among *Escherichia coli* isolates from repetitive-element PCR by maximizing correspondence with multilocus sequence typing data. Appl Environ Microbiol 72:6049–6052.

Goldberg, T.L., T.R. Gillespie, I.B. Rwego, E.R. Wheeler, E.E. Estoff, and C.A. Chapman. 2007. Patterns of gastrointestinal bacterial exchange between chimpanzees and humans involved in research and tourism in western Uganda. Biol Conserv 135:511–517.

Goldberg, T.L., C.A. Chapman, K. Cameron, T. Saj, W.B. Karesh, N. Wolfe, S.W. Wong, M.E. Dubois, and M.K. Slifka. 2008a. Serologic evidence for novel poxvius in endangered red colobus monkeys, western Uganda. Emerg Infect Dis 14:801–803.

Goldberg, T.L., T.R. Gillespie, and I.B. Rwego. 2008b. Health and disease in the people, primates, and domestic animals of Kibale National Park: implications for conservation. *In* R. Wrangham and E. Ross, eds. Science and conservation in African forests: the benefits of long-term research, pp. 75–87. Cambridge University Press, UK.

Goldberg, T.L., T.R. Gillespie, I.B. Rwego, E.E. Estoff, and C.A. Chapman. 2008c. Forest fragmentation as cause of bacterial transmission among primates, humans, and livestock, Uganda. Emerg Infect Dis 14:1375–1382.

Goldberg, T.L., D.M. Sintasath, C.A. Chapman, K.M. Cameron, W.B. Karesh, S. Tang, N.D. Wolfe, I.B. Rwego, N. Ting, and W.M. Switzer. 2009. Coinfection of Ugandan red colobus (*Procolobus [Piliocolobus] rufomitratus tephrosceles*) with novel, divergent delta-, lenti-, and spumaretroviruses. J Virol 83:11318–11329.

Graczyk, T.K., A.B. Mudakikwa, M.R. Cranfield, and U. Eilenberger. 2001. Hyperkeratotic mange caused by *Sarcoptes scabiei* (Acariformes: Sarcoptidae) in juvenile human-habituated mountain gorillas (*Gorilla gorilla beringei*). Parasitol Res 87:1024–1028.

Graczyk, T.K., J. Bosco-Nizeyi, B. Ssebide, R.C. Thompson, C. Read, and M.R. Cranfield. 2002. Anthropozoonotic *Giardia duodenalis* genotype (assemblage) A infections in habitats of free-ranging human-habituated gorillas, Uganda. J Parasitol 88:905–909.

Hartter, J., and J. Southworth. 2009. Dwindling resources and fragmentation of landscapes around parks: wetlands and forest patches around Kibale National Park, Uganda. Landscape Ecol 24:643–656.

Howard, P.C. 1991. Nature conservation in Uganda's tropical forest reserves. IUCN Gland, Switzerland and Cambridge, UK.

Johnston, A.R., T.R. Gillespie, I.B. Rwego, T.L. Tranby McLachlan, A.D. Kent, and T.L. Goldberg. 2010. Molecular epidemiology of cross-species Giardia duodenalis transmission in western Uganda. PLoS Neglect Trop Dis 4:e683.

Jones, K.E., N.G. Patel, M.A. Levy, A. Storeygard, D. Balk, J.L. Gittleman, and P. Daszak. 2008. Global trends in emerging infectious diseases. Nature 451:990–993.

Kalema-Zikusoka, G. 2002. Scabies in free-ranging mountain gorillas (*Gorilla beringei beringei*) in Bwindi Impenetrable National Park, Uganda. Vet Rec 150:12–14.

Kalema-Zikusoka, G. 2004. Conservation through public health. Gorilla J 28:9–11.

Kalema-Zikusoka, G., and L. Gaffikin. 2008. Sharing the forest: protecting gorillas and helping families in Uganda. Smithsonian Institution, Washington, D.C.

Kaur, T., J. Singh, S. Tong, C. Humphrey, D. Clevenger, W. Tan, B. Szekely, Y. Wang, Y. Li, E. Alex Muse, M. Kiyono, S. Hanamura, E. Inoue, M. Nakamura, M.A. Huffman, B. Jiang, and T. Nishida. 2008. Descriptive epidemiology of fatal respiratory outbreaks and detection of a human-related metapneumovirus in wild chimpanzees (*Pan troglodytes*) at Mahale Mountains National Park, Western Tanzania. Am J Primatol 70:755–765.

Keiser, J., B.H. Singer, and J. Utzinger. 2005. Reducing the burden of malaria in different eco-epidemiological settings with environmental management: a systematic review. Lancet Infect Dis 5:695–708.

Kondgen, S., H. Kuhl, P.K. N'Goran, P.D. Walsh, S. Schenk, N. Ernst, R. Biek, P. Formenty, K. Matz-Rensing, B. Schweiger, S. Junglen, H. Ellerbrok, A. Nitsche, T. Briese, W.I. Lipkin, G. Pauli, C. Boesch, and F.H. Leendertz. 2008. Pandemic human viruses cause decline of endangered great apes. Curr Biol 18:260–264.

Krebs-Smith, S.M., H. Smiciklas-Wright, H.A. Guthrie, and J. Krebs-Smith. 1987. The effects of variety in food choices on dietary quality. J Am Diet Assoc 87:897–903.

Lauck, M., D. Hyeroba, A. Tumukunde, G. Weny, S.M. Lank, C.A Chapman, D.H. O'Connor, T.C. Friedrich, and T.L. Goldberg. 2011. Novel, divergent simian hemorrhagic fever viruses in a wild Ugandan red colobus monkey discovered using direct pyrosequencing. PLoS One 6:e19056.

Leroy, E.M., P. Rouquet, P. Formenty, S. Souquiere, A. Kilbourne, J.M. Froment, M. Bermejo, S. Smit, W. Karesh, R. Swanepoel, S.R. Zaki, and P.E. Rollin. 2004. Multiple Ebola virus transmission events and rapid decline of central African wildlife. Science 303:387–390.

Marmot, M.G., and R.G. Wilson. 1999. Social determinants of health. Oxford University Press, New York.

Mayer, J.D. 1996. The political ecology of disease as one new focus for medical geography. Progr Hum Geog 20:441–456.

Muller, O., and M. Krawinkel. 2005. Malnutrition and health in developing countries. CMAJ 173: 279–86.

Murcia, C. 1995. Edge effects in fragmented forests: implications for conservation. Trends Ecol Evol 10:58–62.

Naughton-Treves, L. 1997. Farming the forest edge: vulnerable places and people around Kibale National Park, Uganda. Geog Rev 87:27–46.

Naughton-Treves, L. 1998. Predicting patterns of crop damage by wildlife around Kibale National Park, Uganda. Conserv Biol 12:156–168.

Naughton-Treves, L. 1999. Whose animals? A history of property rights to wildlife in Toro, western Uganda. Land Degr Develop 10:311–328.

Naughton-Treves, L., D.M. Kammen, and C.A. Chapman. 2006. Burning biodiversity: woody biomass use by commercial and subsistence groups in western Uganda. Biodivers Conserv 34:232–241.

Nizeyi, J.B., R.B. Innocent, J. Erume, G.R. Kalema, M.R. Cranfield, and T.K. Graczyk. 2001. Campylobacteriosis, salmonellosis, and shigellosis in free-ranging human-habituated mountain gorillas of Uganda. J Wildl Dis 37:239–244.

Nizeyi, J.B., D. Sebunya, A.J. Dasilva, M.R. Cranfield, N.J. Pieniazek, and T.K. Graczyk. 2002. Cryptosporidiosis in people sharing habitats with free-ranging mountain gorillas (*Gorilla gorilla beringei*), Uganda. Am J Trop Med Hyg 66:442–444.

Oldewage-Theron, W.H., and R. Kruger. 2008. Food variety and dietary diversity as indicators of the dietary adequacy and health status of an elderly population in Sharpeville, South Africa. J Nutr Elder 27:101–133.

Onderdonk, D.A., and C.A. Chapman. 2000. Coping with forest fragmentation: The primates of Kibale National Park, Uganda. Int J Primatol 21:587–611.

Pariyo, G.W., E. Ekirapa-Kiracho, O. Okui, M.H. Rahman, S. Peterson, D.M. Bishai, H. Lucas, and D.H. Peters. 2009. Changes in utilization of health services among poor and rural residents in Uganda: are reforms benefitting the poor? Int J Equity Health 8:39.

Pedersen, A., and J. Davies. 2010. Cross species pathogen transmission and disease emergence in primates. EcoHealth 6:496–508.

Rapport, D. 1998. Defining ecosystem health. *In* D. Rapport, R. Costanza, P. Epstein, C. Gaudet, and R. Levins, eds. Ecosystem health, pp. 18–33. Blackwell Science, Inc. Malden, Massachusetts.

Rode, K.D., P.I. Chiyo, C.A. Chapman, and L.R. McDowell. 2006. Nutritional ecology of elephants in Kibale National Park, Uganda, and its relationship with crop-raiding behaviour. J Trop Ecol 22:441–449.

Rwego, I.B., T.R. Gillespie, G. Isabirye-Basuta, and T.L. Goldberg. 2008a. High rates of *Escherichia coli* transmission between livestock and humans in rural Uganda. J Clin Microbiol 46:3187–3191.

Rwego, I.B., G. Isabirye-Basuta, T.R. Gillespie, and T.L. Goldberg. 2008b. Gastrointestinal bacterial transmission among humans, mountain gorillas, and livestock in Bwindi impenetrable National Park, Uganda. Conserv Biol 22:1600–1607.

Rwego, I.B., G. Isabirye-Basuta, T.R. Gillespie, and T.L. Goldberg. 2009. Bacterial exchange between gorillas, humans, and livestock in Bwindi. Gorilla J 38:16–18.

Salzer, J.S., I.B. Rwego, T.L. Goldberg, M.S. Kuhlenschmidt, and T.R. Gillespie. 2007. *Giardia* sp. and Cryptosporidium sp. infections in primates in fragmented and undisturbed forest in western Uganda. J Parasitol 93:439–440.

Scrimshaw, N.S., and J.P. SanGiovanni. 1997. Synergism of nutrition, infection, and immunity: an overview. Am J Clin Nutr 66:S464–S477.

Struhsaker, T.T. 1997. Ecology of an African rain forest: logging in Kibale and the conflict between conservation and exploitation. University Press of Florida, Gainesville, Florida.

Taylor, R.G., L. Mileham, C. Tindimugaya, A. Majugu, A. Muwanga, and B. Nakileza. 2006. Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature. Geophys ResLett 33:doi:10/1029/2006GRL025962.

Trabulsi, L., R. Keller, and T. Tardelli-Gomes. 2002. Typical and atypical enteropathogenic *Escherichia coli*. Emerg Inf Dis 8:508–513.

van Orsdol, K.G. 1986. Agricultural encroachment in Uganda's Kibale Forest. Oryx 20:115–117.

Walsh, P.D., T. Breuer, C. Sanz, D. Morgan, and D. Doran-Sheehy. 2007. Potential for Ebola transmission between gorilla and chimpanzee social groups. Am Nat 169:684–689.

Wanyama, F., R. Muhabwe, A.J. Plumptre, C.A. Chapman, and J.M. Rothman. 2010. Censusing large mammals in Kibale National Park: evaluation of the intensity of sampling required to determine change. Afr J Ecol 48:953–961.

Wolfe, N.D., W.M. Switzer, J.K. Carr, V.B. Bhullar, V. Shanmugam, U. Tamoufe, A.T. Prosser, J.N. Torimiro, A. Wright, E. Mpoudi-Ngole, F.E. McCutchan, D.L. Birx, T.M. Folks, D.S. Burke, and W. Heneine. 2004. Naturally acquired simian retrovirus infections in central African hunters. Lancet 363: 932–937.

Wolfe, N.D., P. Daszak, A.M. Kilpatrick, and D.S. Burke. 2005a. Bushmeat hunting, deforestation, and predicting zoonotic emergence. Emerg Infect Dis 11:1822–1827.

Wolfe, N., W. Heneine, J.K. Carr, A.D. Garcia, V. Shanmugam, U. Tamoufe, J.N. Torimiro, A.T. Prosser, M. Lebreton, E. Mpoudi-Ngole, F.E. McCutchan, D.L. Birx, T.M. Folks, D.S. Burke, and W.M. Switzer. 2005b. Emergence of unique primate T-lymphotropic viruses among central African bushmeat hunters. Proc Natl Acad Sci USA 102:7994–7999.

World Health Organization. 1948. Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference, New York, 19–June 22, 1946; signed on July 22, 1946 by the representatives of 61 States (Official Records of the World Health Organization, no. 2, p. 100) and entered into force on April 7, 1948.