OPINION

Interdisciplinarity and Infectious Diseases: An Ebola Case Study

Vanessa O. Ezenwa1,*, Anne-Helene Prieur-Richard2, Benjamin Roche3, Xavier Bailly4, Pierre Becquart5, Gabriel E. García-Peña6,5, Parviz R. Hosseini7, Felicia Keesing8, Annapaola Rizzoli9, Gerardo Suzán10, Marco Vignuzzi11, Marion Vittecoq12, James N. Mills13, Jean-François Guégan9

1 Odum School of Ecology and Department of Infectious Diseases, College of Veterinary Medicine, University of Georgia, Athens, Georgia, United States of America, 2 DIVERSITAS, Muséum National d’Histoire Naturelle, Paris, France, 3 UMI IRD/UPMC 209 UMMISCO, Bondy, France, 4 INRA, UR346 Épidémiologie Animale, Saint Genès Champanelle, France, 5 UMR 5290 IRD-CNRS-Université de Montpellier, Centre IRD de Montpellier, Montpellier, France, 6 CESAB—Centre de Synthèse et d’Analyse sur la Biodiversité, Aix-en-Provence, France, 7 EcoHealth Alliance, New York, New York, United States of America, 8 Biology Program, Bard College, Annandale-on-Hudson, New York, United States of America, 9 Fondazione Edmund Mach, Department of Biodiversity and Molecular Ecology, San Michele all’Adige (TN), Italy, 10 Facultad de Medicina Veterinaria Zootecnia, Universidad Nacional Autónoma de México, Ciudad Universitaria, México, Distrito Federal, México, 11 Institut Pasteur, Viral Populations and Pathogenesis, CNRS UMR 3569, Paris, France, 12 Centre de recherche de la Tour du Valat, Le Sambuc, Arles, France, 13 Population Biology, Ecology, and Evolution Program, Emory University, Atlanta, Georgia, United States of America

* vezennwa@uga.edu

High-profile epidemics such as Ebola, avian influenza, and severe acute respiratory syndrome (SARS) repeatedly thrust infectious diseases into the limelight. Because the emergence of diseases involves so many factors, the need for interdisciplinary approaches to studying emerging infections, particularly those originating from animals (i.e., zoonoses), is frequently discussed [1–4]. However, effective integration across disciplines is challenging in practice. Ecological ideas, for example, are rarely considered in biomedical research, while insights from biomedicine are often neglected in ecological studies of infectious diseases. One practical reason for this is that researchers in these fields focus on vastly different scales of biological organization (Fig 1), which are difficult to bridge both intellectually and methodologically. Nevertheless, integration across biological scales is increasingly needed for solving the complex problems zoonotic diseases pose to human and animal well-being. Motivated by current events, we use Ebola virus as a case study to highlight fundamental questions about zoonoses that can be addressed by integrating insights and approaches across scales.

Ebola Severity: A Cell-to-Ecological Community Perspective

Zaire ebolavirus (EBOV), the virus responsible for the 2014 Ebola outbreak in West Africa, causes a deadly haemorrhagic disease in humans with case fatality rates ranging from 60%–88% [5]. Although well-known for its lethality, Ebola severity is variable at the individual level; some people die of infection, some survive, and some never develop symptoms [6–8]. Asymptomatic infection is poorly understood but may have important implications for how EBOV spreads. After a 1996 outbreak in Gabon, one study found that 45% of household contacts of symptomatic patients never developed disease symptoms despite becoming infected with the virus and mounting EBOV-specific immune responses [7]. Intriguingly, asymptomatic
infection might also result from contact between humans and animals. As an example, a 2010 serological survey of over 4,000 people from 220 villages in Gabon found that 15% of people overall, and 19% of those in forested regions, had EBOV-specific immunoglobulin G (IgG) antibodies [9]. Detection of EBOV-specific T cell responses in a subset of IgG+ individuals corroborated that these individuals were exposed to EBOV. Based on the known epidemiology of Ebola in Gabon, the authors ruled out human-to-human transmission as a sufficient explanation for the high antibody prevalence. Instead, they hypothesized that human–animal contact, specifically human contact with noninfectious virus particles in the environment (e.g., by eating or handling fruit contaminated with the saliva of infected bats), may have triggered virus-specific immune responses. If the immune responses detected in Gabon are protective against...
subsequent EBOV infection, large-scale phenomena occurring at the level of the ecological community might interact with molecular and cellular-level processes to influence the severity of any given Ebola outbreak.

Using an epidemiological model, Bellan et al. [10] showed that accounting for asymptomatic infections that induce protective immunity reduced Ebola incidence projections for Liberia by 50%. Ultimately, the relative frequency of protective asymptomatic infections determines the size of this effect. Although the model was predicated on asymptomatic infection occurring during human-to-human transmission, asymptomatic cases that arise from environmental exposure, as hypothesized by Becquart et al. [9], could have similar dampening effects on epidemic spread. The frequency of such environmental exposure would depend on the animal community in a region. If certain bat species are the natural reservoirs of EBOV [11], their presence, relative abundance, and behaviour could all affect the frequency with which humans come into contact with them and thereby develop “environmentally-induced” immune protection. Of course, human contact with bats also triggers Ebola outbreaks [12], so understanding the context in which human–bat contact is protective (e.g., induces asymptomatic infection and immunity) rather than hazardous (e.g., causes symptomatic infection and epidemic spread) requires investigating phenomena occurring in both humans and bats, from the drivers and frequency of contact between humans, bats, and other relevant species to the characteristics of host cell–virus interactions upon contact.

Ecosystem Dynamics, Viral Evolution, and Human Epidemics

The Ebola outbreak in West Africa and punctuated outbreaks in Central Africa since the 1970s raise fundamental questions about what drives disease spillover to humans. Ebola outbreaks are not limited to human populations. Wildlife die-offs occur routinely before or during human epidemics, indicating that the virus circulates in a range of other mammal species, including great apes and forest antelopes [13–16]. Even though these species are not considered natural reservoirs, circulation of EBOV in these animals still has implications for human disease. First, human contact with these species can directly trigger disease outbreaks [17]. Second, these animals might affect spillover risk by influencing rates of virus evolution. Phylogenetic analysis of EBOV in great apes [18] suggests that genetic variation can accumulate rapidly during EBOV transmission in these populations. Importantly, virus evolution in animal hosts may facilitate the emergence of strains that spread more efficiently to humans or that cause more severe disease.

Although unknown for EBOV, the idea that virus circulation in wild species can drive changes that impact human–virus interactions has support for other RNA viruses such as SARS coronavirus and influenza A virus (see Table 1) [19,20]. Given evidence from these other viruses, understanding if and how animal hosts affect EBOV evolution is crucial. Doing this requires studies that connect large-scale environmental and ecosystem processes to small-scale genetic and molecular processes. For example, food web or habitat structure may determine the diets of target wildlife species, and host nutrition could affect rates of infection, virus replication, and shedding. Likewise, contact rates among species determine levels of cross species virus transmission, which may influence virus mutation or recombination rates. These examples, though speculative, highlight how cross scale chains of events might influence disease emergence in humans.

Towards a More Integrative Future

The Ebola outbreak in West Africa reminds us that zoonotic diseases continue to be a major threat. The benefits of cross scale research are evident for several high-profile zoonoses
<table>
<thead>
<tr>
<th>Disease/Pathogen</th>
<th>Question(s)</th>
<th>Scales of Research</th>
<th>Key insights</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influenza / influenza A virus (global, 1800s–present)</td>
<td>What drives the emergence of pandemic strains?</td>
<td>Environment</td>
<td>In temperate regions, absolute humidity interacts with levels of susceptibility and human-to-human contact patterns to influence the timing of pandemic influenza outbreaks.</td>
<td>[20–24]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Population</td>
<td>The diversity of influenza virus strains circulating in bird populations is driven by both population mechanisms (transmission ecology) and pathogen characteristics (substitution rates).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gene</td>
<td>Pandemic virus strains in human populations have arisen from the introduction of genes from avian and swine influenza viruses.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Population</td>
<td>Specific individuals with disproportionately high contact rates (super spreaders) were responsible for a majority of virus transmission events in humans.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cell</td>
<td>Single amino acid substitutions in SARS-CoV of palm civet origin can enhance viral entry into human angiotensin-converting enzyme 2 (ACE2) receptor-expressing cells.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gene</td>
<td>The receptor binding domain of the SARS-CoV Spike protein underwent rapid evolution in nonreservoir “intermediate” hosts such as palm civets, potentially facilitating virus transmission to humans.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Population/ individual</td>
<td>Temporal and spatial pulses of virus shedding in bats may be influenced by individual host traits such as nutritional stress or reproductive status. The amount of virus released in any area is a function of local bat density and the shedding status of individual bats in the population.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cell</td>
<td>Only a subset of exposed horses are identified as spillover cases. Upon exposure, some horses eliminate infection with a strong innate immune response and some mount an acquired response after asymptomatic infection or clinical disease, while others experience fulminating infection.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Population</td>
<td>Rodent reservoir populations greatly increased in size as a result of improved food availability.</td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
Nevertheless, this type of work is far from the norm, and successful integration of research approaches across vastly different biological scales remains challenging. A first step toward greater integration involves student training. Training programs in infectious disease typically focus on a single or narrow range of biological scales, but more crosscutting approaches are needed. Training grants focused on multiscale literacy in infectious disease research should be a priority for funding agencies, for example. Professional societies could also lead the way by sponsoring workshops, symposia, and other events on integration across disciplines. The involvement of professional societies has the added benefit of allowing infectious disease researchers to expand their perspectives beyond their years of formal training. Updating our collective mind-set in these and other ways will put us in a much better position to tackle the next zoonotic disease threat.

**References**


tigation of severe acute respiratory syndrome coronavirus-like virus in palm civets at an animal market
PMID: 15695582
325–344. PMID: 17848070
Arch Virol Suppl: 45–57. PMID: 16355867
host diversity and community composition on Lyme disease risk. Proc Natl Acad Sci USA 100: 567–
571. PMID: 12525705
37. Schwanz LE, Voordouw MJ, Brisson D, Ostfeld RS (2011) Borrelia burgdorferi has minimal impact on
the Lyme disease reservoir host Peromyscus leucopus. Vector Borne Zoonotic Dis 11: 117–124. doi:
10.1089/vbz.2009.0215 PMID: 20569016
38. Hersh MH, LaDeau SL, Previtali MA, Ostfeld RS (2014) When is a parasite not a parasite? Effects of
larval tick burdens on white-footed mouse survival. Ecology 95:1360–1369. PMID: 25000767