Conservation implications of disease control

Julia C Buck[1,*], Sara B Weinstein[2], Georgia Titcomb[3], and Hillary S Young[3]

Infectious diseases have indelibly altered human history and, in doing so, have shaped the ecology and conservation of the natural world. Attempts to control diseases often result in adverse environmental impacts, including habitat degradation and unintended outcomes such as effects on non-target species. However, in instances where the most effective strategy is to physically avoid specific species or habitats, disease can also provide critical de facto conservation benefits to organisms and ecosystems. Increasingly, new genome-editing technologies offer the potential to eradicate long-term health scourges, which disproportionately affect people in developing countries. It will be critical to incorporate an understanding of the ecological consequences of disease control – including those mediated by changes in human behavior – into management strategies, and to do so without propagating environmental injustice. In this way, scientists, resource managers, and health practitioners can help to ensure that gains for human health do not result in losses for the natural world.

Front Ecol Environ 2020; 18(6):329–334, doi:10.1002/fee.2215

Across kingdoms of life, organisms avoid infectious agents when it is feasible to do so and when the benefits of remaining disease-free outweigh the costs of avoidance. These behaviors can have major impacts at all levels of ecological organization (Buck *et al.* 2018; Weinstein *et al.* 2018). Humans also avoid infectious agents (Curtis 2014), and as the most impactful creature on the planet, our disease avoidance behaviors can have correspondingly immense effects on ecosystems. Whereas most organisms must choose to either avoid an infectious agent or continue their normal behaviors and risk exposure, human ingenuity allows us to employ a unique third strategy – to target the infectious agent, its non-human hosts, or its ecosystem for eradication. Now accomplished mainly through the development and administration of medication (including vaccines), disease control has historically involved a substantial amount of habitat modification and destruction, pesticide and poison application, and mass culling of affected species (WebTable 1). For example, extensive killing of raccoons, foxes, bats, and badgers has been largely ineffective at controlling rabies and bovine tuberculosis (Donnelly *et al.* 2003; Lederman 2016). Despite its well-documented environmental impacts, the insecticide DDT continues to be used to control the mosquitoes that transmit malaria (WHO 2011). Following recent Ebola and Marburg virus outbreaks, attempts to eliminate reservoir species included cave fumigation, poisoned bait distribution, and forest destruction (Amman *et al.* 2014; Egbetade *et al.* 2015). Even purportedly ecofriendly methods can have severe ecological impacts. For instance, mosquitofish (*Gambusia* spp), widely introduced to control virus-carrying mosquitoes, are now implicated in population declines of fishes, amphibians, and invertebrates globally (Pyke 2008). As such examples illustrate, human efforts to eradicate disease often have major environmental consequences.

In a nutshell:

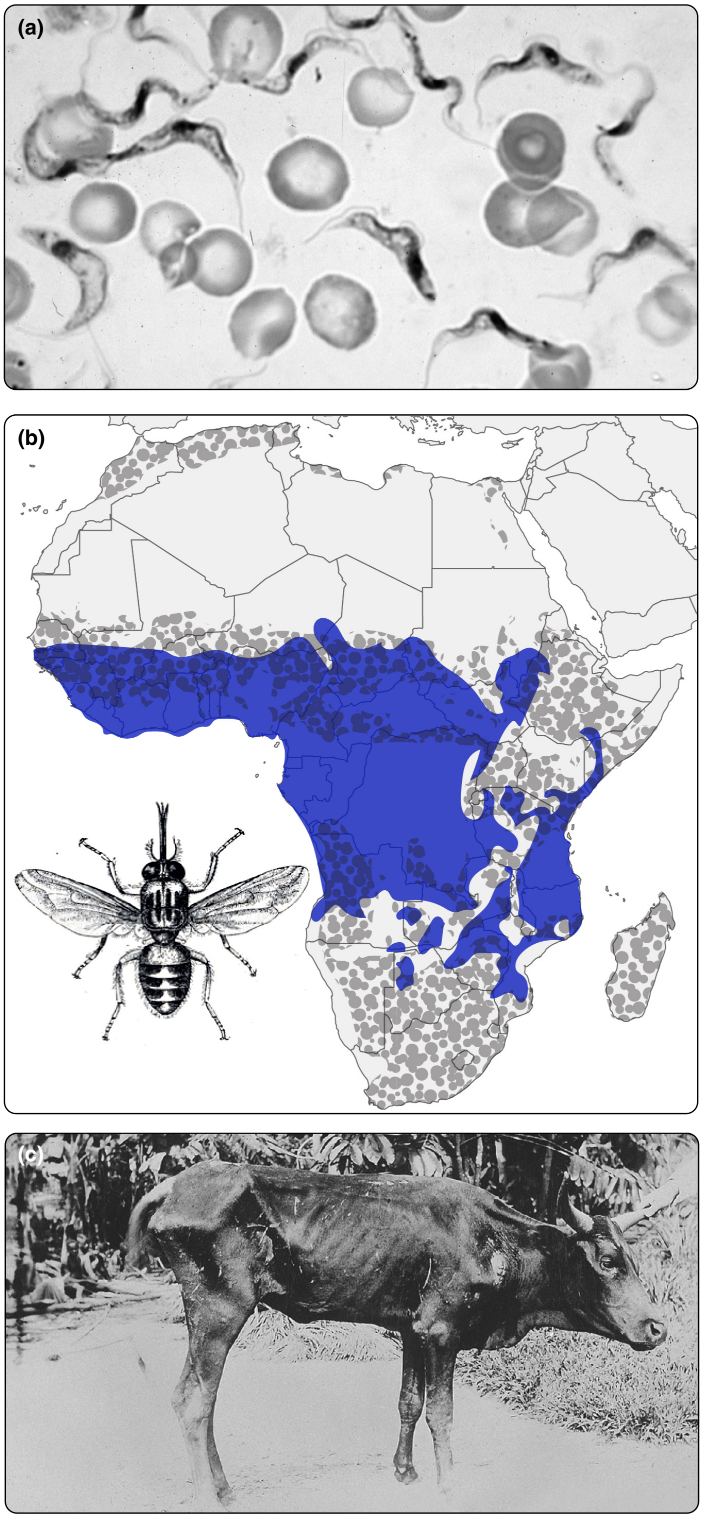
- Throughout recorded history, humans have avoided species and ecosystems associated with infectious disease, sometimes providing unexpected conservation benefits
- Disease control efforts can erode such benefits; for instance, in sub-Saharan Africa, efforts to control the parasite that causes river blindness have disturbed sensitive riparian areas
- Genome-editing technologies now hold the potential to eradicate long-standing scourges of humanity; while these innovations are a boon for human health, altered human behavior following successful disease control could have negative impacts on the natural world
- Disease control efforts must take potential environmental outcomes into account, including those likely to be caused by changes in human behavior
- By incorporating disease risk into development plans, scientists can better ensure equitable and sustainable progress

However, when humans avoid disease instead of seeking to eradicate it, this behavior can provide de facto environmental protection. For this to occur, perceived risk must be high enough to alter the way humans interact with species or habitats of conservation value, and disease control must be economically or socially impracticable. The object of avoidance can range from an individual organism to an ecosystem, resulting in protection at different scales. Taboos and cultural prohibitions against harvesting specific animals often have origins in disease transmission and can confer protection to focal species (eg Jones *et al.* 2008). For instance, during the recent Ebola virus outbreak in West Africa, bushmeat con-

---

[1] *Department of Biology and Marine Biology, University of North Carolina–Wilmington, Wilmington, NC *(buckj@uncw.edu); [2] School of Biological Sciences, University of Utah, Salt Lake City, UT; [3] Department of Ecology, Evolution, and Marine Biology, University of California–Santa Barbara, Santa Barbara, CA*

sumption decreased across all income levels (Ordaz-Nemeth *et al.* 2017). After the recent outbreak of SARS-CoV-2 ("COVID-19"), China banned wildlife trade and consumption in an effort to prevent future pathogen spillover events (*Science* 2020). Although laws targeting the wildlife trade have been enacted previously, public buy-in – motivated by pathogen avoidance – could make this attempt successful, with accompanying conservation benefits to numerous threatened species. At larger scales, disease avoidance can protect entire habitats. For example, eye gnats (*Hippelates pusio*), which spread conjunctivitis, delayed the development of the Coachella Valley in California (Hall 1932). Diseases need not infect humans to provide conservation benefits. For instance, the widespread distribution of nagana (animal trypanosomiasis) across the tsetse belt (associated with tsetse flies [*Glossina* spp]) of sub-Saharan Africa has hindered large-scale agricultural and pastoral development and promoted lower intensity nomadism throughout this region (Figure 1; Rogers and Randolph 1988). However, while disease avoidance can protect species and habitats, these protections are not immutable.



AR Walker

Wellcome Collection

Figure 1. In sub-Saharan Africa, (a) trypanosomes are transmitted by (b, inset) tsetse flies (*Glossina* spp) to humans and livestock, causing human sleeping sickness and (c) nagana (animal trypanosomiasis), respectively. Throughout human history, these diseases have prevented development in the region, thereby providing conservation benefits. Map in (b): cattle distribution shown in gray stippling, based on Hanotte *et al.* (2002); tsetse fly distribution shown in blue, based on Gifford-Gonzalez (2000). Image in (c) used under CC BY 4.0 (creativecommons.org/licenses/by/4.0).

Factors influencing ecological consequences

When risk is associated with a species or habitat, disease avoidance by humans appears to have threshold effects on conservation that depend on (1) the perceived human cost of the disease, and (2) the technical, economic, and social feasibility of disease control (Figure 2). The human cost, which is a function of disease severity and the number of people affected, varies widely between infectious agents. When human cost is low, due to either low pathogenicity (severity; eg trombiculiasis from North American chiggers [*Trombicula* spp]) or low prevalence (eg angiostrongyliasis from rat lungworm [*Angiostrongylus cantonensis*]), inaction, individual medication, and minor behavioral modifications usually dominate, resulting in minimal conservation impacts. In contrast, when human cost is high (eg malaria, COVID-19), attempts to reduce exposure lead to either disease avoidance or disease control, with conservation implications that depend on the feasibility of the latter. Whether or not a disease can be controlled is a function of technical feasibility (the ability to identify and manage the disease source) and the resources and community support necessary to implement control efforts. When knowledge of the control efforts improves or when costs associated with control efforts change, the conservation benefits of disease can rapidly disappear or even reverse (Figure 3). For example, mosquito-borne diseases thwarted early attempts to construct the Panama Canal in what was at the time pristine wetland habitat. However, in 1897, Ronald Ross discovered that mosquitoes are the primary vectors of the protozoan parasites that cause malaria. With a newly identified control target and financial support from the US Government, the Isthmian Canal Commission (the US administrative commission overseeing construction of the Canal) eliminated standing water, fumigated buildings, distributed quinine, and quarantined infected individuals (CDC 2017). These efforts made possible the completion of the Panama Canal, resulting in extensive habitat destruction.

Notably, the conservation benefits of disease can reverse due to changes in the feasibility of control, even when such control does not directly harm hosts or ecosystems. For example, river blindness (onchocerciasis), which is vectored by river-breeding black flies (*Simulium* spp), limited settlement and farming in sensitive riparian habitats across much of sub-Saharan Africa until the relatively recent discovery and distribution of the anthelmintic ivermectin (Amazigo *et al.* 2006). Through drug distribution and carefully monitored larvicide application, river blindness was successfully controlled with minimal direct environmental consequences. However, in eliminating the disease threat, control efforts also eliminated protection of biodiverse riparian areas, which are now heavily populated, extensively deforested, and intensively farmed (Calamari *et al.* 1998).

Technological advancements

Understanding the conservation implications of disease avoidance is critical because humanity's technological arsenal is rapidly changing in ways that could greatly alter conservation outcomes. Historically, disease control was facilitated by advances such as the elucidation of life cycles and the development of pesticides. More recently, *Wolbachia*-infected mosquitoes, which are less likely to transmit mosquito-borne diseases than their uninfected counterparts, have been intentionally released in several countries, with promising results (Servick 2019). Now, a new wave of interventions is on the horizon, with genome-editing tools providing the potential to eradicate once-common infectious agents, hosts, and vectors (Eckhoff *et al.* 2017; Lovett *et al.* 2019). For example, researchers have used the CRISPR–Cas9 genome-editing technique to "drive" genes for sterility and malaria resistance into laboratory populations of mosquitoes. Because these genes are reliably passed to progeny, such modifications could rapidly limit mosquito populations in the wild, possibly to the extent that malaria transmission will no longer occur (Gantz *et al.* 2015; Hammond *et al.* 2016). Other genetic engineering projects have proposed to make white-footed mice (*Peromyscus leucopus*) resistant to Lyme disease (Buchthal *et al.* 2019), to increase drug susceptibility in *Cryptosporidium* (Vinayak *et al.* 2015), and to target other infectious agents of importance to human health, such as *Leishmania*, *Trypanosoma cruzi*, and *Toxoplasma gondii* (Bryant *et al.* 2019). As such, scientists may soon possess the tools necessary to eliminate diseases that have plagued humans throughout our evolutionary history.

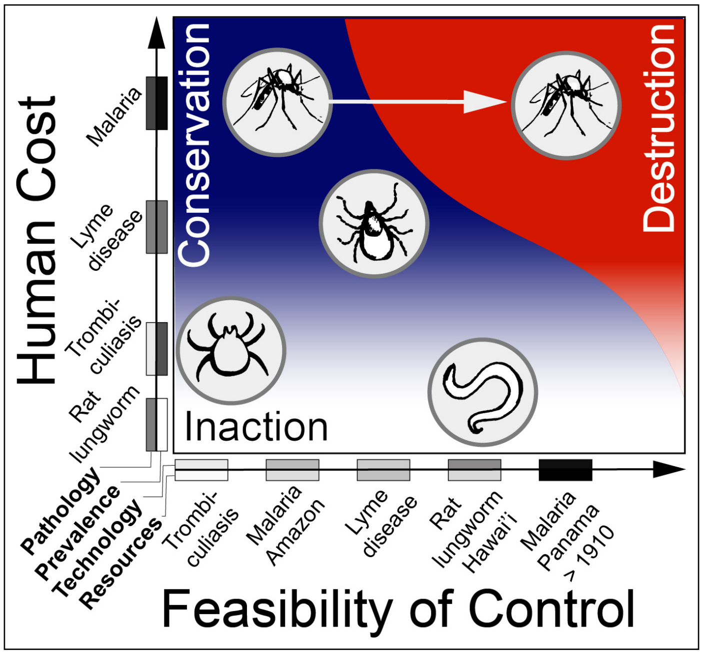


Figure 2. When the cost of a disease is high (due to high pathogenicity and/or prevalence), humans take action to avoid that disease. For depicted diseases, increasingly dark shading in boxes along the y axis corresponds to increasing pathology and prevalence, and increasingly dark shading in boxes along the x axis represents increasing levels of technology and resources needed for control. Whether that action results in conservation (blue) or destruction (red) of species or habitats depends on the feasibility of control (availability of technology and resources). With new technological innovations, diseases that once conferred de facto conservation protection may now instead drive destruction of species or habitats.

Although these technological innovations promise to be more like a delicate scalpel than the heavy-handed cudgel of DDT and wetland destruction of the past, they will nonetheless have major environmental impacts. Previous authors have examined the consequences of escape (ie the accidental release of genetically modified organisms; Webber *et al.* 2015; Courtier-Orgogozo *et al.* 2017) and potential impacts mediated by changes to food webs (eg Webber *et al.* 2015; Snow 2019), but here we consider consequences mediated by changes in human behavior. For example, eliminating the threat of malaria could hasten development in the Amazon Basin (MacDonald and Mordecai 2019), as have disease control efforts in the past (Griffing *et al.* 2015). Similarly, eliminating Lyme disease in the eastern US could incentivize development by increasing property values (Larsen *et al.* 2014). Yet despite the vast potential for ecological repercussions, these considerations have been largely ignored in discussions of the promises and perils of these new approaches. Before such interventions are attempted, biotechnologists should consult with local stakeholders and ecologists to carefully examine potential environmental impacts, including those likely to be caused by the resulting changes in human behavior and development.

M Luo

Figure 3. Disease avoidance can drive either conservation or large-scale biodiversity loss. For example, wetlands were long considered "uninhabitable" based on high disease risk and were therefore largely spared from development pressure. However, as mosquito control became technologically feasible (eg via wetland modification and DDT application), severe ecological consequences ensued, with destruction ceasing only when the conservation costs of these management strategies became widely recognized and environmental protection was codified into law.

Equity considerations

Conversations about trade-offs between health and conservation must also consider equity. Throughout human history, disease avoidance has often been a privilege reserved for the wealthy. For example, during the 1800s, cholera outbreaks disproportionately affected poor people who were unable to avoid contaminated water (Evans 1988). Efforts to stem the trade and consumption of wildlife often disproportionately affect the poor who depend on bushmeat for protein or who harvest wildlife and lack other sources of income (Brashares *et al.* 2011). At a global scale, the burden of infectious diseases is currently unevenly distributed, with people living in low-income countries in the tropics and sub-tropics particularly vulnerable (Bonds *et al.* 2012; Wood *et al.* 2017). Indeed, poverty and infectious disease can even reinforce one another, a relationship termed the "poverty trap" (Bonds *et al.* 2010). Current differences in infectious disease burdens reflect a long history of disparities on a global scale. Technological advancements to control disease have not been uniformly or equitably distributed, and conservation efforts in developing countries have often amounted to colonialism, perhaps even contributing to negative health outcomes for Indigenous peoples (Adams *et al.* 2004; Fairhead *et al.* 2012). Efforts to target diseases in under-resourced locations therefore hold the greatest potential to improve livelihoods and reduce economic inequality. These projects must continue to move forward because health justice in the developing world is non-negotiable. Nevertheless, due to substantial overlap between biodiversity, disease burden, and poverty (Figure 4), these advancements could simultaneously increase pressure to develop areas of conservation value. Early recognition of the potential impacts of these projects could allow scientists and policy makers to plan for and mitigate any negative impacts before they occur. Instead of affirming narratives that frame poverty and human suffering as an acceptable price for leaving nature intact, ecologists should incorporate disease risk into development plans to limit the creation of new poverty traps, while also buffering against loss of conservation protection. Partnerships between local communities, governments, scientists, conservation organizations, and health organizations that also consider the consequences of changes in human behavior will be critical for reducing disease burdens while at the same time ensuring equitable and sustainable development. In Borneo, for instance, the non-profit Health in Harmony provides high-quality, affordable healthcare to residents of 23 villages around Gunung Palung National Park, thereby reducing incentives for villagers to engage in illegal logging (Webb *et al.* 2018). This project demonstrates how human health initiatives can be tied to conservation goals to provide win–win solutions for people and nature.

Conclusions

Through technological advancements, disease, once considered by colonial powers as "a striking angel with a flaming sword of deadly fevers, who prevents us from penetrating into the interior to the springs of this garden" (de Barros 1552), is steadily losing its protective power. While we applaud new innovations to protect human health, it must also be acknowledged that these changes will have major ramifications for conservation, as they have throughout human history. To better ensure that these long-awaited gains for human health do not result in substantial losses for the natural world (and ultimately for humans, whose continued existence depends on critical ecosystem services), ecologists need to recognize the previously underappreciated conservation impacts of disease eradication and proactively manage for a world where de facto conservation benefits are no longer provided by infectious disease.

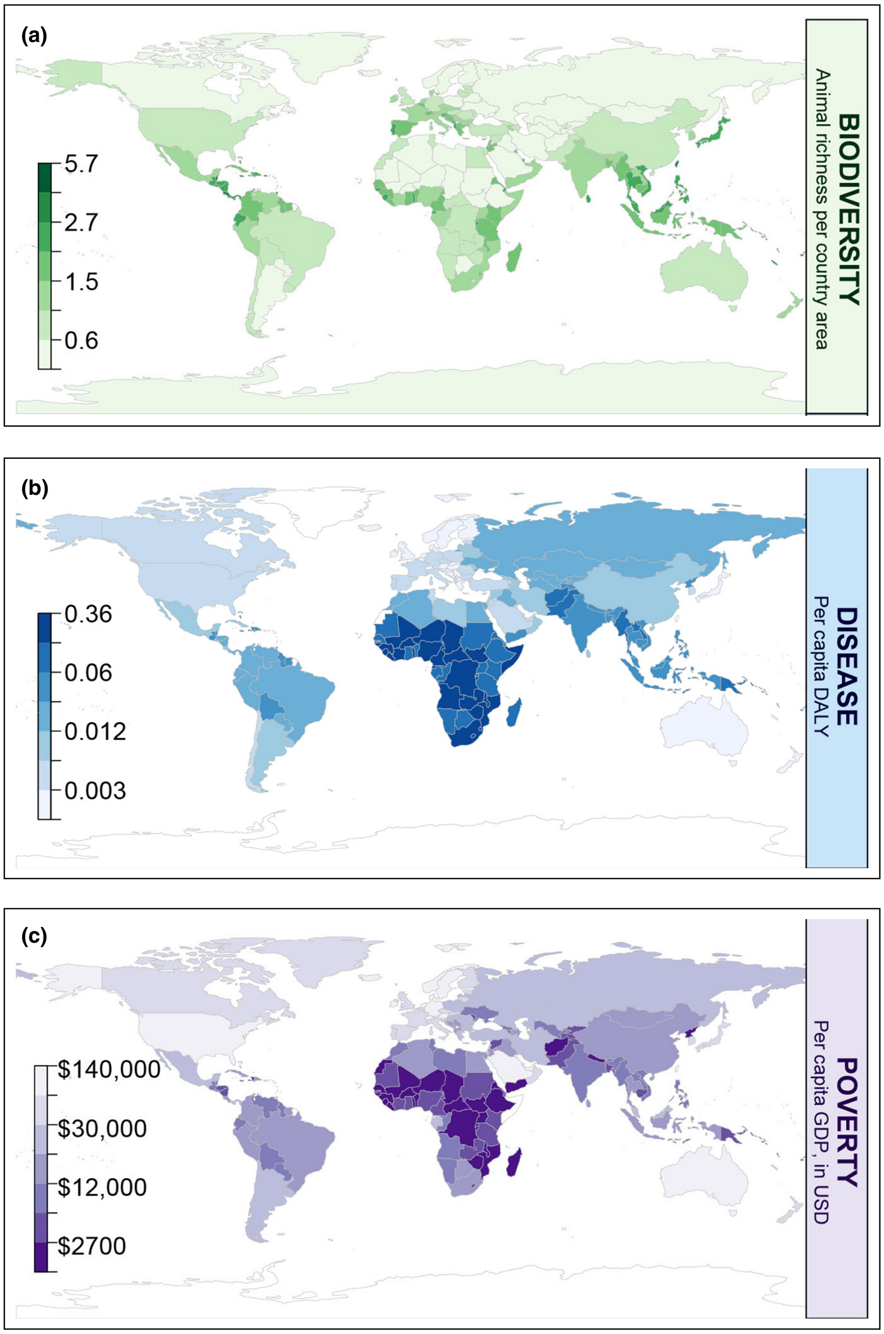


Figure 4. The overlap between biodiversity, disease burden, and poverty. (a) Biodiversity, measured as per country estimated animal (vertebrate and invertebrate) species richness (IUCN 2019) scaled by country area (CIA 2019). These species richness estimates likely underestimate biodiversity, particularly for invertebrates in the tropics. (b) Disease burden, measured as per-capita disability adjusted life years (DALY) caused by "Infectious and Parasitic Diseases" (WHO 2017). (c) Poverty, measured as per capita gross domestic product (GDP; CIA 2017). All metrics are calculated at the country level, recognizing that this may obscure complex local patterns.

Acknowledgements

We thank J Childress, C Carlson, and A Lund for useful discussions and comments on the manuscript. We thank the NCEAS SNAPP Ecological Levers for Health working group for providing data on disease burden. SBW's participation was supported by NIH T32AI055434 from the NIAID.

References

Adams WM, Aveling R, Brockington D, *et al*. 2004. Biodiversity conservation and the eradication of poverty. *Science* **306**: 1146–49.

Amazigo U, Noma M, Bump J, *et al*. 2006. Onchocerciasis. In: Jamison DT, Feachem RG, Makgoba MW, *et al*. (Eds). Disease and mortality in sub-Saharan Africa. Washington, DC: World Bank.

Amman B, Nyakarahuka L, McElroy AK, *et al*. 2014. Marburgvirus resurgence in Kitaka Mine bat population after extermination attempts, Uganda. *Emerg Infect Dis* **20**: 1761–64.

Bonds MH, Dobson AP, and Keenan DC. 2012. Disease ecology, biodiversity, and the latitudinal gradient in income. *PLoS Biol* **10**: e1001456.

Bonds MH, Keenan DC, Rohani P, and Sachs JD. 2010. Poverty trap formed by the ecology of infectious diseases. *P Roy Soc B-Biol Sci* **277**: 1185–92.

Brashares JS, Golden CD, Weinbaum KZ, *et al*. 2011. Economic and geographic drivers of wildlife consumption in rural Africa. *P Natl Acad Sci USA* **108**: 13931–36.

Bryant JM, Baumgarten S, Glover L, *et al*. 2019. CRISPR in parasitology: not exactly cut and dried! *Trends Parasitol* **35**: 409–22.

Buchthal J, Evans SW, Lunshof J, *et al*. 2019. Mice against ticks: an experimental community-guided effort to prevent tick-borne disease by altering the shared environment. *Philos T Roy Soc B* **374**: 20180105.

Buck JC, Weinstein SB, and Young HS. 2018. Ecological and evolutionary consequences of parasite avoidance. *Trends Ecol Evol* **33**: 619–32.

Calamari D, Yameogo L, Hougard JM, and Leveque C. 1998. Environmental assessment of larvicide use in the onchocerciasis control programme. *Parasitol Today* **14**: 485–89.

CDC (Centers for Disease Control and Prevention). 2017. The Panama Canal. Atlanta, GA: CDC. https://www.cdc.gov/malaria/about/history/panama_canal.html. Viewed 13 Jan 2020.

CIA (Central Intelligence Agency). 2017. Country comparison: GDP – per capita (PPP). Langley, VA: CIA. https://bit.ly/36JDOSY. Viewed 13 Jan 2020.

CIA (Central Intelligence Agency). 2019. Country comparison: area. Langley, VA: CIA. https://bit.ly/3cf3Uyb. Viewed 13 Jan 2020.

Courtier-Orgogozo V, Morizot B, and Boëte C. 2017. Agricultural pest control with CRISPR-based gene drive: time for public debate. *EMBO Rep* **18**: 878–80.

Curtis VA. 2014. Infection-avoidance behaviour in humans and other animals. *Trends Immunol* **35**: 457–64.

de Barros J. 1552. Primeira decada da Asia. Lisbon, Portugal.

Donnelly CA, Woodroffe R, Cox DR, *et al.* 2003. Impact of localized badger culling on tuberculosis incidence in British cattle. *Nature* **426**: 834–37.

Eckhoff PA, Wenger EA, Godfray HCJ, and Burt A. 2017. Impact of mosquito gene drive on malaria elimination in a computational model with explicit spatial and temporal dynamics. *P Natl Acad Sci USA* **114**: E255–64.

Egbetade AO, Sonibare AO, Meseko CA, *et al.* 2015. Implications of Ebola virus disease on wildlife conservation in Nigeria. *Pan African Med J* **22**: 16.

Evans RJ. 1988. Epidemics and revolutions: cholera in nineteenth-century Europe. *Past Present* **120**: 123–46.

Fairhead J, Leach M, and Scoones I. 2012. Green grabbing: a new appropriation of nature? *J Peasant Stud* **39**: 237–61.

Gantz VM, Jasinskiene N, Tatarenkova O, *et al.* 2015. Highly efficient Cas9-mediated gene drive for population modification of the malaria vector mosquito *Anopheles stephensi*. *P Natl Acad Sci USA* **112**: E6736–43.

Gifford-Gonzalez D. 2000. Animal disease challenges to the emergence of pastoralism in sub-Saharan Africa. *Afr Archaeol Rev* **17**: 95–139.

Griffing SM, Tauil PL, Udhayakumar V, and Silva-Flannery L. 2015. A historical perspective on malaria control in Brazil. *Mem I Oswaldo Cruz* **110**: 701–18.

Hall DG. 1932. Some studies on the breeding media, development, and stages of the eye gnat *Hippelates pusio* Loew (Diptera: Chloropidae). *Am J Epidemiol* **16**: 854–64.

Hammond A, Galizi R, Kyrou K, *et al.* 2016. A CRISPR-Cas9 gene drive system targeting female reproduction in the malaria mosquito vector *Anopheles gambiae*. *Nat Biotechnol* **34**: 78–83.

Hanotte O, Bradley DG, Ochieng JW, *et al.* 2002. African pastoralism: genetic imprints of origins and migrations. *Science* **296**: 336–39.

IUCN (International Union for Conservation of Nature). 2019. The IUCN Red List of Threatened Species, v2019–2. Gland, Switzerland: IUCN.

Jones JPG, Andriamarovololona MM, and Hockley N. 2008. The importance of taboos and social norms to conservation in Madagascar. *Conserv Biol* **22**: 976–86.

Larsen AE, MacDonald AJ, and Plantinga AJ. 2014. Lyme disease risk influences human settlement in the wildland–urban interface: evidence from a longitudinal analysis of counties in the northeastern United States. *Am J Trop Med Hyg* **91**: 747–55.

Lederman Z. 2016. One Health and culling as a public health measure. *Public Health Eth-UK* **9**: 5–23.

Lovett B, Bilgo E, Millogo SA, *et al.* 2019. Transgenic *Metarhizium* rapidly kills mosquitoes in a malaria-endemic region of Burkina Faso. *Science* **364**: 894–97.

MacDonald AJ and Mordecai EA. 2019. Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *P Natl Acad Sci USA* **116**: 22212–18.

Ordaz-Nemeth I, Arandjelovic M, Boesch L, *et al.* 2017. The socio-economic drivers of bushmeat consumption during the West African Ebola crisis. *PLoS Neglect Trop D* **11**: e0005450.

Pyke GH. 2008. Plague minnow or mosquito fish? A review of the biology and impacts of introduced *Gambusia* species. *Annu Rev Ecol Evol S* **39**: 171–91.

Rogers DJ and Randolph SE. 1988. Tsetse flies in Africa: bane or boon? *Conserv Biol* **2**: 57–65.

Science. 2020. In brief. News at a glance. China bans wildlife trade. *Science* **367**: 960. 28 Feb; doi.org/10.1126/science.367.6481.960.

Servick K. 2019. Mosquitoes armed with bacteria beat back dengue virus. https://www.sciencemag.org/news/2019/11/mosquitoes-armed-bacteria-beat-back-dengue-virus. Viewed 13 Jan 2020.

Snow AA. 2019. Genetically engineering wild mice to combat Lyme disease: an ecological perspective. *BioScience* **69**: 746–56.

Vinayak S, Pawlowic MC, Sateriale A, *et al.* 2015. Genetic modification of the diarrhoeal pathogen *Cryptosporidium parvum*. *Nature* **523**: 477–80.

Webb K, Jennings J, and Minovi D. 2018. A community-based approach integrating conservation, livelihoods, and health care in Indonesian Borneo. *Lancet Planetary Health* **2**: S26.

Webber BL, Raghu S, and Edwards OR. 2015. Opinion: is CRISPR-based gene drive a biocontrol silver bullet or global conservation threat? *P Natl Acad Sci USA* **112**: 10565–67.

Weinstein SB, Buck JC, and Young HS. 2018. A landscape of disgust. *Science* **359**: 1213–14.

WHO (World Health Organization). 2011. The use of DDT in malaria vector control. Geneva, Switzerland: WHO.

WHO (World Health Organization). 2017. WHO methods and data sources for global burden of disease estimates 2000–2015. Geneva, Switzerland: WHO.

Wood CL, McInturff A, Young HS, *et al.* 2017. Human infectious disease burdens decrease with urbanization but not with biodiversity. *Philos T Roy Soc B* **372**: 20160122.

Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.2215/suppinfo