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.

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.

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-
Consumption 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.

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

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).
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.

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.
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.

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**References**


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/supportinfo