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COMMENTARY

The role of infectious disease in the loss of biodiversity

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Discussion of the relationship of infectious disease and biodiversity loss most commonly is framed in terms of the impact of diminishing biodiversity on zoonotic diseases among humans. This concern has been propelled in recent decades by a cascade of zoonotic epidemics and pandemics including AIDS, Ebola, SARS, MERS, and COVID-19 [1]. Less examined is the role of infectious disease as a direct driver of biodiversity loss through species declines, local extirpations, and global extinctions. As Magnet and Izquierdo [2] stress, "Infections can lead to the extinction or the decline of specific populations of vertebrates and invertebrates. The impact of infectious diseases on the wildlife population has been significant, leading to a loss of biodiversity and ecosystem services." Furthermore, recent studies suggest that infectious diseases in wildlife populations are emerging at notably high rates. The diversity of emerging infectious diseases, magnified by the likelihood that there will be an increased frequency of outbreaks over time, have raised concern that infectious disease may play a strong role in wildlife species extinctions [3]. The purpose of this Commentary is to draw attention to the growing role infectious pathogens are having in wild animal biodiversity loss and ecosystem disruption, changes which, in turn, rebound on human health and wellbeing.

Infectious diseases can cause population declines in species by reducing maturation and development, ecological fitness (including ability to cope with change), and survival of their hosts. Infectious agents constitute a particular risk to already threatened and endangered species. In some cases, infectious disease may tip the balance to extinction or extirpation in species hard hit by anthropomorphic environmental and climatic disruptions. Marine turtles, for example, currently classified into seven living species, play fundamental roles in two different ecosystems: the ocean system and the beach and lower dune system [4–6]. In the former ecosystem, grazing by species like the endangered green turtle (*Chelonia mydas*) helps keep seagrass beds healthy, leatherbacks (*Dermochelys coriacea*) contribute to the management of the number of jellyfish in the ocean, while critically endangered hawksbills (*Eretmochelys* imbricata) support reefs by eating sponges that compete with coral for space. In the latter ecosystem, nesting sea turtles contribute to beach preservation through egg laying. Eggshells and unhatched eggs offer nutrients that support dune vegetation, such as beach grasses. The deep roots of beach grass are critical in stabilizing dunes and helping to slow down waves and limit coastal erosion. Most existing dune research suggests that greater size, density, and diversity of beach vegetation are associated with less erosion, except, perhaps, during extreme weather events [7]. Sea turtle hatchlings are an important seasonal source of food for various species, including fish, birds, crabs, and mammals like racoons and foxes. Sea turtles, however, are seriously endangered by anthropogenic factors including climate change and temperature increase, chemical pollution, entanglement in fishing gear, boat strikes, plastic ingestion, coastal development, predation of eggs, meat, and shells (especially in Central America and Asia), and illegal trade (e.g., hawksbill shells). These factors increase vulnerability to opportunistic infectious and parasitic diseases that push sea turtles closer to extinction. Currently, six out of the seven sea turtle species are on the International Union for Conservation of Nature (IUCN) Red List of endangered species.

Beyond a few publicized examples, the impact of infectious disease is probably underestimated as a cause of both local and global extinction. This is because infection often co-occurs with other more visible drivers of extinction, and signs of infection can be easily overlooked. Sometimes, however, extinctions occur that leaves traces of the role of infection. For example, over ten species of land birds in Hawaii disappeared near the turn of the 20th century. This loss coincided with the first detection of avian malaria *Plasmodium relictum* on the islands. Although testing the susceptibility of extinct birds to malaria is not possible, several otherwise missing species still persist at high altitudes, areas that are too cold for *Culex quinquefasciatus* the mosquito vector involved in Hawaiian malaria transmission. Moreover, avian pox, a viral infection, also spread by C. quinquefasciatus, has had additional significant adverse impact on native Hawaiian bird fauna [8]. In other cases, such as facial tumor disease, a transmissible parasite-linked cancer that has killed the majority of Tasmanian devils (*Sarcophilus harrisii*) [9]; white-nose syndrome, a deadly fungal disease caused by *Pseudogymnoascus destructans* that has decimated North American bat populations during hibernation [10]; and chytridiomycosis, a fungal skin disease spread by *Batrachochytrium dendrobatidium* and *Batrachochytrium salamandrivorans,* that is responsible for significant population declines and, in some cases, extinctions in hundreds of amphibian species worldwide [11], infectious diseases pose uncontested but also understudied threat to biodiversity.

A common pattern of wild animal/infectious disease interaction is illustrated by the Mediterranean population of striped dolphins (*Stenella coeruleoalba*) which are deemed to be a vulnerable species on the IUCN Red List of Threatened Species. While the majority of epidemiological studies focus on terrestrial animals, there are also significant biodiversity issues facing aquatic creatures. Morbillivirus has been responsible for major epizootic diseases in various cetaceans, causing many of the largest mass die-offs worldwide. The Mediterranean population of striped dolphins has suffered severe depletion since two cetacean morbillivirus-linked die-offs occurred in 1990-1992 and 2006-2008, impactful events from which these dolphins have not recovered. While human activity, such as release of contaminants and over-fishing of prey fish, is linked to susceptibility to morbillivirus infection, further depletion after the die-offs is associated with ongoing threats from pollutants and drift net bycatch [12, 13]. Confirmation of morbillivirus is based on necropsy and sample collection performed in beach-stranded animals.

Similarly, many local populations of koala (*Phascolarctos cinereus*) are affected by the sexually transmitted infectious disease chlamydia (caused two bacteria, *Chlamydia pecorum* and *Chlamydia pneumoniae*). Infection is linked to pneumonia, infertility, blindness, severe bladder inflammation, and death in koalas. Infected animals may have difficult moving around and finding food. Chlamydia is considered one of the most impactful infectious diseases among koalas, affecting between 20% and 90% of koala populations across Australia. Existing research suggests chlamydia is particularly important in combination with multiple stressors, such as habitat loss and fragmentation, dog attacks, bushfires and climate change, all threats emanating from human activities [14].

An alternative pattern involves human-to-animal infectious disease transmission, a threat, for example, to African great ape populations. Over the last several decades, both eastern and western gorilla populations have suffered loses estimated to be more than 70% and 80%, respectively. Habit loss, due to agriculture, forestry and deforestation, road building, mining, and human settlements, and climate change have been highlighted as the primary drivers of this devastating decline. Less studied are respiratory diseases of viral or bacterial origin, although they are the main infectious causes of morbidity and mortality among wild gorillas in many settings. Also, viruses like human rhinovirus C, that tend to be relatively benign in humans, can cause lethal outbreaks in ape populations, suggesting poor host adaptation and a lack of immune resistance in apes. There is a limited body of evidence indicating that airborne virus transmission can occur between infected humans and wild great apes. This is particularly true for adenoviruses, coronavirus, and metapneumovirus. As humans have gradually come into closer proximity with wild great ape populations (e.g., through ecotourism), finding human-related viruses, such as human metapneumovirus and human respiratory syncytial virus, in habituated communities is not uncommon. Indeed, respiratory disease is now considered the second leading cause of death in human-habituated mountain gorillas of all ages [15]. In Uganda, antibiotic-resistance was found in 17% of *E. coli* infections in mountain gorillas. The prevalence of resistant *E. coli* strains was directly proportional to the extent of the overlap of gorilla and human habitats [16].

To date, most examinations of infectious disease among wild species have focused on a single infectious agent, overlooking the fact that co-infection is common. Building on the suggested importance of wildlife syndemics [17], Sweeney et al. [18] propose that the adoption of syndemic theory in disease ecology may offer novel insights into complex infection outcomes in animals. Syndemics involve adverse interaction among two or more diseases (including either infectious or non-infectious conditions) that: 1) have clustered in a population and that 2) magnify adverse health outcomes [19]. Thus, it is well-established that endemic parasites can enhance the burden of other pathogens present within a wildlife population. Sweeny and colleagues suggest the concept of "synzootics," which they define as interactions among two or more enzootic or epizootic disease processes that increase health burdens in wild animals under conditions of stress due to human impacts. This innovative approach warrants further study in ascertaining the precise roll of infection in biodiversity loss.

Variation in wildlife species and local environments, combined with limited research on animal diseases that do not directly threaten human populations, encumbers understanding the full significance of infectious threats to biodiversity. Available research suggests that infectious disease is rarely the sole driver of extinction, but rather that pathogens appear to increase in importance as a species numbers fall due to other, usually anthropogenic, threats, but this varies by host taxonomy [20]. At the local level, infection may play a greater role in extirpations, even if the species fairs well in other locations [21]. Far greater in depth examination is needed of the relationship of infectious disease to the loss of biodiversity, both as a way to strengthening conservation of vital ecosystems and because of the growing risk of zoonotic spill over into human populations.

Conflict of interest

The author declares there is no conflict of interest.

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