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Disease Risk to Endemic Animals From Introduced Species on Madagascar

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Introduction

In different areas of our planet, human activities such as deforestation and hunting are threatening the survival of many wildlife species. Additionally, accidental or intentional introduction of different organisms is exerting additional pressures on native animal species, and in certain cases the former becomes invasive.[1] In natural habitats, introduced animals have been shown to reduce or eliminate populations of endemic species through different mechanisms, such as direct predation or the reduction of available resources.[2] This increase in native-exotic animal interactions also presents a potential for "pathogen pollution," or the introduction of a pathogen into a new geographic area or host species.[3] Invaders may also act as an additional competent host for native pathogens, thereby increasing infection rates of native species via spillback mechanisms.[4] Additionally, invader-borne pathogens may have more subtle and persistent effects and alter the outcomes of trophic or competitive interactions.[5] In fact, a shared pathogen can have considerable impact on the population size and the distribution of native species, even if the introduced species does not compete directly with the native species for resources; this is called "apparent competition" and is illustrated by the success of the invasive gray squirrel *(Sciurus carolinensis)* and the decline of the native red squirrel *(S. vulgaris)* in the United Kingdom—the result of apparent competition mediated by a parapox virus.[6,7]

Species inhabiting island ecosystems tend to be more heavily affected by invasive species because they lack appropriate behavioral traits or immunologic capacity, making them particularly vulnerable to the threat of introduced species and/or their associated pathogens.[8,9] The high rate of bird extinction on Hawaii due to the introduction of arthropod vectors and the transmission of avian malaria and avipoxvirus are cases in point.[10,11]

Madagascar is a well-known biodiversity hot spot with approximately 90% of plant and animal species being endemic, including all nonhuman primates (superfamily: Lemuroidea), all native rodents (subfamily Nesomyinae), a radiation of insectivore-like animals (family Tenrecidae), and 9 of its 10 wild carnivorans (family Eupleridae).[12] Through a series of colonization events, probably during the Tertiary Period via some sort of over-water rafting, the ancestor for each of the four groups of terrestrial mammals occurring on the island (primates, rodents, insectivores, and carnivorans) established initial populations; their subsequent adaptive radiations produced the high diversity and 100% endemism rate observed today.[13] The diversity of the herpetofauna of Madagascar is even more impressive, with 390 species of nonmarine reptile species described on Madagascar up to 2013.[14] Of these reptile species, more than 92% are considered endemic and almost all of the 400 amphibian species are also endemic.[15,16]

Madagascar's fauna is remarkable not only by the diversity of endemic taxa found on the island but also because of the absence of entire families that are otherwise present in nearby continental Africa. For instance, no member of the families Canidae, Felidae, and Bovidae have naturally crossed the 400-km Mozambique Channel separating mainland Africa from Madagascar. The different dispersal filters and subsequent isolation of the animals that were able to colonize the island successfully may have important implications for the sensitivity of Malagasy animals to diseases carried by exotic species.

Human colonization of the island occurred some 4000 years ago and since then was associated with a series of introductions of domestic and peridomestic animals such as zebu, dogs, cats, rats (*Rattus* spp.), and mice *(Mus musculus)*.[17] These introduced animals are negatively impacting endemic species and may even lead some native species to extinction. For instance, a survey has shown that in some areas of Madagascar, black rats *(Rattus rattus)* now constitute 95%–100% of the rodent population, effectively replacing the endemic rodents, even in rainforest habitats away from human habitation (Dammhahn, unpublished data).[18] Likewise, research on carnivorans inhabiting several regions of Madagascar has shown an alarming correlation between increasing numbers of introduced cats and dogs and decreasing detection of endemic euplerids and lemurs.[19] As

elsewhere in the world, the reason for the observed declines is likely a combination of factors, including resource competition, predation, and disease.[20,21] This chapter attempts to review the literature on pathogen introduction from exotic hosts and highlights the risks of disease introduction on the rich and unique fauna of Madagascar.

Disease Risks From Introduced Amphibians

The Asian common toad *(Duttarphrynus melanosticus)* was first reported in Madagascar in 2014.[22] This invasive alien amphibian species is widely distributed across many environmental types in Asia and may competitively exclude Malagasy amphibians. It has also been hypothesized that these toads might affect Madagascar's native carnivorans through their cardiotoxic toxins.[23]

An additional concern regarding this invasive toad species is the cointroduction of pathogens, particularly Ranavirus and the amphibian chytrid fungus *Batrachochytridium dendrobatidis* (Bd). Both have been associated with major declines in amphibian populations elsewhere in the world.[24,25] Madagascar was previously considered to be one of the last major land masses without this amphibian fungal pathogen.[26] Despite several surveys and long-term research, the presence of the pathogen was not confirmed on Madagascar before 2010.[26,27] More recently, the fungus was detected on several amphibians shipped from Madagascar to the United States.[28] Subsequently, and as a result of coordinated efforts, the pathogen was found in wild frogs in multiple areas across the island, where representatives of all anuran families have tested Bd-positive.[26,28] However, results from field surveys from the same sites are conflicting, and there has been no evidence of mass amphibian mortalities, raising the question of whether the pathogen is firmly established or is recurrently introduced.[29]

In its native range, the Asian common toad is also known to harbor potentially zoonotic pathogens such as *Salmonella*[30]; by extrapolation, its introduction to Madagascar may also become a concern for public health or the native Malagasy fauna. In any case, further research is needed regarding the pathogens that this toad may carry.

Disease Risks From Introduced Birds

Approximately 209 of the 283 bird species found on Madagascar are breeding residents and a few have regular seasonal migration between sub-Saharan Africa and islands in the western Indian Ocean. The number of Palearctic migrants, particularly Passeriformes, passing through Madagascar is very limited compared with continental Africa; this has important implications for the potential transmission of pathogens between birds.[31] In addition, several species have been introduced either intentionally for food production (e.g., poultry and other domestic fowl) or pest control (common myna *[Acridotheres tristis]*) or accidentally (house sparrow *[Passer domesticus]* and house crow *[Corvus splendens]*). These nonnative birds may facilitate the introduction of pathogens and pose different threats to the native Malagasy avifauna, as has been the case for bird populations elsewhere.[10,11] For example, in the Galápagos, it is thought that the introduction of the avipoxvirus and *Haemoproteus* blood pathogens in the 19th century was associated with either pet caged birds or natural songbird migration.[32] Some species of *Haemoproteus* are known to reduce the physical condition and reproductive success of captive and wild birds; on Madagascar, this genus and *Plasmodium* are transmitted by numerous species of mosquitoes living sympatrically with native birds.[33,34] Most studies of bird pathogens on Madagascar focus on domestic fowl, and only a few investigations have documented pathogens infecting the island's native birds.[33,35]

West Nile virus (WNV), a member of the family Flaviviridae, is widely distributed in parts of the Old World. During the summer of 1999, this virus was introduced in the Western Hemisphere presumably by the transport of infected humans, birds, or mosquitoes and spread rapidly, causing morbidity and mortality of birds and mammals in the United States and Canada.[36,37] On Madagascar, evidence of WNV exposure was found in both introduced and native animal species including birds, peridomestic rodents, fruit bats *(Pteropus rufus)*, and several lemur species.[31,38–40] However, the phylogenetics of the WNV strains isolated on Madagascar suggest a local WNV transmission cycle with no new, recent introductions of WNV despite the migration and introduction of several bird and arthropod species on the island.[31,39] The introduction to Madagascar of a foreign strain of WNV might have a dramatic effect on the local fauna.

Similarly, Newcastle disease virus (NDV), a member of the Paramyxoviridae, is distributed throughout the world and infects a wide range of birds. Virulent forms of NDV cause widespread and highly contagious disease in both domestic and wild birds.[41] It is responsible for the high mortality of chickens in rural Madagascar, which in turn causes important economic burdens.[42] In most cases, domestic bird infections on the island implicate genotype XI of NDV, a form related to the variant responsible for the first pandemic of Newcastle disease (genotype IV), whereas wild birds are primarily infected by genotype Ib, although some are also infected by genotype XI.[43,44] These results suggest that genotype XI circulates across Madagascar between wild and domestic birds and may potentially affect either the native or exotic bird populations via spillover and spillback mechanisms.[45]

A recent study has disclosed that certain coronaviruses, specifically of the genus *Gammacoronavirus*, are present in wild Malagasy birds, particularly species living in aquatic habitats.[46] Coronaviruses are found in a variety of animals, in which they can cause respiratory, enteric, and neurologic diseases. This particular genus is associated with infectious bronchitis virus, but birds that tested positive did not appear to be affected.[46] The strains of avian coronaviruses detected

on the island were closely related to viruses found in Russia and Cambodia, prompting questions on the origins of these viruses on Madagascar.[46] The implications of these results with respect to the presence of this virus group in domestic and introduced birds, their potential impact on the health of the native Malagasy avifauna, and the emergence of new coronaviruses are in need of further research.

Disease Risks From Humans

On Madagascar, human activities, most importantly associated with habitat destruction and hunting, are threatening a large proportion of native animal species. In addition, accidental events such as the introduction of pathogens and disease outbreaks may further place native animals at risk. Elsewhere, humans have served as hosts for pathogens that subsequently had a substantial impact on native species.[47] Studies on the island have shown that lemurs inhabiting human-disturbed habitats have compromised health conditions compared with those living in more pristine habitats.[48,49] This may affect lemur populations by reducing their fitness or facilitating the transmission of pathogens from alien species. For example, the human-adapted protozoan *Cryptosporidium hominis* is now found in the eastern rufous mouse lemur *(Microcebus rufus)* and the greater bamboo lemur *(Prolemur simus)* living in Ranomafana National Park, as well as the ring-tailed lemur *(Lemur catta)* in southwestern Madagascar.[50,51] This zoonotic protozoan has a high prevalence rate in people, domestic animals, and peridomestic rodents inhabiting villages in the vicinity of protected areas; the parasite was most likely transmitted to lemurs as a result of increased exposure to humans.[52] In captive lemurs, *Cryptosporidium* sp. has caused high morbidity and mortality.[53]

Similarly, lemurs inhabiting anthropogenically disturbed habitats are more likely to be infected with potentially pathogenic Enterobacteraceae, which are commonly found in humans, livestock, and peridomestic rodents; such pathogens include enterotoxinogenic *Escherichia coli*, *Shigella*, *Salmonella*, *Yersinia*, and *Vibrio cholerae*, all major causes of diarrhea and mortality in captive lemurs.[54,55]

Disease Risks From Exotic Carnivorans

Interactions between exotic and endemic animals may have important negative impacts on the latter, including disease transmission. In rural areas of Madagascar, dogs and cats are free-roaming within and outside of villages and occupy areas used by wild and endemic carnivorans as well as primates.[19] This contact may potentially facilitate the transmission of diseases such as rabies and canine distemper. For example, the rabies virus has circulated on Madagascar since the 19th century, and dogs constitute the main source of rabies arising in humans and other animals on the island. Reports of rabies virus (RABV) in wild animals from Madagascar are rare, but the strain of lyssavirus isolated from a case involving the euplerid fossa *(Cryptoprocta ferox)* was confirmed to be RABV, phylogenetically close to the types circulating in dogs on Madagascar.[56] Because rabies is transmitted primarily by bites, this result indicates that dogs and the fossa are interacting directly and in some cases may transmit pathogens.

• **Figure 43.1** Indirect interactions between exotic and endemic carnivores on Madagascar. The interval in this sequence between the passage of introduced dogs *(above)* and *Cryptoprocta ferox (below)*, an endemic species of euplerid carnivore, at a single camera trap station was less than 2 hours.

Endemic animals may also acquire pathogens through indirect interactions, as when an endemic animal visits a location following the visit of an exotic species (Fig. 43.1). These sites of indirect interaction tend to be in the general vicinity of villages with trails that give people and domestic animals direct access to natural habitats or near villages with open collections of trash (Rasambainarivo, unpublished data). The time interval between visits by a domestic or feral animal and a native animal may be sufficiently short to allow transmission of pathogens such as canine parvovirus or other environmentally resistant pathogens (Rasambainarivo, unpublished data). Serologic analyses from dogs living in rural areas of Madagascar suggest an enzootic transmission of the canine parvovirus, which could spill over to the native fauna.[57] In western Madagascar, researchers found that one of five analyzed narrow-striped vontsira *(Mungotictis decemlineata)* was previously exposed to canine parvovirus-2.[57]

The spirurid parasite *Spirocerca lupi* is another pathogen transmitted by introduced dogs that may negatively affect the native fauna of Madagascar.[58] This nematode parasite is prevalent in free-roaming rural dogs on the island and is presumably responsible for the death of several captive lemurs through the formation of aortic aneurysms and their subsequent rupture.[59] Whether these parasites negatively affect endemic population of lemurs and carnivorans is unknown and warrants further research.

Additionally, it has recently been found that some brown lemurs *(Eulemur albifrons)* had antibodies to *Toxoplasma gondii,* a protozoan whose only known definitive hosts are members of the family Felidae, represented on Madagascar by introduced cats.[60] This indicates a disease spillover from exotic felids to the endemic mammalian fauna of the island. Similarly, 95% ($n = 44$) of the *Cryptoprocta* evaluated in two western protected areas had antibodies against *T. gondii.*[57] This parasite was associated with neurologic disease and death in several captive Malagasy species and may potentially affect wild endemic euplerid and lemur populations.[61,62]

Disease Risks From Introduced Rodents

Pathogenic genospecies of *Leptospira* bacteria were also detected in a large proportion of introduced rodents in various parts of Madagascar, notably *Leptospira interrogans* in *Rattus rattus.*[63] *Leptospira interrogans* is of particular concern because it is known to be pathogenic in more than 150 animal species.[64] Infected *Rattus*, then, constitute a threat to both public health and animal conservation.[64,65] One of the interesting results of these studies is the genetic uniqueness of several *Leptospira* forms among native Malagasy terrestrial and volant mammals, indicating probable isolation and evolution in deep time.[66] This suggests little exchange of *Leptospira* between *Rattus* and native small mammals.[66] Exposure of other native species including lemurs and carnivorans to *Leptospira interrogans* from invasive rodents is unknown.

In a similar pattern, native rodents seem to harbor different species of trypanostomid parasites than their introduced counterparts. In the Ranomafana National Park, 30% of *R. rattus* examined during a survey were infected by *Trypanosoma lewisii*, whereas the native and sympatric nesomyines belonging to the genus *Eliurus* were infected with a morphologically different trypanostomid.[67] The authors suggest that native rodents may not be infected by the parasite from introduced species or that the relatively recent invasion of *Rattus* in the interior of the park has not yet resulted in the transmission of these parasites. Elsewhere, on Christmas Island, *Trypanosoma lewisii* carried by *R. rattus* was associated with the infection and subsequent decline of *R. macleari*, a native rodent.[68]

Recent research on Madagascar has found a virus of the genus *Morbillivirus* that is currently considered as unclassified Morbilli-related paramyoxoviruses (UMRVs).[69] This virus is thought to be widespread among endemic rodents, tenrecs, and bats as well as introduced rodents, specifically *R. rattus.*[69] Members of the Paramyxoviridae viral family have been associated with a number of emerging diseases that affect humans and natural animal populations. Evidence indicates that *R. rattus* is an important spreader of UMRVs and that there is considerable lateral exchange of UMRVs between sympatrically occurring mammals.[69] To our knowledge, no data are available on the isolation of *Morbillivirus* among lemurs and carnivorans on Madagascar.

Conclusions

Introduced species are an increasingly dominant part of many natural and human-modified landscapes. It is estimated that invasive species, particularly invasive mammal predators such as dogs and cats, have caused the extinction of at least 87 species of birds, 45 species of mammals, and 10 species of reptiles and that they are threatening many more.[70] Some of these extinctions may be mediated by the introduction of pathogens.[71] On Madagascar, several of the "worst invasive species" were introduced following human colonization.[72] Their impacts, including those of associated pathogens, on the fauna of Madagascar warrant further research and monitoring. It is hoped that the data generated from such research will ultimately pave the way to successful strategies for managing the risks of "pathogen pollution" and disease spillover to the native fauna of Madagascar.

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