A Plague Upon Them

Helping Wildlife Adapt to Climate Changes and Disease

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Defenders of Wildlife

Chapter 1. Avian Malaria

Malaria is a debilitating illness caused by protozoan parasites – single-celled organisms that are much larger and more complex than bacteria or viruses. Because it is a protozoan, malaria cannot be treated with antibiotics, nor has a vaccine been developed. In humans, malaria poses an enormous public health challenge, with 900 million cases per year and 2.7 million deaths (USAID, undated). It is recognized as a major barrier to economic development in Africa and other tropical regions (USAID, undated). However, malaria strikes animals as well: there are dozens of different strains of malaria, each a different species of the genus *Plasmodium*. Four of these strains affect humans (WHO, undated), while other strains strike other mammals, reptiles or birds. Avian malaria in particular has been a major conservation tragedy in the Hawaiian Islands, and climate change is poised to worsen the threat.

The Malaria Life Cycle

All strains of *Plasmodium* share two important characteristics: 1) they cause illness by attacking the host's red blood cells, reducing the blood's ability to deliver oxygen to the cells and tissues of the body; and 2) all depend on a mosquito to help them complete their life cycle. Unlike a cold, which can be transmitted directly between people, malaria requires a "vector" to transmit the disease between potential hosts. The main vector for human malaria is a group of mosquitoes in the genus *Anopheles*. Avian malaria is spread by a different group called *Culex* mosquitoes. Only female mosquitoes bite: they feed on the blood of humans and animals because they need the high protein and iron food in order to lay eggs. If a mosquito bites a person or animal with malaria, some of the infected blood cells within the blood meal will contain specialized male and female forms of the pathogen. These "gametocytes" take up residence in the mosquito's gut, where they reproduce. The offspring do not harm the mosquito, but migrate to its salivary glands in preparation for the mosquito's next blood meal.

When a mosquito bites a vertebrate, it pierces the skin with a syringe-like proboscis and injects some saliva, which is thought to assist in locating a blood vessel on which to feed (Ribiero et al 1984). If the mosquito is infected with malaria, the plasmodium protozoans that were waiting within the salivary glands enter the bloodstream along with the saliva that the mosquito injects. The parasites quickly migrate to the liver, where they quickly divide (via asexual reproduction) into thousands of identical “daughter cells.” These proceed from the liver and infect red blood cells feeding on the hemoglobin and dividing further. The parasites eventually destroy enough cells to cause anemia and other symptoms. The body also has a difficult time fighting the pathogen, because it spends most of its life hidden within the cells of the blood or liver. However, as each new wave of daughter cells moves out to infect new blood cells, an immune response is triggered: the classic recurrent high fever of the malaria patient. Some of the daughter cells also differentiate into male and female “gametocyte” forms, in preparation for the continuation of the disease’s life cycle.

Malaria and Climate

Malaria is endemic to tropical regions around the world, found through much of Africa, South and Southeast Asia, and Central and South America. This distribution is tied strongly to climate factors, particularly rainfall and temperature. All mosquitoes begin their life cycle in water. The adult female lays eggs in a small pool of standing water, preferably one containing dead leaves or other organic material. The eggs hatch into larvae, which feed upon the organic matter and grow for a while before developing into pupae. The pupa is a resting phase during which the mosquito transforms into an adult phase, at which point it from the water. Mosquitoes therefore depend on the presence of water, and prefer still or stagnant water where the larvae won’t be washed away. They also prefer small pools, which are likely to have fewer predators, but require regular intervals of rainfall to persist.

External temperature strongly influences the development and activity of the mosquitoes that carry malaria. According to one study, *Culex* mosquitoes at 20°C took 25 days after hatching to develop to adults, but only 7.1 days at 35°C (Mottram et al. 1986). These researchers also found that below 15.6°C the mosquitoes didn’t develop at all. *Culex* mosquitoes also feed less at lower temperatures (Eldridge 1968).

In addition to affecting mosquito development, low temperatures also inhibit the lifecycle phase that occurs inside the gut of the mosquito. Only female mosquitoes bite: they feed on the blood of humans and animals because they need the high protein and iron food in order to lay eggs. The adult female mosquitoes that transmit malaria don’t live very long--an average of 9 to 14 days under normal circumstances (Scholte et al. 2003). Therefore, the developing parasite is in something of a race against the clock. The plasmodium taken up when a mosquito bites an infected person must mature and reach the mosquito's salivary glands in time to be injected into new victim before the mosquito dies.

Researchers have known since the early 1900s that low temperatures are lethal to the human malaria strains, particularly early in their development. The parasite was killed outright by exposure to temperatures below 17ºC within the first 1.5 days after a mosquito bites an infected person (Grassi 1900, Stratman-Thomas 1940). The parasite is better able to tolerate temperature drops after the crucial early phase, but does take longer to develop. Avian malaria shows a similar pattern: long periods of cold exposure shortly after infection curtails development of the parasite (Chao and Ball 1962). Optimal development of the parasite inside a mosquito occurs at 27ºC. A temperature of 18ºC doubles the length of time it takes for the parasites to develop and migrate to the salivary glands, and the parasites also require an additional five days to mature to the point where they are capable of transmitting an infection (Ball & Chao 1965).

Because temperature determines the rate at which the plasmodium develops in the mosquito, it plays a critical role in determining whether malaria will be passed on. At 17ºC, there is only a 0.001% chance that infective parasites will "beat the clock" and mature before the mosquito dies. At 20ºC, the chance is 5.9%, and the probability rises to a maximum of 37% at 30ºC (Snow et al. undated). Above this 30ºC, the probability drops even though the parasites mature very quickly, because the mosquitoes die of heat stress.

Malaria is endemic throughout most of tropical regions where temperatures remain for extended periods within the favorable zone for parasite development and transmission. The main tropical areas outside the favorable zone are at higher elevations where cooler weather predominates and the parasite has less of a chance of getting a foothold. It is no accident that many of the largest cities within the tropics are located at fairly high elevations. For instance Nairobi, Kenya, is located at 5450 feet and Harare, Zimbabwe, is at 4865 feet.

Malaria Conservation Threat

Many tropical birds have evolved with the threat of avian malaria and have thus built up some resistance to the disease over time. This is not the case where avian malaria has been introduced recently and the native birds are entirely without defense. In these areas, effects of the disease have been devastating.

One case in point is the birds of Hawaii. The isolation of the archipelago in the Pacific Ocean made Hawaii is a hot spot for bird evolution. Since so few colonizing animals were able to traverse the expanse of ocean to reach the islands, those that made it found a wide array of open habitats and niches, along with very few predators. These few colonists diversified via adaptive radiation to fill various niches: it is thought that as many as 53 Hawaiian endemic species evolved from just 15 colonists to the island chain (Berger 1981).

With this extraordinary array of diversity came an unusual fragility: because Hawaii's birds evolved to fill distinct niches and in the absence of predators and diseases, they are highly vulnerable to changes in habitat and to introduction of exotic predators and parasites. Nearly 40 species were pushed to extinction following Polynesian colonization of the islands, probably due to hunting and destruction of lowland habitats (Olson and James 1982). European colonization brought additional habitat destruction, direct exploitation, and exotic species introduction that caused the extinction or endangerment of dozens more. Of the 71 endemic taxa present on the islands at the time of European contact in the late 1700s, twenty-three were extinct by 1995 (Jacobi and Atkinson 1995), and by 2006 a further eleven had most likely vanished (USFWS 2006).

Among the introductions that eventually proved most devastating was the vector for avian malaria, a *Culex* mosquito, which is thought to have first arrived to Maui's port of Lahaina in 1826 as an unwanted guest on the ship the "Wellington" (van Dine 1904). The mosquito's range remained relatively confined for about 50 years, but spread rapidly throughout Maui and the rest of the islands with the advent of road-building and expanding inter-island travel in the late 1800s (van Dine 1904). The date and route of entry for malaria itself is unknown (LaPointe et al 2005). One possibility is that migratory ducks and shorebirds might have brought the disease, which was later transmitted to resident birds following the introduction and spread of the necessary vector (Warner 1968). Others have pointed to the near-absence of the parasite in migratory individuals and implicate the wave of deliberate introductions of Asian birds in the early 1900s as the source of the infection (van Riper et al. 1986)

By the early 1900s it was apparent that birds were disappearing from lowlands, even in suitable forest habitats: “So far as the human eye can see, their old home offers to the birds practically all that it used to, but the birds themselves are no longer there,” wrote H.W. Henshaw in 1902. Six endemics had disappeared from Oahu by 1900 (Warner 1968) and birds on Lanai were becoming increasingly confined to the uplands, despite plenty of remaining habitat in the lowlands (Munro 1944). Contemporary chroniclers of Hawaiian avifauna described sightings birds suffering visible symptoms of viral avian pox, another detrimental introduced disease. However, they also recorded sightings of dead birds, particularly in lowland forests, that showed no outward symptoms, and many of these probably suffered from avian malaria (Warner 1968).

Richard Warner (1968) demonstrated the lethality of avian malaria to native birds by exposing highland-caught honeycreepers to lowland mosquito conditions in large-mesh cages. These birds invariably sickened and died, and post-mortem examination revealed high levels of *Plasmodium* infection in each bird’s bloodstream. Warner found that infections were more severe and more likely fatal in the honeycreepers, as compared to introduced finches and white-eyes, suggesting immunological naïveté. He also observed that the native birds exhibited a behavioral naïveté as well: the introduced birds tended to sleep with their feet and faces drawn tightly into their feathers, denying the mosquitoes a good place to feed. The native birds, on the other hand, slept with their faces and feet exposed, and the researchers observed many more *Culex* mosquitoes feeding upon the native birds.

The Climate Change Connection

As described above, the development and transmission of the malaria parasite is strongly dependent on temperature. Below a certain threshold, the parasites do not reach infectivity within the lifespan of the vector mosquito. For the strain of malaria in Hawaii, no transmission of malaria occurs below 13ºC, and very little occurs between 13ºC and 17ºC (LaPointe et al 2005). At issue in the conservation of Hawaii’s avifauna is to what elevation that temperature threshold corresponds, and is that threshold moving upslope with the onset of climate change? The answers to these questions will ultimately determine the extent and location of the malaria-free refugia for Hawaii’s endemic species.

In his 1968 examination of malaria in honeycreepers, Richard Warner cited 600 meters in elevation as the critical threshold for the temperature limitation of avian malaria. The major islands in the archipelago range from 1000 meters to 4000 meters in height, and on the higher islands the upper limit of the forested area is about 1900 meters (Juvik & Juvik 1998). Thus, the 600-meter threshold suggested that substantial areas of most of the islands were available as disease-free refugia for honeycreepers and other malaria-sensitive island endemics.

Unfortunately, later work by other researchers contradicted this assertion: van Riper and colleagues (1986) found breeding mosquitoes and malaria-infected birds up to 1500 meters in wet forest habitats and up to 1350 meters in dry forests, where there are fewer pools of water for mosquitoes to breed in. This higher threshold substantially contracts the available malaria-free habitat zone. All of Oahu and Lanai, and most of Molokai, lie below this elevation, and high-elevation forest habitat on Kauai, Maui and Hawaii is considerably restricted.

Under plausible scenarios of the impacts of impending climate change on the Hawaiian Islands, the malaria-free area constricts sharply. A warming climate shifts the thresholds for malaria up the slopes of the mountains and further shrinks the area where the disease is absent. One recent analysis of the potential effects of a 2°C increase on protected forested areas was particularly discouraging, because it found that the upslope shifts cut sharply into the available forest habitat (Benning et al. 2002). On Maui, a 2°C increase shrinks the area of very low malaria risk (below 13°C) from 665 hectares to 285 hectares of forested habitat, and the area of medium risk (between 13 and 17°C) from 1,236 hectares to 886 hectares. On the other large islands the situation was even worse. Because the maximum elevation of Kauai is less than 1600 meters, the island already lacks the lowest risk temperature zone, and a 2°C increase cuts the medium risk area from over 15,000 hectares to less than 2,500 hectares. Hawaii, despite having the highest elevation of all the islands and therefore the largest low-temperature zone, suffers from the presence of unforested pasture land upslope from its largest reserve, so a 2°C temperature increase shifts the critical isotherms into unsuitable habitat: the lowest risk area shrinks from 3,120 hectares to 130 hectares. However, the medium risk zone on Hawaii remained the largest of the three islands–7,669 hectares, down from the current 9,229 hectares (Benning et al. 2002).

The dire predictions of the model are already being borne out by observations. By 2001, avian malaria was present in 5.4% of forest birds at 1900 meters in Hawaii's Hakalau Forest National Wildlife Refuge (Freed et al. 2005), the same refuge modeled above. This represented a doubling of the presence of malaria compared to a decade earlier. Mean air temperature has risen slightly over the past decade; perhaps more importantly, the mean air temperature during warm spells has increased significantly. A two-week sequence of air temperatures averaging 15.4°C seems to have provided an opening for the parasite to gain a foothold in the upper reaches of the Refuge's forest habitat. Given that forest gives way to pasture shortly above this elevation, it is clear that rising temperatures are in fact depriving Hawaii's birds of their last refuge.

Helping Wildlife Adapt to the Climate Change & Malaria Threat

Protect and restore appropriately located forested habitat. Models of the impact of climate change on malaria and its mosquito vector indicate that on the island of Hawaii, the malaria-free zone is predicted to move upslope and into a region dominated by pasture rather than forest habitat (Benning et al. 2002). These authors conclude that, "restoration of high-elevation forests above [the Hakalau Wildlife Refuge] is crucial to improving the chances for survival of the honeycreeper species, particularly the Hawaii àkepa, a cavity nester that requires large trees." Forest fragmentation and agricultural land use also increase the likelihood of mosquito presence (Reiter & LaPointe 2007), so reforestation of buffer areas adjacent to refuges may also reduce the rate of the spread of malaria within forest refuges.

Locate and protect surviving birds at low elevations. Despite the apparent doom of the climate change and malaria scenario, there is evidence that resistance to the diseases is beginning to emerge in some species. In particular, the amakihi is now found at lower elevations (Atkinson et al 2000, Woodworth et al. 2005) and these low-elevation populations exhibit genetic differences from upslope birds that indicate evolved resistance to malaria (Foster et al. 2007). Therefore, low-elevation habitats, far from being "sacrifice" zones, may contain crucial reservoirs of birds that have evolved resistance to malaria. Birds found at low elevations could be crucial components of captive breeding programs. Tolerance of malaria may be emerging in the 'I'iwi and the Hawaii 'Akepa as well (Freed et al. 2005).

Reduce other stressors to birds in order to increase the likelihood of evolution of resistance. As mentioned previously, malaria is only one in a long list of threats to Hawaii's native birds. Another devastating factor was the introduction of rats, cats and mongoose to islands that were previously free of mammalian predators on nests and nestlings (Atkinson 1977). If, as mentioned above, tolerance of or resistance to malaria is beginning to emerge naturally in Hawaii's birds, a critical conservation issue will be to make sure that birds exhibiting tolerance live to pass it on to their offspring. Reducing nest predation by controlling rodents and other predators may pay great dividends in facilitating the spread of the genes that confer malaria resistance (Kilpatrick 2005).

Continue research on disease and vector control methods. Continued attempts to develop a safe and effective vaccine for avian malaria should continue, as should attempts to control mosquitoes with low-toxicity methods like sterile insect release. Furthermore, control of feral pigs might reduce malaria transmission because their foraging behavior creates small pools that enhance mosquito breeding success.

Prevent the introduction of diseases and vectors in other locations. The role of careless introductions in Hawaii's extinction tragedy serves as a cautionary tale for islands everywhere. As climate change alters landscapes around the world, even more vigilance is needed to prevent the introduction of malaria and other diseases to locations that might previously have proved inhospitable for a tropical disease like malaria. Imports of live poultry and exotic birds pose severe risks, as do any cargo consignments likely to contain stagnant water, such as used tires.