

CHAPTER SEVENTEEN

## Managing Disease

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The extinction and decline of Hawaiian avifauna due to introduced mosquito-borne disease has become a classic example of the impact of introduced diseases on naïve wildlife populations (Warner 1968; this volume, Chapter 9). Along with rinderpest virus and rabies virus, avian malaria (*Plasmodium relictum*) and avian pox virus (*Avipoxvirus sp.*) stood for decades as rare cases of invasive pathogens in wildlife species (Gulland 1995). Today, however, with ever-increasing globalization, emergent and invasive human and wildlife diseases are on the rise (Daszak et al. 2000, Gubler 2001, Friend et al. 2004). Once an academic curiosity to conservation biologists outside of Hawai‘i, avian malaria and pox and their impact on Hawaii’s native forest birds now have continental relevance with West Nile virus’s sweep across North America and its potential threat to endangered species populations (Marra et al. 2004, Kilpatrick et al. 2007).

The Hawaiian Islands, like other isolated oceanic islands, experienced limited natural colonization by terrestrial biota. These founders brought few, if any, parasites and pathogens with them (Torchin et al. 2003; this volume, Chapter 1). For parasites with complex life cycles, alternate hosts were absent, as were the insect vectors of pathogens, such as mosquitoes, black flies, biting midges, and others. This all changed with the arrival of Westerners to the Hawaiian Islands in 1778 and the subsequent introduction of mosquitoes and mosquito-borne avian disease. Introduced mosquito-borne avian disease is considered a major factor limiting Hawaiian forest bird populations and an obstacle to the restoration of the islands’ avifauna (U.S. Fish and Wildlife Service 2006). Future efforts to protect remaining Hawaiian forest bird species and to restore their populations

will rely on the development of disease management strategies that can be applied at the landscape level. The long history documenting the control of vector-borne human disease (Harrison 1978) suggests that there will be no simple solutions and that an integrative and diligent approach will be necessary (Rose 2001).

In this chapter we (1) provide a brief overview of the mosquitoes in Hawai‘i and the pathogens they vector to birds (see Chapter 9 for a more detailed account of disease biology); (2) outline possible management practices and evaluate them in the context of endemic Hawaiian bird conservation, from single-species captive populations to intact communities across broad landscapes; and (3), in synthesis, suggest management strategies to minimize the impact of vector-borne disease in Hawaiian forest birds.

#### **KNOW THINE ENEMY**

##### **Mosquito Vectors of Avian Pathogens in Hawai‘i**

Six biting species of mosquito have become established in the Hawaiian Islands since the nineteenth century: *Culex quinquefasciatus* (established by ca. 1826), *Aedes aegypti* (ca. 1892), *Aedes albopictus* (ca. 1902), *Aedes vexans nocturnus* (ca. 1962), *Wyeomyia mitchellii* (ca. 1981), and *Aedes japonicus* (ca. 2003) (Hardy 1960, Joyce and Nakagawa 1963, Shroyer 1981, Larish and Savage 2005) (Fig. 17.1). The first three species are known vectors of human pathogens and have been widely distributed throughout the tropic and subtropic regions by Western commerce (LaPointe 2007). By contrast, *A. v. nocturnus* and *A. japonicus* are competent laboratory hosts of encephalitis viruses but are not documented vectors of human or wildlife pathogens (Turell et al. 2001, Sardelis et al. 2003). *W. mitchellii* is not known to transmit any vertebrate pathogens (Shroyer 1981).

Only *C. quinquefasciatus*, *A. albopictus*, *A. japonicus*, and *W. mitchellii* have been found in

native forest bird habitats, and only *C. quinquefasciatus* is presently common above 900 m in elevation (Goff and van Riper 1980, LaPointe 2000). *Culex quinquefasciatus* is a known vector of avian malaria in Hawai‘i (LaPointe et al. 2005) and is the most likely vector of avian pox virus (van Riper et al. 2002). Only a few individuals of *A. albopictus* and *W. mitchellii* were found to support sporogony of *Plasmodium relictum* in the laboratory (LaPointe et al. 2005). Preliminary trials with the newly established *A. japonicus* suggest that this species does not support sporogony in the laboratory (LaPointe, unpubl. data). Avian pox virus does not require a specific vector and may be transmitted by any mosquito or biting arthropod. Although these three mosquito species may be more or less opportunistic in host selection (Tempelis et al. 1970, Edman and Haeger 1977, Tanaka et al. 1979) and abundant in some lowland Hawaiian forests, their marginal susceptibility to avian malaria and limited altitudinal distribution make them unlikely to be important vectors of either avian malaria or pox. Their possible role as minor, incidental vectors of avian malaria or pox is still unknown. Thus, due to its high level of vector competence and altitudinal distribution, *C. quinquefasciatus* can alone account for the current distribution and prevalence of avian malaria and pox in forest bird communities.

##### **Hawaiian Landscapes, Feral Pigs, and Mosquito Abundance**

Larval mosquitoes are aquatic and can be found in a wide range of temporary and permanent waters. *C. quinquefasciatus* larvae occur in natural and artificial containers, ditches, puddles, irrigation channels, cesspools, and the margins of ponds and flowing streams. This species is adapted to eutrophic waters heavily enriched with organic matter. Although generally not found in forest ground pools or open bogs in Hawai‘i (Fig. 17.2), *C. quinquefasciatus* larvae have been recovered from ground pools and wallows where fecal

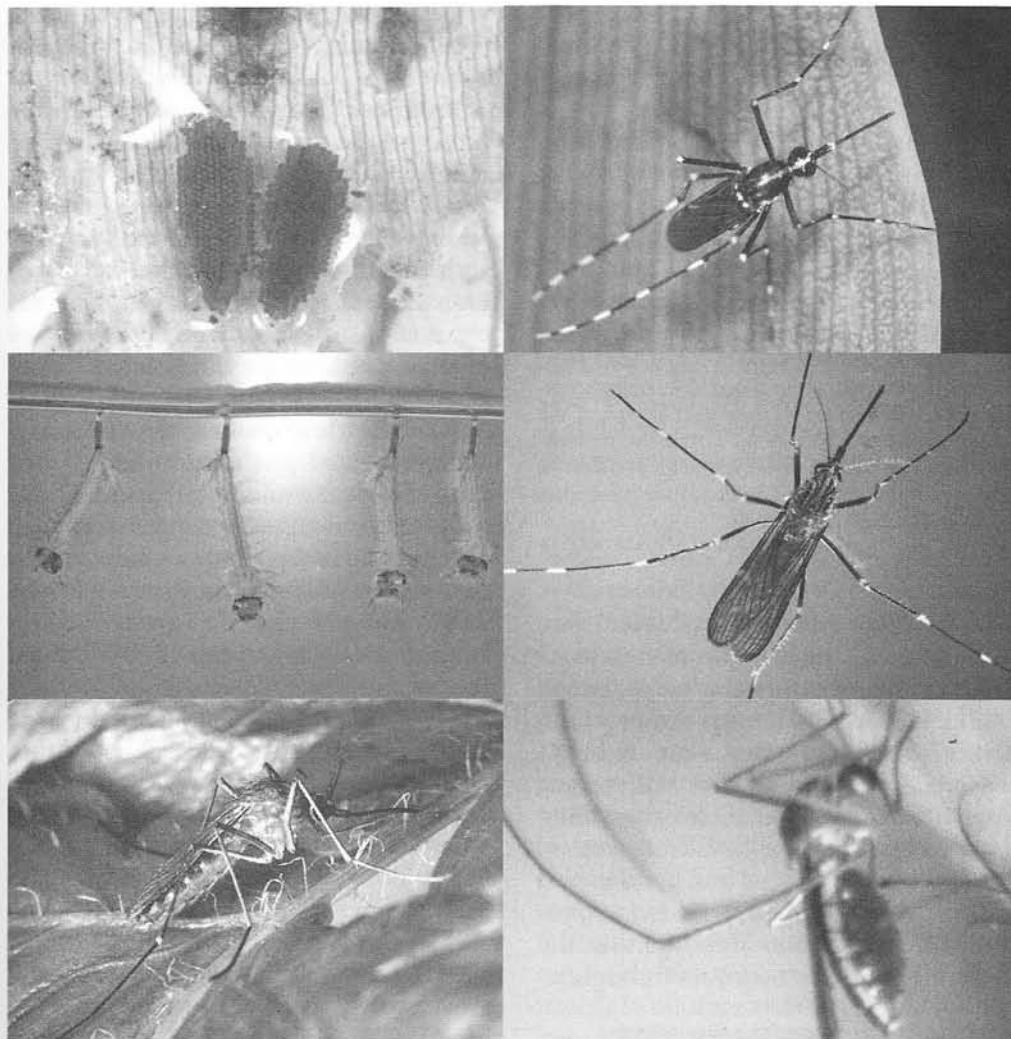


Figure 17.1. Common mosquito species found in forest bird habitats on Hawai'i Island. Left side, top to bottom: Egg rafts, larvae, and adult female *Culex quinquefasciatus*, the main vector of avian disease in the Hawaiian Islands. Right side, top to bottom: *Aedes albopictus*, *Aedes japonicus*, and *Wyeomyia mitchellii*. Source: Photos by Dennis LaPointe, U.S. Geological Survey.

matter from livestock or feral ungulates may have enhanced the microhabitat (D. LaPointe, pers. obs.).

Mosquitoes do not typically occur in many natural areas in the Hawaiian Islands because of temperature constraints on their development or the absence of suitable larval habitat. Adult and larval mosquitoes were rarely encountered in windward for-

ests above 1,500 m in elevation on Hawai'i Island (Goff and van Riper 1980, LaPointe 2000). Intermittent and ephemeral streams, however, may be important larval mosquito habitats in some Hawaiian landscapes. Surveys in Kīpahulu Valley on Maui documented *C. quinquefasciatus* larvae in rock pools of intermittent streambeds (Aruch et al. 2007).

In stark contrast, the younger volcanic landscapes of the east flank of Mauna Loa, Hawai'i Island, are all but devoid of permanent surface water. *C. quinquefasciatus*, however, are abundant in these wet forests, where their larvae rely primarily on rainwater-filled cavities in the native tree fern,

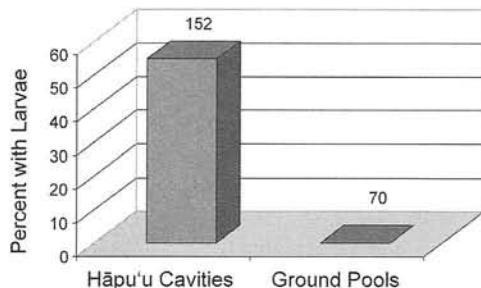


Figure 17.2. Larval *Culex quinquefasciatus* occupancy of available aquatic habitats in windward Mauna Loa forests, Hawai'i Island. The numbers over the columns represent the total number of individual habitats of the habitat type sampled for mosquito larvae that were encountered in 4.5 ha of forest. Although prevalent in these forests, ground pools do not appear to support mosquito larvae (LaPointe 2000).

hāpu'u (*Cibotium* spp.) (Fig. 17.3). These cavities are formed by the feral descendants of domestic pigs (*Sus scrofa*), which feed on the starchy core of the tree fern. After extracting the starch, a cup- or bowl-shaped cavity remains that will collect rainwater and leaf litter, thereby providing a favorable habitat for larval mosquitoes. Although the geological and hydrological nature of the Mauna Loa landscape precludes the production of mosquitoes, the occurrence of hāpu'u cavities throughout

large tracts of forest undermines this natural protection (LaPointe 2000) (see Fig. 17.2).

Feral pigs, however, are not the only culprits. The numbers of *C. quinquefasciatus* are much greater in suburban and agricultural areas than in natural areas. Conservation areas in Hawai'i often abut residential and agricultural communities that can produce high densities of mosquitoes through the creation of larval habitat and the presence of abundant hosts for blood meals (Mian et al. 1990, Reisen et al. 1990, Reisen et al. 1992). The rural community of Volcano Village, located just outside the boundaries of Hawai'i Volcanoes National Park, serves as an excellent example. Mosquito capture rates in the village are nearly three times greater than capture rates within the nearby forest (Reiter and LaPointe 2007). Household water storage in residential areas contributes to local mosquito abundance, but the impact of artificial containers and impoundments may be several times

Figure 17.3. Water-filled cavity in a hāpu'u tree fern (*Cibotium glaucum*) trunk created by feral pig feeding. Such cavities are the main breeding sites for mosquitoes in some native forests. Removal of feral pigs would reduce the number of breeding sites, which in turn would potentially reduce disease transmission among birds.  
Source: Photo by Daniel Lease, U.S. Geological Survey.



greater on agricultural lands. Cattle operations, in particular, create favorable habitats for *C. quinquefasciatus* in the form of stock ponds, troughs, cisterns, settlement ponds, and the old tires and tarps commonly used to cover feed (Reiter and LaPointe 2007).

Because the native tree 'ohi'a-lehua (*Metrosideros polymorpha*) still dominates many of these residential and agricultural landscapes, birds such as 'Apapane (*Himatione s. sanguinea*) and 'I'iwi (*Vestiaria coccinea*) move readily between the forests and suburban or agricultural areas where the likelihood of exposure to malaria and pox may be greater. Mosquitoes from these areas may also be dispersing into forests, thereby augmenting forest populations. Female *C. quinquefasciatus* were recaptured at the 3 km trap boundary during mark-release-recapture experiments in a closed-canopy Hawaiian forest. After accounting for trap density, 1.6 km would be a conservative estimate of the average dispersal of *C. quinquefasciatus* in 10 days (LaPointe 2008). Mainland studies in urban environments showed that *C. quinquefasciatus* can disperse up to 12.6 km (Reisen et al. 1992). The dispersal ability of this species has serious implications for disease management in fragmented areas.

On Mauna Loa's east flank, forest mosquito populations disappear during droughts but return after sufficient rain, suggesting that residential or lowland areas may serve as the source of these rebounding populations (LaPointe 2000). Low-elevation mosquito populations outside of forest bird habitats might hypothetically contribute to avian malaria and pox transmission if carried by wind to higher elevations (Scott et al. 1986).

#### POTENTIAL DISEASE MANAGEMENT STRATEGIES

##### Manipulation of Susceptible Hosts by Chemotherapy and Vaccination

The successes in vaccine development and the use of antimicrobial agents in the con-

trol of infectious disease in humans and domestic animals are well documented. However, these approaches have not been as successful in wild animal populations. Chemotherapy of wildlife populations is generally limited to very local situations, and immunizations of wildlife are dependent on novel methods of vaccine delivery (Wobeser 2002). Most wildlife vaccines are directed at mammalian reservoirs of human disease (Slate et al. 2005), livestock disease (Wilkinson et al. 2004), or critically endangered populations (Hastings et al. 1991). There are no examples of vaccine use in wild birds.

#### ANTIMALARIAL AGENTS

Chemotherapy of birds has been used only in captive or closely managed flocks. Common antimalarial agents used to treat human malaria, such as chloroquine and primaquine, were first evaluated in birds and may work as a prophylaxis, as supportive treatment, or as a radical cure for malaria in captive birds (Hewitt 1940, Stoskopf and Beier 1979). For example, chloroquine and primaquine were used to treat captive-reared, endangered 'Alalā (Hawaiian Crows, *Corvus hawaiiensis*) that became infected with malaria while acclimating in outdoor aviaries prior to release. The crows recovered completely and were ultimately released (Massey et al. 1996).

The value of antimalarial agents in the treatment of wild birds is limited by the difficulties of delivery. Dosing wild birds via artificial nectar feeders is impractical and likely to fail at the landscape level because dosages cannot be regulated, and low doses could lead to rapid selection for drug-resistant parasites (White 2004). Similarly, deliberate exposure of birds to malaria and chemotherapeutic control of the acute phases of infection might allow individuals to mount an immune response that would ultimately be able to regulate and control chronic infections. However, this approach will also ultimately select for drug

resistance in the parasite population. In addition, chronic infections may relapse or recrudesce when birds are immunologically stressed (Valkiūnas 2005).

#### AVIAN MALARIA VACCINE

Vaccines against protozoan pathogens have been notoriously difficult to develop, but they can avoid some of the problems associated with chemotherapy and drug resistance (Jones and Hoffman 1994). Attempts to develop subunit vaccines for human malaria have been unsuccessful because of the complex life cycle of the parasite, coinfection of multiple strains, and the ability of *Plasmodium* to change its antigenic, surface proteins (Desowitz 2000). However, recently there has been renewed interest in using irradiated sporozoites as a live, attenuated human vaccine. In laboratory trials with rodents and human subjects, this approach provided protective immunity for at least 10 months (Nussenzweig et al. 1967, Clyde et al. 1975, Hoffman et al. 2002). Its potential for use in Hawaiian birds has yet to be evaluated.

A technically more sophisticated approach is the use of DNA vaccines based on short sequences of specific genes (Doolan et al. 1996). Recently, a DNA vaccine using the circumsporozoite protein (CSP) of *P. relictum* afforded moderate but short-lived protection in canaries (McCutchan et al. 2004). In a similar CSP vaccine trial, the prevalence of malaria in a captive flock of penguins was reduced from 50% to 17% following vaccination. The vaccination of part of the captive flock also protected unvaccinated individuals by decreasing the proportion of susceptible individuals (Grim et al. 2004). DNA vaccines have clear benefits for captive populations, but the short duration of the immunity afforded limits their effectiveness in wild populations.

#### AVIAN POX VIRUS VACCINE

Attenuated live pox virus vaccines have been available for domestic birds since the

1940s and are commonly used in high-risk areas where birds and/or mosquitoes occur in high densities (Ritchie 1995). The vaccine is typically delivered by injection into the wing web, but reimmunization is often necessary, limiting its usefulness in wild birds. Another major concern is recombination of the attenuated virus in the vaccine with other viral strains or pox viruses, resulting in more virulent strains. Vaccine contaminants are also of concern. Reticuloendotheliosis virus causes immunosuppressive disease in domestic fowl and is a common contaminant of commercial fowlpox vaccine (Garcia et al. 2003). Finally, immune responses to avian pox can be very host-species specific, and additional information on the diversity and pathogenicity of avian pox in Hawai'i is needed before an effective vaccine can be developed (Tripathy et al. 2000; Jarvi, Triglia, et al. 2008).

Even in the event of the development of a successful malaria or pox vaccine, difficulties in the method of delivery remain a formidable obstacle to the immunization of large wild populations. But technological advances offer some hope. It is now theoretically feasible to have a ubiquitous and potentially benign virus, such as fowl pox, vector recombinant DNA for the antigenic proteins of any number of potential pathogens (Paoletti 1996). Because pox viruses are easily transmitted by mosquito, a nonpathogenic pox virus or viral strain might serve as a vector for a *Plasmodium* or arboviral gene. A fitting irony would be use of the mosquito as the ultimate delivery system of this engineered vaccine.

#### Naturally Malaria-Tolerant Birds

There is evidence that some lowland populations of Hawai'i 'Amakihi (*Hemignathus virens*) may be evolving an innate tolerance to avian malaria (Woodworth et al. 2005). Translocation of tolerant birds to new sites may introduce this presumably heritable trait to currently vulnerable populations. However, translocated birds may introduce

pathogenetically different strains of malaria or new pathogens into the recipient population and should be properly screened and/or treated before release (Atkinson and van Riper 1991, Cunningham 1996). It has also been suggested that tolerant individuals be brought into captivity as a breeding population for propagation and future release into the wild.

Whether translocated or captive-bred birds are used, the presumed heritable traits of disease tolerance may not become fixed in the wild populations if similar selective pressures—especially perennial malaria transmission—do not prevail at the release site or if gene flow from distant populations overcomes the introduced resistant genes. The latter is most likely to occur with highly vagile species such as 'I'iwi and 'Apapane (Fancy and Ralph 1997). For these reasons, the translocation of disease-tolerant individuals may have its greatest value in facilitating the lowland expansion of naturally evolving, disease-tolerant populations.

### Manipulation of the Vector

Reduction of vector abundance and longevity remains the central control strategy for mosquito-borne disease today. Whether the pathogen is dependent on the vector to complete transmission (as in the case of *Plasmodium* and arboviruses) or the vector merely facilitates mechanical transmission (as with avian pox), the mosquito is the crucial link between infected and susceptible host. Remove the link, and transmission ceases. The early successes in human malaria and yellow fever control were both brought about through the control of the mosquito vector.

Many characteristics of the Hawaiian avian disease system would seem to make control through vector reduction an unattainable goal (Chapter 9). First, avian malaria and avian pox are pervasive in the Hawaiian Islands, and the prevailing climate favors transmission throughout most of the year. Second, the combined effects

of a highly competent vector, a favorable climate, and an ample reservoir of hosts make for efficient transmission even at low densities of *C. quinquefasciatus* relative to mainland areas. Third, native birds with chronic malarial infections are reservoirs for life (Jarvi et al. 2002), and although there are no estimates of species longevity, there are records of individually banded native passerines' living in excess of 10 years (Lindsey et al. 1998). Finally, the land needing control is enormous; approximately 25% of the state's land area (405,000 ha) is under some form of natural resource protection (Loope and Juvik 1998). These limitations suggest that management of avian disease in Hawai'i will require control methods that are exceptionally effective, cost-efficient, environmentally safe, and indefinitely maintained.

### SOURCE REDUCTION OF LARVAL MOSQUITO HABITAT

The most effective way to limit mosquito numbers is to remove larval mosquito habitats, a practice referred to as source reduction. From the time of the Roman Empire to recent times, great efforts were made to drain swamps and lowlands where human malaria was common (Harrison 1978). These efforts were successful, and source reduction was practiced widely throughout the world until the environmental movement of the 1970s raised the alarm that wetlands were invaluable ecosystems of great productivity and biodiversity (Mitsch and Gosselink 1993). Although swamps and wetlands are no longer drained in the name of mosquito control, source reduction of artificial habitats or altered natural habitats remains a valuable component of most mosquito abatement programs.

Perhaps the greatest potential use of source reduction in Hawai'i lies in the residential and agricultural communities that encroach on natural areas. Catchment systems for household water are common in rural Hawai'i and are often poorly

maintained. Artificial containers, particularly cemetery vases, refuse containers, discarded tires, and construction materials, may harbor hundreds of mosquito larvae in a relatively small volume of water. Unfortunately, control of mosquito production by means of source reduction requires considerable cooperation and vigilance from the public, and without strong incentives (or penalties) community-based campaigns are seldom successful. Source reduction campaigns are more likely to succeed on government-owned lands where environmental management practices can be mandated. On a small scale, such as in an atoll refuge, mandated source reduction has the potential to eliminate vectors entirely.

In Midway Atoll National Wildlife Refuge, removal of refuse containers and tarpaulins associated with environmental mitigation work and the decommissioning of military infrastructure was followed by a decrease in the occurrence of avian pox in nestling seabirds (J. Hale, U.S. Fish and Wildlife Service, pers. comm.). Unfortunately, *C. quinquefasciatus* and *A. albopictus* are still present on Midway Atoll, and in 2005 an avian pox outbreak occurred in nestling Laysan Albatrosses (*Phoebastria immutabilis*) (J. Klavitter, pers. comm.). The creation of artificial wetlands for the restoration of Laysan Ducks (*Anas laysanensis*) on Midway (U.S. Fish and Wildlife Service 2004b) may have inadvertently increased mosquito populations.

Similarly, in Hawai'i Volcanoes National Park, the feasibility of breaking avian malaria transmission through the source reduction of larval mosquito habitat was tested at a 100 ha former cattle ranch where the larval mosquito habitat was associated with ranch infrastructure. Though unpublished, the study demonstrated that the removal and treatment of troughs and cisterns virtually eliminated mosquitoes (D. LaPointe, unpubl. data). Unfortunately, the mosquito population rebounded when a new larval habitat was created by a nearby

construction project. These examples emphasize that for source reduction to succeed, mosquito control must be a priority whenever alterations to refuge lands are considered.

Source reduction need not be entirely limited to human infrastructure. As mentioned earlier, feral pigs create larval mosquito habitats throughout the wet forests of Hawai'i. Source reduction of hāpu'u cavities by elimination of the feral pig is feasible but not without great cost and controversy. The costs of pig eradication in Hawai'i Volcanoes National Park during the 1980s were estimated to be \$24,000 per km for fencing, \$25,000 per year for fence maintenance and inspection on 71 km of fence line, and an average of \$95 per pig for hunting (Hone and Stone 1989, Katahira et al. 1993). However, the cost of feral pig control is not the only obstacle. Feral pigs are a favored game species, and proposals to control or eliminate them from public lands have been met with opposition from some hunters. After years of dialogue between conservationists and hunters, the controversy over the control of feral pigs on some public lands continues (Tummons 1997).

#### CHEMICAL CONTROL OF MOSQUITO VECTORS

The use of insecticides to control mosquitoes has saved countless lives worldwide from the ravages of vector-borne disease. Chemical approaches to mosquito control also have had a negative impact on the environment. Over the past century, the chemical control of mosquitoes has shifted from treating for larvae (larviciding) with coal oil (kerosene) (Van Dine 1904) and the chlorinated hydrocarbon DDT to targeting adults (adulticiding) with organophosphates and pyrethroids (Nakagawa 1964, Mulla 1994, Rose 2001). In the past three decades, concern over the impact of pesticides on human health and the environment has brought about a more

integrated approach to mosquito control, combining source reduction and biological control with novel, environmentally sound larvicides and ultralow-volume (ULV) adulticiding (Mulla 1994, Rose 2001).

When source reduction is inappropriate and larval mosquito habitats are accessible, larviciding is often the preferred method of control. Since the 1970s, artificial insect growth regulators and surfactants have been used in natural and man-made waters for control of mosquito larvae (Mulla 1994). Insect growth regulators such as methoprene (Altosid®) interfere with pupal molting by mimicking a hormone common to all insects and crustaceans, whereas surfactant monomolecular films alter the surface tension of natural waters and affect surface-respiring invertebrates. Although some adverse nontarget effects have been reported, these chemicals are essentially nontoxic to vertebrates and most invertebrates when applied at recommended rates (Nayar and Ali 2003, Pinkney et al. 2005). These larvicides can be effectively used in suburban and agricultural settings, but larval mosquito habitats in Hawaiian forests are too widely dispersed and inaccessible to allow employment of conventional larviciding.

When environmental conditions are not suitable for larviciding or when faced with a public health emergency, mosquito control professionals rely on adulticiding. Modern ULV adulticiding applies a small amount of organophosphate or pyrethroid insecticides per hectare and, using aerial applications, can treat vast areas in a short time. Under ideal conditions, ULV adulticiding can achieve 90% control without detectable nontarget effects (Mount 1998, Jensen et al. 1999, Zhong et al. 2003). Still, ULV adulticiding is no more likely to aid in the control of avian disease in Hawai'i than is conventional larviciding. ULV applications are not as effective in dense vegetation (Mount 1998) and therefore are unlikely to penetrate a closed-canopy Hawaiian forest. Furthermore, adult

mosquito numbers often rebound quickly after adulticiding. In Hawai'i, *C. quinquefasciatus* has multiple cohorts throughout the year and would require continuous applications to suppress adults for any length of time. Although chemical control may be effective in large open wetlands or in suburban or agricultural environments, it is difficult to imagine a cost-efficient and effective landscape-level broadcast of insecticides over native Hawaiian forests.

Aside from the economic and logistical constraints, there are greater concerns regarding the use of chemical pesticides. Evolving insecticide resistance makes chemical control subject to complete failure. Attempts to manage resistance may postpone or even prevent failure of chemical control, but such management would require exceptional coordination with the agricultural community (Brogdon and McAllister 1998). The final factor weighing against chemical control is the actual and perceived adverse impact of insecticides on human health and the environment. Mainland monitoring for nontarget effects associated with ULV adulticiding has been largely limited to a few indicator species (Mount 1998). Little is known about the long-term effects of adulticiding on biodiversity. Hawai'i has more than 5,000 endemic arthropod species, including more than 20 species proposed for federal listing as endangered (Howarth and Mull 1992). The regulatory hurdles required just to initiate adulticiding in Hawaiian natural areas would be daunting and likely insurmountable. Given the nonselective toxicity of these chemicals and the already fragile status of Hawaii's native fauna, it would be extremely problematic to consider chemical control in Hawaiian forest bird habitats.

#### CLASSICAL BIOLOGICAL CONTROL OF MOSQUITO VECTORS

Classical biological control can be defined as the control of a pest species by introduced natural enemies. The earliest

attempts to control mosquitoes in Hawai'i included the establishment of the wrinkled frog (*Rana rugosa*) and the dart-poison frog (*Dendrobates auratus*). Both species failed to control mosquito numbers (Oliver and Shaw 1953).

A number of poeciliid fish have been identified as predators of mosquito larvae and have been used extensively in Hawai'i (Nakagawa and Ikeda 1969). The first species imported for mosquito control were the western mosquito fish (*Gambusia affinis*), sailfin molly (*Poecilia latipinna*), guppy (*Poecilia reticulata*), green swordtail (*Xiphophorus hellerii*), and southern platyfish (*Xiphophorus maculatus*) (Van Dine 1907, Brock 1960). The western mosquito fish is extremely adaptable and effectively reduces mosquito numbers. Unfortunately, it also displaces native fish species (Meisch 1985). The guppy is more effective in polluted waters than mosquito fish and has been used in Hawai'i to control *C. quinquefasciatus* in poultry waste runoff (Bay 1985). Both species were released in natural areas as well as artificial impoundments, so today these fish are ubiquitous in lowland waters of the state. Introduced poeciliid fish have been implicated in the population loss of native *Megalagrion* damselflies in Hawai'i (Englund 1999). Due to their proven negative impact on native aquatic biodiversity, introduced fish should not be considered for mosquito control in natural areas.

Over the past century, a number of invertebrate predators have been considered for mosquito control (Lacey and Orr 1994). *Toxorhynchites* is a genus of tree hole-inhabiting mosquitoes characterized by large predacious larvae that prey on smaller mosquito larvae. The iridescent blue-green adults are notably larger than other mosquitoes and do not feed on blood (Steffan 1968). Two species, *T. brevipalpis* and *T. amboinensis*, were released between the years 1950 and 1959 (Bonnet and Hu 1951, Nakagawa 1963, Steffan 1968). Although both species are probably established on all major islands, they have not reduced

the populations of *A. albopictus* or any other container-inhabiting species (Nakagawa 1963). The failure of *Toxorhynchites* as a self-sustaining biocontrol agent in Hawai'i is consistent with other attempts made worldwide; only through inundative releases of this predator has control been achieved (Lacey and Orr 1994).

Copepods in the genus *Mesocyclops* have shown some promise for the control of container-inhabiting mosquitoes (Riviere and Thirel 1981). Marten (1984) observed that in Hawai'i *A. albopictus* larvae were readily fed upon by a naturally occurring copepod, *M. leuckarti pilosa*. Under experimental conditions, these copepods provided complete control of the mosquito. Similar success using various *Mesocyclops* spp. has been reported for other container-inhabiting *Aedes* spp. (Gorrochotegui-Escalante et al. 1998, Kay et al. 2002, Nam et al. 2005). *Mesocyclops* are less effective at controlling *C. quinquefasciatus*, although some species show promise. A few copepod species have been adventitiously established in the Hawaiian Islands, including a species commonly used in control, *Mesocyclops aspericornis* (Nishida 2002). Copepods are frequently encountered in streambed rock pools even at high elevations (1,800 m), but their significance in limiting mosquito populations is unknown (D. LaPointe, unpubl. data). The value of *Mesocyclops* for control of mosquitoes in natural areas is greatly minimized by its susceptibility to desiccation and limited dispersal ability. As in the case of other invertebrate predators, periodic augmentation of copepod populations would be necessary to achieve lasting control (Lacey and Orr 1994).

Microbial pathogens of mosquitoes include protozoa, fungi, bacteria, and viruses. Many of these agents do not recycle or reproduce and must be reapplied in the manner of a chemical agent. They are commonly referred to as biopesticides. The most extensively used agent is the bacterium *Bacillus thuringiensis israelensis* (B.t.i.) (Margalit and Dean 1985). It produces a toxin very

selective for mosquitoes and other nematoceran flies such as midges, blackflies, and biting midges. No significant adverse non-target effects have been reported from numerous laboratory and field trials (Lacey and Mulla 1990). However, there is evidence that the long-term use of *B.t.i.* may alter aquatic invertebrate communities (Hershey et al. 1998). In Hawai'i, there is great concern that microbial agents will impact already threatened native species such as *Megalagrion* damselflies (Howarth 1991), but there is little evidence of direct or indirect toxicity of *B.t.i.* to odonates (Painter et al. 1996). The major disadvantages of *B.t.i.* use are its reduced efficacy in polluted water, its nonresidual nature, and difficulties associated with its application in dense vegetation.

*Bacillus sphaericus* came into commercial use later than *B.t.i.* and is particularly effective against *Culex* species (Singer 1985). Unlike *B.t.i.*, *B.sphaericus* provides good residual control, in part due to some natural recycling in the environment (Lacey et al. 1987). Some *C.pipiens* complex populations have developed resistance to *B.sphaericus*, but there is no evidence of cross-resistance with *B.t.i.* Thus, simple rotation of control agents in operational use should delay or prevent resistance development (Zahiri and Mulla 2003). No acute toxicity to or toxic trophic effects on nontarget species have been reported (Aly and Mulla 1987).

The most recently discovered microbe showing some promise for controlling *C.quinquefasciatus* populations is a baculovirus found naturally infecting *C.nigripalpus* (Becnel et al. 2001). This baculovirus has undergone limited testing to date and appears to infect only *Culex* species. It is a likely candidate for further development as a biopesticide (Andreadis et al. 2003).

In recent decades, the practice of biological control has been reevaluated as a growing body of evidence has clearly demonstrated the loss of native biota following the introduction of biological control agents (Simberloff and Stiling 1996). Some of the

most compelling evidence comes from the Hawaiian Islands, where early agricultural researchers introduced hundreds of generalist predators and parasitoids, to the detriment of native insects (Howarth 1991, Brenner et al. 2002). Certainly, the early introductions of fish for mosquito control have had an impact on the native aquatic biota of the islands (Englund 1999). It would appear that neither vertebrate nor invertebrate predators are suitable for control of mosquitoes in Hawaiian natural areas, because these generalists might depredate an already naturally depauperate aquatic fauna. Short-lived, selective biopesticides pose the least environmental hazard and have their greatest value in artificial impoundments, although they may prove useful in streambeds or constructed wetlands. Both *B.t.i.* and *B.sphaericus* are currently used by Hawai'i Department of Health (HDOH) Vector Control for mosquito control in artificial impoundments. *B.sphaericus* has been approved for use in natural wetlands.

#### THE STERILE MALE TECHNIQUE AND CYTOPLASMIC INCOMPATIBILITY

Perhaps the most efficient and elegant form of mosquito control would make the mosquito the agent of its own demise. Autocidal control methods have been considered since the 1940s and employ radio- or chemosterilization of males, genetic translocations, or bacterial symbionts to interfere with insect reproduction.

The sterile male technique (SMT) has been employed numerous times against both agricultural pests and vectors of human or livestock disease (Asman et al. 1981, Klassen 2003). However, most attempts have had limited success in suppressing or eliminating populations, and many of those that have been successful have targeted island or incipient populations (Vreysen et al. 2000, Koyama et al. 2004). Perhaps the most successful attempt to suppress a mosquito population

with SMT was conducted on Seahorse Key in Florida in 1969. The daily release of as many as 18,000 chemosterilized males for 10 weeks effectively eliminated *C. quinquefasciatus* from the key (Patterson et al. 1970). Later attempts by Patterson and co-workers (1977) were not as successful, and their failure was attributed to reduced sexual competitiveness in radiosterilized males and immigration into the target area by inseminated females.

Cytoplasmic incompatibility (CI) was first observed in the 1950s when researchers reported that some crosses of mosquito populations in the *C. pipiens* complex resulted in aborted embryonic development (Laven 1959). Originally thought to be a genetic effect, this phenomenon was later discovered to be caused by a maternally inherited bacterium, *Wolbachia pipiensis* (Yen and Barr 1971). CI can occur when an infected male mates with an uninfected female or when infected males and females of different crossing types mate (Bourtzis and O'Neill 1998). The potential use of CI for the control of mosquitoes was demonstrated by Laven (1967), who was able to eradicate a wild population of *C. quinquefasciatus* in Burma through the repeated releases of incompatible males. Despite the apparent success of this early trial, CI has been largely ignored as a control strategy.

Successful suppression or eradication of mosquitoes using SMT or CI requires that certain biological and logistical criteria be met: (1) target species should display female monogamy and male polygyny, (2) target populations should be limited in number and isolated from immigration from native inseminated females or mosquitoes of different CI crossing types, (3) sterile or *Wolbachia*-infected males should exhibit competitive mating behavior, (4) the technique must achieve a rate of sterility >95 %, (5) there must be adequate facilities and proven techniques for the mass production of sterile or *Wolbachia*-infected males and the 100% exclusion of females, and (6) a reliable delivery system

must be in place (Asman et al. 1981, Townson 2002).

*C. quinquefasciatus* populations have been suppressed in isolated villages and islets using SMT and CI, but is either approach applicable to the control of avian disease in the Hawaiian Islands? U.S. Department of Agriculture facilities and programs for the mass rearing and sterilization of tephritid fruit flies have been in Hawai'i for some time, and many of the logistical considerations about the rearing and release of these insects could be adapted for mosquitoes. An archipelago-wide survey for *Wolbachia* infection in *C. quinquefasciatus* needs to be conducted to determine if multiple crossing types are present or if an incompatible synthetic strain could be developed.

The size and landscape heterogeneity of the larger Hawaiian Islands would be insurmountable obstacles to mosquito eradication by SMT or CI. These techniques are more appropriate to smaller islands and atolls. Midway Atoll is geographically isolated, small, and accessible by air transport, making it an excellent location for an SMT or CI project. Complete eradication of mosquitoes on Midway Atoll would open the way for the translocation of Northwestern Island endemic passerines such as Nihoa Finches (*Telespiza ultima*) or Laysan Finches (*T. cantans*).

#### TRANSGENIC OR GENETICALLY MODIFIED MOSQUITOES (GMMS)

SMT and CI approaches to mosquito suppression have been largely eclipsed in recent years by genetic engineering, and the theoretical replacement of vector populations with a refractory transgenic mosquito (Box 17.1) has become the new Holy Grail of malaria control (Crampton et al. 1990, Morel et al. 2002). The main thrust of this research has been the development of molecular tools for the stable genetic transformation of mosquitoes (Catteruccia et al. 2000, Allen et al. 2001),

identification of refractory effector genes that will block parasite development (Niare et al. 2002), and the development of mechanisms to drive the refractory genotype into wild mosquito populations (Rasgon and Gould 2005). Much of this work has focused on the Anopheline vectors of human malaria, most notably *Anopheles gambiae*. The recently completed genome map of *A. gambiae* may aid the development of a refractory transgenic mosquito (Holt et al. 2002), but finding an efficient genetic drive mechanism remains the major technical obstacle and may take several more years to resolve (Morel et al. 2002).

There are many concerns associated with the transgenic approach to malaria control, ranging from the ethical to the ecological. General criticism focuses on the redirection of available malaria research dollars away from integrated control strategies and toward the transgenic approach. Some biological concerns include the outright failure of this approach to reduce transmission, the variability in phenotypic expression of the transgene, the transgene's impact on fitness, inadvertent enhanced virulence, and a breakdown in efficacy over time, followed by a pandemic resulting from a loss of population immunity (Spielman 1994, Scott et al. 2002, Tabachnick 2003).

What is unanimously agreed upon is that any responsible trial release of a trans-

genic mosquito should be done in such a way that any negative consequences would be limited in both geographical extent and impact on the target population. The avian malaria system in the Hawaiian Islands has many of the recognized criteria of a responsible (from an anthropocentric perspective) test location (Clarke 2002), and the first step in developing a transgenic *C. quinquefasciatus* has already been taken (Allen et al. 2001). It remains to be seen if further consideration of the Hawaiian avian malaria system in transgenic research will materialize. Transgenic techniques might have greater immediate value in the development of markers or conditional lethal genes for mosquitoes used in CI or SMT programs (Benedict and Robinson 2003). Even if this long-shot technique were feasible, changing the vector competence of a mosquito population for malaria would have no impact on the mosquito's ability to serve as a mechanical vector of avian pox.

#### PROTECTING ENDANGERED BIRD POPULATIONS

A number of high-elevation refugia with intact endemic forest bird communities were identified on the islands of Kaua'i, Maui, and Hawai'i (Scott et al. 1986). Only some of this land was already under federal, state, or private management (Chapter 16).

#### Box 17.1. Transgenic Mosquitoes 101

In genetic engineering, genes from one organism are incorporated into the genome of another organism. The resulting offspring that have successfully received the transgene are said to be transformed or transgenic. Initial transformation is achieved by direct injection of the target gene and a transposable element into the recipient eggs with a microsyringe. The transposable element is a segment of

DNA that moves genes about—the molecular equivalent of cutting and pasting. Refractory effector genes encode for mechanisms that prevent the development of the parasite or pathogen in a mosquito, and they are the target genes for malaria vector transformation. A genetic drive mechanism is a method by which the refractory genes are spread throughout a vector population.

In 1985, land was set aside for the Hakalau Forest National Wildlife Refuge (NWR), and in 1986 the Hanawī Natural Area Reserve was established on Maui. Preservation of high-elevation forest has continued with the acquisition of the South Kona subunit of Hakalau Forest NWR (1998) and the new Kahuku unit of Hawai'i Volcanoes National Park (2003). Studies of malaria prevalence in birds at high elevations (above ~1,500 m) suggest that local transmission is at most a very rare event (Feldman et al. 1995; Atkinson et al. 2005; this volume, Chapter 9) constrained by low-temperature effects on vector and parasite development (LaPointe 2000, Ahumada et al. 2004).

### Maintaining Transmission-Free Refugia

Acquisition and management of transmission-free high-elevation habitat is crucial to the preservation and restoration of native Hawaiian forest birds but is valuable only if it can be maintained as such well into the future. Barring the possible effects of global warming or a land use change that would create a warmer microclimate, these refugia should remain avian malaria transmission-free zones even in the presence of increasing mosquito numbers. Global warming could increase the altitudinal distribution of avian disease and would particularly threaten present-day refugia where the geology or land use, such as cattle grazing, might impede the upslope expansion of suitable forest habitat (Benning et al. 2002). Securing deforested and pasture land adjacent to protected refugia and managing it for forest growth is the best long-term contingency plan against a warming scenario.

Of more immediate concern is the nature of land use change after cattle ranching operations are phased out. Should land use in these adjacent areas instead shift to a more intensive agricultural or residential use, the effect of infrastructure and water

impoundment on transmission could be significant. Vector densities would increase as available larval habitat became more abundant, and temperature constraints on parasite development might be circumvented by infrastructure microclimates (Garnham 1948). Artificial structures absorb radiant energy, creating microclimates that foster parasite development. Careful consideration must be given to the construction of water impoundments and infrastructure so as not to create an environment conducive to high-elevation transmission of disease.

Even some techniques employed for game bird management, conservation, and habitat restoration work can backfire to support pathogen transmission. The use of black plastic tubs, barrels, or pond liners to provide water for game birds, outplantings, or bait for feral ungulates can support mosquito populations in areas where natural water sources or favorable water temperatures (through absorbed solar radiation) do not exist (D. LaPointe, pers. obs.). The construction of artificial wetlands for native waterfowl, such as Koloa (Hawaiian Ducks, *Anas wyvilliana*), is particularly risky and should be weighed against the potential harm to the overall avian community of the area. Approval of constructed wetlands should be contingent on routine monitoring for mosquito production and control when necessary.

### Creating Small Disease-Free Refugia

In the Hawaiian avian disease system, very low vector numbers support high rates of transmission. Therefore, a mere reduction in vector numbers may not be sufficient to prevent disease. Whenever feasible, control measures should strive for local eradication. Although SMT and CI strategies might be viable options for eradication of mosquitoes on smaller islands (Ni'ihau, Lāna'i, and Kaho'olawe) and atolls (Midway), source reduction is the best strategy

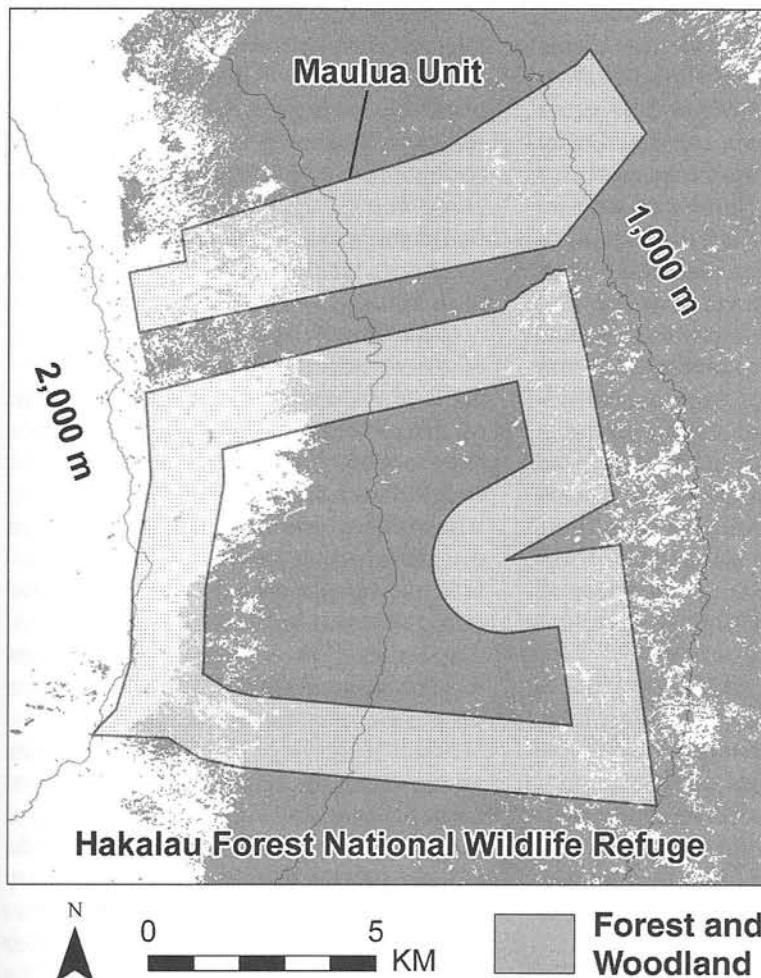


Figure 17.4. A model of mosquito ingressation at the Hakalau Forest National Wildlife Refuge. The stippling indicates the zone of mosquito penetration from unmanaged lands outside the refuge and is based on the conservative estimate of *Culex quinquefasciatus* dispersal at 1.6 km mean dispersal distance. In this scenario, mosquitoes have the potential to inundate the entire area of the detached northern Maulua Unit and reduce the effective transmission-free area of the main refuge by 60%. This figure emphasizes the importance of refuge configuration to avoid unmanaged inholdings and to realize the significance of unmanaged adjacent lands in disease transmission. Source: Adapted from LaPointe 2008: 607, Fig. 5, with permission from The Entomological Society of America.

for the main islands. Source reduction will most likely succeed in habitats that are already marginal for vectors.

Unlike wet forests, where natural and feral pig-associated larval mosquito habitats are likely to be abundant, xeric and mesic forests may produce mosquitoes only through human activities that accidentally or purposely impound water. Source reduction and/or treatment of impoundments can be accomplished with far less effort and environmental harm than use of such strategies in more natural habitats. Eliminating local production of mosquitoes will not be sufficient, however, if there are substantial nearby populations that can

disperse into the refuge. Kīpuka—islands of forest surrounded by lava flows—would make ideal sites for future refuges. Their natural isolation by younger lava flows would provide a maintenance-free buffer against dispersing vectors. Contiguous habitat would require the creation of a buffer to protect the core habitat from dispersing vectors. The extent of this buffer should be no less than 1.6 km, preferably 2–3 km, and refuge design should strive for a low ratio of perimeter to volume to minimize edge effects (Fig. 17.4). As a final consideration, planned refuges should not be in alignment with or adjacent to residential areas, roadways, or unmanaged wet forests along the path of prevailing winds. These areas might provide an abundance of vectors or corridors for wind-aided dispersal.

#### DISEASE MANAGEMENT IN LANDSCAPE-SCALE CONSERVATION UNITS

The prevalence of avian malaria and its impact on host populations vary greatly over the altitudinal range of forest bird habitat, so native Hawaiian forest birds are conspicuously missing from suitable habitat. On the high islands in particular, large tracts of native forest still extend the breadth of their elevational range, from coast to timberline, yet native bird densities and diversity are severely depleted at lower elevations (Scott et al. 1986).

#### The Landscape of Mosquito-Borne Avian Disease

Although pathogen transmission is virtually absent in high elevation forests (>1,500 m elevation), it is common seasonally in native birds in midelevation forests, often resulting in fatal epizootics. Most intriguing, however, is the situation in low coastal forests, where disease prevalence is extremely high and yet at least one group of honeycreepers, the ‘amakihi

(*Hemignathus spp.*), appears to have evolved tolerance. The year-round transmission that is characteristic of these coastal forests could be driving evolved tolerance. Low-elevation, disease-ridden forests may not be the endemic bird wasteland once supposed; instead they may serve as the principal habitat for coevolution of introduced pathogens and native birds (Woodworth et al. 2005).

What seems clear is that the restoration of native Hawaiian forest birds will depend on the preservation of the full extent of native forest habitat, from the high-elevation refugia through the epizootic zone at middle elevations down to the coast, where coevolutionary adaptation toward disease tolerance can occur. Ideal conservation landscapes would emulate the traditional Hawaiian unit of land division, the ahupua‘a, extending from mountains to seashore, and efforts to control disease should focus on midelevation forests.

Most of the large, midelevation forests remaining in the Hawaiian Islands are wet to mesic forests where *C. quinquefasciatus* and malaria are prevalent. The windward side of the main Hawaiian islands receives heavy rainfall (2,500–11,000 mm annual precipitation) (Giambelluca and Schroeder 1998). However, precipitation is not the sole predictor of a landscape’s potential for production of vectors or transmission of disease. Climate, geology, surface hydrology, and land use are strong determinants of disease prevalence. Currently, eradication of mosquitoes is unlikely in wet forests, but some strategies may reduce their overall abundance and limit their populations during years of favorable conditions.

#### Mosquito Control over Broad Landscapes

Although high-tech solutions such as vaccines and GMMs should not be ruled out, there are proven traditional approaches to mosquito control that are applicable and immediately available. Elimination of feral pigs and source reduction of artificial lar-

val mosquito habitats should be considered the first step in eliminating or reducing vector numbers. On windward Mauna Loa, for example, mosquito populations in large tracts of wet forests could be virtually eradicated through indirect source reduction in the form of feral pig removal. Though this management strategy is expensive and politically challenging, its potential overall benefit to the restoration of forest bird populations is unparalleled.

Due to the dispersal capability of *C. quinquefasciatus*, however, the success of feral pig removal in reducing transmission will be dependent on the size and shape of the managed land and on adjacent land use. Conservation units are better protected from immigrating mosquitoes when they are shaped to minimize edge effects and large enough to include a minimum dispersal buffer. The creation of narrow conservation units along altitudinal contours is to be avoided, because such units are more vulnerable to upslope, wind-enhanced mosquito dispersal.

For residential and agricultural areas adjacent to conservation units, integrated methods may be the best strategy. Initial survey and control measures could be conducted by the HDOH Vector Control staff and community volunteers while training landowners to identify and eliminate mosquito production on their personal property. Simple yard sanitation will suffice in many cases. However, domestic and agricultural impoundments that cannot be removed or covered may have to be treated with fish or a biopesticide such as *B.t.i.* Care should be taken when using fish to ensure that accidental introduction into natural waterways does not occur, and the continued use of biopesticides should include some rotation of agents to avoid resistance. The success of such efforts will depend on annual outreach, assistance from HDOH Vector Control, and the strength of neighborhood organizations.

In landscapes where intermittent streams produce the majority of vectors, there are

few realistic options for control. It remains to be determined if streambeds can be successfully treated by aerial application of biopesticides, and the cost is expected to be great. Aerial applications may be limited to years of low rainfall, when streambeds make significant contributions to mosquito numbers. Additionally, *C. quinquefasciatus* production in riparian landscapes may be reduced by protecting streams from fecal contamination by feral and domestic ungulates.

#### LESSONS FROM 100 YEARS OF HUMAN MALARIA CONTROL EFFORTS

Since the early 1900s, many nations have been engaged in malaria control. The early successes of Gorgas in reducing yellow fever in Panama, Soper's eradication of *A. gambiae* in Brazil, and Italy's success in the Pontina and Sardinia fueled an optimism that with enough financial resources and manpower, malaria could be eradicated (Harrison 1978). With the introduction and use of DDT, a formal worldwide malaria eradication campaign was launched by the World Health Organization (WHO) in 1956 (Desowitz 1991, Spielman et al. 1993).

The key strategy of the campaign centered on the use of a residual pesticide, DDT, to kill infected females and in turn break transmission long enough for existing cases of malaria to self-cure, a period estimated at five years. Additionally, active infections were treated with chloroquine, the most effective chemotherapeutic agent at the time. By 1967, a handful of European and Caribbean nations claimed eradication, and India, Pakistan, and Sri Lanka had greatly reduced malaria transmission. However, resistance to DDT and chloroquine quickly turned the tables. Five years later, WHO formally abandoned the goal of global eradication and advocated instead for malaria control, first by new anti-malarial drugs and later by an elusive

malarial vaccine that has never materialized (Desowitz 1991). By the time of the malaria eradication campaign's demise, malaria had undergone a global resurgence and the campaign had cost the United States alone \$790 million (Desowitz 1991).

The failure of the Global Eradication of Malaria Project was due to many factors. Poor communication from the field to policy makers led to an illusion of success, and a strict and unrealistic time frame derailed project funding before success could be achieved (Desowitz 1991, Spielman et al. 1993). For some regions, such as sub-Saharan Africa, the project failed because planners grossly underestimated the variability and plasticity of the vector and pathogen (Spielman et al. 1993). As pesticide and drug resistance spread around the world, the fallacy of reliance on a single control strategy was made clear. One of the most obvious errors of the program was the diversion of financial resources to control efforts with an almost complete abandonment of research and training (Spielman et al. 1993). When the old techniques failed, there were few alternative control methods to try, and few individuals were trained to take over the fight.

Although world health agencies are still lured by modern technology, pursuing elusive vaccines and the ultimate engineered mosquito, it is unlikely that a panacea for malaria will ever be found. Low-tech solutions, such as the use of insecticide-treated bed nets, have resulted in modest reductions in transmission, but when combined with traditional mosquito control and pharmaceutical treatment they could have a greater and lasting impact (Vogel 2002). Local, conservatively sized projects using integrated strategies are more likely to be sustainable and effective in malaria control (Spielman et al. 1993).

Though carried out at a much smaller scale, management actions to control mosquito-borne avian disease in Hawai'i (Table 17.1) would do well to heed these lessons. Eradication is realistic only for

geographically isolated areas where mosquitoes cannot reinvoke and where source reduction can completely eliminate larval habitat. For larger, more heterogeneous landscapes, an adaptive and sustainable management approach using integrative control strategies coupled with an active research program will ensure the selection of locally effective methods. Technologically sophisticated approaches such as transgenic refractory mosquitoes may be a risky investment but offer some potential. Finally, it is important to recognize that control efforts may require years of investment before significant results become evident and bird populations begin to recover.

## SUMMARY

In the past century, Hawaiian forest birds have undergone extinctions and steep population declines largely due to introduced, mosquito-borne avian pox and malaria. Today, while a few bird species appear to be coevolving to exist with these pathogens, most populations of endemic species continue to be severely limited by them. Disease is most prevalent in wet forests below 1,500 m, where the climate is favorable to both the introduced mosquito vector and avian malaria. Feral pigs have a key role in this disease system, for they often create the only or most favored larval habitat. As we begin to understand the dynamics and impacts of these diseases, it is clear that control of avian disease will be crucial to the recovery and restoration of native Hawaiian birds.

Due to the difficulties of mass administration or immunization, the use of antimalarial drugs and vaccines is limited to the protection of captive birds. Resistant bird populations may seem a ready source of individuals for restoration, but these populations and the epidemiological conditions that maintain them are relatively rare. Therefore, the options for avian disease control in wild birds must target vec-

Table 17.1. A summary of management strategies for the control of avian disease through vector manipulation and potential obstacles to their use

Management Recommendation	Technology Available?	Research or Technological Development Needed?	Politically Sensitive?	Environmentally Sensitive?
Improve communication with HDOH Vector Control	Yes	No	Maybe	No
Develop and disseminate outreach materials	Yes	Yes	No	No
Mandate source reduction and mosquito-proof design of refuge infrastructure	Yes	No	No	No
Consider vector movements during refuge acquisition and design	Yes	No	No	No
Eliminate feral pigs from conservation lands	Yes	No	Yes	No
Attempt eradication of mosquitoes on Midway Atoll using SMT or CI	Yes	Yes	No	No
Monitor and control mosquitoes in refuge wetlands	Yes	Yes	Maybe	Yes
Evaluate efficacy and nontarget impacts of <i>B.t.i.</i> control in natural streambeds	Yes	Yes	Maybe	Yes
Support disinfection of aircraft and container cargo	No	Yes	Yes	No
Develop and release a GM refractory mosquito	No	Yes	Yes	Maybe

tor abatement. Traditional pesticides and growth regulators offer little applicability in conservation areas where larval habitats are difficult to locate and treat and where native wildlife and invertebrates would be affected by nonspecific toxicity. Historically, classical biological control of mosquitoes in the Hawaiian Islands has failed to be self-sustaining or, worse, has led to the decline of native species. Even long-term augmentation and inundative releases of most biocontrol agents are unlikely to succeed given the vast area to be covered and the low density of the target prey. Only the crossover biopesticides are sufficiently biologically selective and cost-effective to be considered for some riparian and wetland areas in Hawai'i.

Source reduction and mosquito-proof design of refuge infrastructure is the first step in avian disease management. Direct source reduction through removal and

modification of artificial containers and impoundments and indirect source reduction through the elimination of feral pigs can successfully reduce and potentially eliminate vector populations. SMT may work to eradicate mosquitoes from small islands and atolls, but the transgenic mosquito approach is too immature for immediate consideration.

It is unlikely that there will be any magic bullets for abating avian malaria and pox in Hawai'i. The most productive conservation strategy would be to keep high-elevation refugia disease free, while the main management emphasis would focus on vector suppression at the middle elevations. We recommend investing resources into integrative mosquito control and the development of long-term disease management strategies. The successes and failures of the Global Malaria Control Program demonstrate the need to adopt and adapt

the old, proven technologies, such as source reduction, while keeping a hand in developing technologies. Avian disease management is essential to the preservation of the Hawaiian avifauna, and with sound research and a commitment from land management agencies, the impact of disease can be minimized.

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