Current and Potential Impacts of Mosquitoes and the Pathogens They Vector in the Pacific Region

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Mosquitoes and the pathogens they transmit are ubiquitous throughout most of the temperate and tropical regions of the world. The natural and pre-European distribution and diversity of mosquitoes and mosquito-borne diseases throughout much of the Pacific region, however, depicts a depauperate and relatively benign fauna reinforcing the dream of "paradise regained". In the central and South Pacific few mosquito species were able to colonize the remotest islands and atolls. Native mosquitoes are limited to a few far-ranging species and island endemics are typically restricted to the genera of *Aedes* and *Culex*. Only lymphatic filariasis appears to have been present as an endemic mosquito-borne disease before European contact.

In nearby Australia, however, some 242 species of mosquitoes are known to occur and more than 70 arboviruses have been identified (Mackenzie 1999). In this regard Australia is more similar to the rest of the tropic and subtropical world than the smaller islands of Oceania. In our ever-shrinking world of global commerce, military activity and travel, the nature of mosquito-borne disease in the Pacific was bound to change. This paper is a brief summary of introduced mosquitoes in the Pacific and their potential impacts on human and wildlife health.

Invasive Mosquitoes in the Pacific

Mosquitoes, as natural colonizers, are limited in their ability to disperse over ocean expanses by the adults' vulnerability to desiccation and the immatures' aquatic life cycle. For shorter distances, saltmarsh and mangrove species naturally fly great distances in search of blood meals. But even for those species that successfully disperse, the scarcity of suitable aquatic larval habitat and the uncertain availability of vertebrate blood are obstacles to establishment. For species that disperse to islands where surface waters are limited or seasonal, drought-resistant eggs and the use of small container habitats are important life history traits.

The first invasive mosquitoes in the Pacific may have accompanied Polynesians on their voyaging canoes as they colonized the islands of the central and south Pacific. These species would most likely have been domestic or peridomestic in habitat, have drought-resistant eggs and been able to use a wide variety of container habitats. This Polynesian-aided dispersal has been suggested for *Aedes polynesiensis* Marks, a widely-distributed member of the *Aedes scutellaris* (Walker) complex (Taylor 1998). Species in the *Aedes kochi* group exclusively use leaf axils as larval habitat but may have been similarly dispersed by Polynesians that carried screwpine (*Pandanus* spp.) or taro (*Colocasia* spp.) during voyages (Taylor 1998).

Notable changes in the global distribution of mosquitoes really began in the 15th century with the European-aided movement of *Aedes aegypti* (Linn.) out of West Africa. From the 17 through the 19th century Western exploration and trade in the old and new world tropics spread the two most domestic species, *Culex quinquefasciatus* Say and *Ae. aegypti,* throughout the tropic and subtropical world (Lounibos 2002). The whaling industry from the late 18th to 19th century probably contributed significantly in the spread of these mosquitoes in the Pacific. In the Hawaiian Islands, where no native mosquitoes exist, *Cx. quinquefasciatus* first appeared on Maui around 1826 (Lounibos 2002). *Culex quinquefasciatus* arrived in New Zealand sometime prior to 1848 (Lounibos 2002) and by the turn of the century was present on most of the major island groups in the Pacific.

By 1892, decades after the introduction of *Cx. quinquefasciatus*, *Ae. aegypti* was widespread and abundant in the Hawaiian Islands but just beginning to spread in the rest of the Pacific (Lounibos 2002). Similarly, by the turn of the century, *Aedes albopictus* (Skuse) was well established in Hawaii but curiously did not spread to other Pacific islands until the latter half of the 20th century. While the records of mosquito distributions at the time are scarce we know that *Cx. quinquefasciatus* and *Ae. aegypti* were widely dispersed throughout the Pacific at the turn of the century (Edwards 1928, Ward 1984). Another species, *Aedes vexans nocturnus* (Theobald), had spread throughout the western Pacific by this time as well.

Military activities during WWII and the Vietnam War contributed to the dispersal of mosquitoes from mainland Asia to the Pacific Islands. Intense surface and air movements of troops and equipment would have provided ample opportunity for adults and immature stages to transverse thousands of miles. The introduced mosquito fauna of Guam attests to the significance of military operations in the spread of mosquito species (Ward 1984). In 1935 O.H. Swezey collected six species of mosquitoes on Guam. Three were the pan-Pacific invasives; *Cx. quinquefasciatus*, *Ae. aegypti* and *Ae. vexans nocturnus*. In 1945 military entomologists reported ten species present on the island and in 1948 the first *Anopheles* found in Micronesia was reported (Reeves and Rudnick 1956).

Anopheles indefinitus (Ludlow) a species related to *Anopheles subpictus* Grassi is believed to have arrived from the Philippines on aircraft associated with troop movements during the WWII (Ward 1984). Similarly troop movements around 1945 are believed to have brought *Ae. albopictus* to Guam from nearby Saipan and Tinian where this species was reported to be abundant (Ward 1984). During the Vietnam War 12 new species of mosquito became established in Guam. Among these were four *Anopheles* species and three *Culex* species all from the Oriental region. Most notable was *An. subpictus*, an important vector of malaria and *Culex tritaeniorhynchus* Giles, the vector of Japanese encephalitis virus in Asia (Ward 1984, Nowell 1987).

The early 1960s also saw a dramatic increase in the amount of commercial air travel to the Pacific. In 1962 C. R. Joyce and P. Y. Nakagawa of the Public Health Service reported the establishment of *Ae. vexans nocturnus* on Oahu (Joyce & Nakagawa 1963). One year earlier Joyce had published data of mosquito interceptions from aircraft landing in Honolulu (Joyce 1961). *Aedes vexans nocturnus* was the most common *Aedes* intercepted and Joyce accurately predicted that this species would be the next exotic mosquito to become established in the Hawaiian Islands.

Today, global commerce and travel continues to facilitate the dispersal of new mosquito species into the Pacific region. A number of *Aedes* and *Ochlerotatus* species whose larvae naturally occur in rock pools and tree holes have made an adaptive shift to water-holding refuse automobile tires. A strong international trade in used tires is associated with the spread of two Asian species to North America (Lounibos 2002). The Asian Tiger mosquito, *Ae. albopictus*, is perhaps the most notorious of invasive mosquitoes having spread across the eastern half of the United States since its discovery in Houston, Texas in 1985 (Hawley 1988). From its native range in the Oriental region, India and the Indian Ocean islands, *Ae. albopictus* has increased its global distribution to include North America, Central and South America, the Caribbean, the Pacific and Southern Europe and all, presumably, by the used tire trade (Lounibos 2002).

The global spread of *Ae. albopictus* offers an object lesson in the value of improving regulation of the used tire trade. Still in 1998 another container mosquito from the Oriental region, *Ochlerotatus japonicus japonicus* (Theobald) became established in the mainland United States. This mosquito continues to spread outward along the Eastern shoreboard of the United States (Lounibos 2002), has become established in Washington State and, as of 2004, confirmed to be present on Hawaii Island (Larish and Savage 2005).

Horticultural imports may also contain mosquito stowaways. In 1981 a bromeliad-inhabiting mosquito *Wyeomyia mitchellii* (Theobald) was discovered on Oahu (Shroyer 1981). This species has since become established on Kauai and Hawaii Island (Nishida 2002). Larvae in the genera *Mansonia*, *Aedeomyia* and *Coquillettidia* are intimately associated with the submerged roots and stems of certain aquatic plants. Therefore it is possible that these mosquitoes may be introduced into new areas as a result of importation of ornamental aquatic plants or unintentionally on plant material attached to float planes (Lounibos 2002). A more recent example of mosquito dispersal through the horticultural trade is the appearance of *Ae. albopictus* in southern California associated with shipments of Lucky Bamboo (*Dracaena* spp.) from China (Madon et al. 2002).

By far the most likely route of entry would appear to be commercial air travel. In Hawaii, hundreds of flights arrive daily from the U.S. mainland and various countries. There has been a dramatic increase in air travel in the last few decades. Many of our visitors already come from the Oriental and Australasian region where mosquito-borne disease is endemic, and as Asian countries grow wealthier, their share in Pacific tourism will increase.

Air travel takes a matter of hours and live adult mosquitoes have been observed in passenger cabins, cargo holds and wheel housings (Gratz et al. 2000, Lounibos 2002). The regular occurrence of airport malaria in Europe and the United States is evidence that airliners are a potential route of entry for alien mosquito species and the diseases they vector (Gratz et al. 2000). In the United States, and many other countries, the practice of aircraft disinsection has been discontinued although it is been cited as the reason so few mosquitoes have been introduced to the Hawaiian Islands (Ward 1984). Today Australia and New Zealand continued to practice aircraft disinsection and have had apparent success at limiting the number of mosquito introductions into those countries (Lounibos 2002).

Endemic and Emerging Mosquito-borne Diseases in the Pacific Region

Most of the mosquito species that have invaded the Pacific islands are known vectors of human and wildlife disease but few mosquito-borne diseases are endemic in the region. From a historical perspective lymphatic filariasis is the only mosquito-borne disease endemic in the central and South Pacific. Lymphatic filariasis occurs throughout the tropics and it is considered the second most important disabling disease in the world today. An estimated 38% of Pacific Islanders are infected with *Wuchereria bancrofti* (Cobbold) the filarial worm that causes variable pathology in the lymphatic system including elephantiasis of the limbs (Burkot et al. 2002).

As there are no non-human hosts of *W. bancrofti*, mass drug administration (MDA) to entire island populations with annual doses of diethylcarbamazine (DEC) and albendazole has been considered to break transmission and eliminate this disease (Burkot et al. 2002). The Pacific Programme for the Elimination of Lymphatic Filariasis (PacELF) is a consortium of 22 South Pacific island nations that hopes to eliminate filariasis in the Pacific by 2010 (Burkot et al. 2002). However, skeptics of the MDA approach point to the extreme efficiency of *Ae. polynesiensis* as a vector and the difficulties associated with control of this species (Burkot et al. 2002). If the MDA approach fails, then the disease could likely undergo resurgence among the growing number of susceptible individuals.

Undoubtedly the most significant mosquito-borne disease of humans in the Pacific region today is dengue. Dengue is caused by four serotypes of a flavivirus that is transmitted between human hosts by three mosquitoes in the Pacific region, *Ae. aegypti*, *Ae. albopictus* or *Ae. polynesiensis*. Dengue fever is a flu-like illness that may leave individuals weakened weeks after initial recovery. Dengue hemorrhagic fever (DHF) is a severe form of the disease characterized by hemorrhaging, plasma leakage, and a case fatality rate of 5% (CDC 2003).

Dengue first appeared in the Pacific shortly after the arrival of *Ae. aegypti*. It was absent in the eastern Pacific for thirty years following WWII but the number of individual cases has been steadily increasing since the 1970's. Pacific-wide epidemics occurred in 1885, 1944, 1971, 1989, 1997 and 2001 and as the inter-epidemic intervals have decreased, the occurrence of DHF has increased (Chungue et al. 1998). *Aedes aegypti,* the principle vector, was virtually eliminated from the Hawaiian Islands and Guam following the 1940's outbreak largely by mosquito control efforts of the U.S. Army. After the 1944 pandemic, dengue did not resurface in Hawaii until 2001 (Effler et al. 2005). The 1975 dengue outbreak on Guam and the recent outbreak in Hawaii have been attributed to *Ae. albopictus* (Lounibos 2002, Effler et al. 2005). While research to develop a dengue vaccine is ongoing the immediate outlook for dengue in the Pacific is guarded with an expectation of more frequent epidemics and increased occurrence of DHF.

Ross River Virus is the most common arbovirus in Australia and the cause of epidemic polyarthritis. Although there is no mortality associated with this disease, the characteristic joint pain and lethargy can persist for months and be quite debilitating (Mackenzie et al. 1998). Like dengue, infected human hosts can infect mosquitoes and an extensive Pacific island outbreak in 1979 is believed to have started with an infected Australian tourist arriving in Fiji (Mackenzie et al. 1998). In Australia, *Culex annulirostris* Skuse has been identified as the principal inland vector but *Ae. polynesiensis* have been implicated in the Pacific islands outbreak (Rosen et al. 1981). While kangaroo and wallabies are believed to be the main enzootic reservoirs in Australia, native fruit bats have also been implicated (Mackenzie et al. 1998). As fruit bats are endemic to several Pacific islands there remains some possibility for Ross River virus to become established in the Pacific region. Certainly further outbreaks of the disease cannot be dismissed wherever *Cx. annulirostris* and *Ae. polynesiensis* are present.

Japanese encephalitis (JE) is another potentially emerging mosquito-borne disease in the Pacific region. Endemic throughout Asia, the JE flavivirus is enzootic in egrets and herons (Mackenzie et al. 1998). Unlike dengue and Ross River virus, a non-human host is required to infect the vector and domestic pigs generally serve as an amplifying host. Human illness can be severe with the case fatality rate averaging about 25% (Mackenzie et al. 1998). The primary vectors are members of the *Cx. tritaeniorhyncus* group but recent outbreaks in Australia have proved *Cx. annulirostris* to be a very competent vector (Russell and Kay 2004). An outbreak in the Marianas in 1947 was associated with endemic *Cx. annulirostris marianae.* As *Cx. annulirostris,* pigs, and herons are common throughout the Pacific it is a wonder that JE has not become established in the region.

West Nile virus (WNV) may pose the most immediate threat to the Hawaiian Islands and the westward Pacific. This flavivirus was first isolated in Uganda in 1937. Early outbreaks in humans were infrequent but recently outbreaks have occurred with increasing frequency and virulence in Africa, Asia, Europe and the Middle East (Campbell et al. 2002). In 1999 an outbreak in New York City started a North American epidemic that swept across the continent in five years. The virus is transmitted primarily by *Culex* mosquitoes and is enzootic in passerine birds. *Aedes albopictus*, *Ae. vexans* and *Ochlerotatus japonicus* have also been implicated as vectors (Turell et al. 2005). Potential vectors of WNV occur on all Pacific Islands.

Since human hosts are not reservoirs, the spread of the disease is thought to be by migratory birds or infective mosquitoes (Campbell et al. 2002). A risk analysis of possible modes of entry into Hawaii concluded that 7–70 infective mosquitoes could arrive from the mainland each year (Kilpatrick et al. 2004). State and federal interior and health agencies have been working together to prevent the introduction of WNv into the islands. Strict quarantine and embargo of live bird importation and the reinstating of aircraft disinsection are potentially protective measures. Early detection and the broad target application of adulticide are planned to prevent establishment of WNv (Olmsted 2005).

Introduced Bosquito-borne Avian Disease in the Hawaiian Islands

Introduced mosquito-borne avian disease may have contributed to the loss of more than half the known species of Hawaiian honeycreepers and continues to have a profound negative impact on native Hawaiian birds (vanRiper et al. 1986). The impact to Hawaiian biota may even cascade to native plants and associated invertebrates following the extinction of avian pollinators. Both avian malaria *Plasmodium relictum* and avian pox virus *Avipoxvirus* spp. were introduced to the Hawaiian Islands most likely through the importation of poultry and later exotic songbirds (vanRiper et al. 1986). Avian extinctions before the turn of the 19th century may have been associated with avian pox but avian malaria is believed to be responsible for extinctions and population declines in the 20th century. After nearly a century of exposure to avian malaria, most native birds still suffer high mortality rates between 60 and 93% (Atkinson et al. 1995). Recent evidence, however, suggests that low elevation populations of amakihi *Hemignathus virens* may be evolving tolerance to the disease (Woodworth et al. 2005). The Hawaiian avifauna may be uniquely susceptible to these diseases. Other Pacific avifauna appear to have co-evolved with similar indigenous pathogens and vectors. In American Samoa, where the native avifauna remains intact, native passerines were found infected with *Plasmodium circumflexum* and two additional mosquito-borne blood parasites (Atkinson et al. 2006).

The threat of WNV is not limited to the human inhabitants of the Pacific. Over 240 wildlife species have been affected by this virus. In the Pacific region endangered endemic raptor, corvid and other passerine species may be particularly vulnerable to WNV (Marra et al. 2004). As seen with avian malaria and avian pox many species in the monophyletic Hawaiian honeycreepers (Drepanidinae) are to susceptible to novel pathogens. Preliminary challenge experiments with amakihi and mainland isolates of WNV suggest that mortality from WNV is similar to that seen with avian malaria (unpublished data). But this applies only to otherwise healthy amakihi under laboratory condition. In a more natural setting amid environmental stressors and concomitant infections, WNV may be fatal.

Summary and Recommendations

Mosquitoes, and the pathogens they transmit, were largely absent from the islands of the Pacific region until Western expansion. During the 19th century, some of the most significant mosquito vectors of human disease invaded the Pacific through commercial pathways and that invasion continues today. With an increase rate of air travel and tourism throughout the region, an increase in the spread of mosquitoes and mosquito-borne disease can be predicted if importation regulations and vector control measures are not reevaluated. Aside from the obvious impact of human mortality and illness, increasing outbreaks of mosquito-borne disease may slow developing economies as vector control and health care costs rise and tourism fails (WHO 2005). In some cases native island biota may also be endangered.

To reduce the likelihood of these predictions the following recommendations should be considered. (1) Pacific-wide aircraft and cargo container disinsection. (2) The importation of vertebrate hosts of arboviral disease should be carefully regulated and adequate quarantine capabilities made available. (3) Importation of all aquatic organisms should be inspected specifically for immature mosquitoes. (4) Sanitary corridors, achieved through source reduction of larval mosquito habitat and population control of potential reservoir hosts, should be developed around all ports of entry.

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