

Original Contribution

Anthropogenic Environmental Change, Mosquito-borne Diseases and Human Health in New Zealand

José G. B. Derraik^{1,3} and David Slaney²

¹Ecology and Health Research Centre, Department of Public Health, Wellington School of Medicine and Health Sciences, University of Otago, P.O. Box 7343, Wellington, New Zealand

²Population and Environmental Health Programme, Institute of Environmental Science and Research Limited, P.O. Box 50-348, Porirua, New Zealand

³Biosecurity New Zealand, Ministry of Agriculture and Forestry, P.O. Box 2526, Wellington, New Zealand

Abstract: Anthropogenic environmental change is acknowledged as a primary factor in the emergence of diseases. New Zealand's history since human occupation has been characterized by extensive anthropogenic disturbance and the establishment of numerous exotic species. As a result, highly modified habitats have been created, which, in conjunction with introduced organisms, provide suitable conditions for the establishment of exotic systems likely to lead to outbreaks of mosquito-borne disease. The interactions among some disturbance factors in the New Zealand environment are discussed, and the potential public health implications.

Keywords: Anthropogenic change, mosquitoes, exotic species, arboviruses

INTRODUCTION

Human activities have been causing dramatic and unprecedented changes to the Earth's ecosystems (Vitousek et al., 1997b). There is an increasing awareness of the consequences of anthropogenic environmental disturbance on human health (Tadei and Thatcher, 2000; Vasconcelos et al., 2001; Waltner-Toews, 2001; Molyneux, 2002; Patz and Wolfe, 2002; Norris, 2004; Weinhold, 2004). Emerging infectious diseases are recognized as one of the greatest threats to public health in recent decades (Daszak et al., 2004; Weinhold, 2004), and 75% of these are estimated to be of zoonotic origin (Brown, 2004; Taylor et al., 2001). As a result, a growing number of outbreaks worldwide relate to the emergence of diseases in new areas or the resurgence of others once thought to be in decline (Gratz, 1997, 1999;

Longbottom, 1997; Gubler, 1998; Solomon and Mallewa, 2001; Patz and Wolfe, 2002).

A number of factors are behind the emergence of infectious diseases, but the main variables are the human-driven changes in the ecology of the diseases (especially pathogen–host relationships); as a result, for example, of human population expansion, destruction of and encroachment into natural habitats, and globalization (Daszak et al., 2000, 2004; Vasconcelos et al., 2001; Brown, 2004). The list of emerging pathogens and infectious diseases of concern include Ebola virus, Nipah virus, and severe acute respiratory syndrome (SARS) (Daszak et al., 2000; Brown, 2004; Li et al., 2005). A large number of vector-borne pathogens are also affecting human populations as a result of such process, for example, West Nile virus (Daszak et al., 2004), Rift Valley fever virus (Brown, 2004) and *Borrelia burgdorferi* (causative agent of Lyme disease) (Ostfeld et al., 2002).

Extensive anthropogenic disturbance is also acknowledged as a primary factor leading to the biological invasion of natural communities (Fox and Fox, 1986; Mack et al., 2000; Shea and Chesson, 2002); land use change and habitat modification, in particular, seem to be the main causes behind the spread of invasive species worldwide (Mooney and Hofgaard, 1999). Habitat fragmentation, for instance, leads to smaller habitats with proportionally more edge habitat that are, therefore, more susceptible to invasions than large contiguous ecosystems (Center et al., 1995). Disturbed edge habitats may function as staging areas from which exotic species invade the surrounding landscape (Center et al., 1995). Mosquitoes are some of the organisms that seem to benefit from such anthropogenic environmental changes. For example, the abundance of anopheline vectors of malaria in human-disturbed areas in the Brazilian Amazon, is on average five times that of undisturbed habitats (Tadei et al., 1998). The list of mosquito vector species that have been shown to be favored by anthropogenic environmental change include *Anopheles darlingi* (Jones, 2003), *Anopheles gambiae* (Holstein, 1954; Frankie and Ehler, 1978; Nelson, 1978), *Aedes aegypti* (Frankie and Ehler, 1978; Nelson, 1978), and *Anopheles albitarsis* and *Culex nigripalpus* (Forattini and Massad, 1998). Other arthropod vectors may thrive particularly well in such disturbed and fragmented habitats, such as the tick vectors of Lyme disease. A number of studies have indicated that there is a considerable increase in the density of infected ticks (i.e., Lyme disease risk) with decreasing forest habitat size (Ostfeld and Keesing, 2000a; Ostfeld et al., 2002; Allan et al., 2003; Weinhold, 2004).

The loss of native biodiversity can also contribute to disease emergence (Ostfeld and Keesing, 2000b). The consequences of species loss may not be immediately noticeable, but it appears to make ecosystems more vulnerable to disturbance and collapse (Peterson et al., 1998), and, therefore, generally more susceptible to invasive species. The decline in native biodiversity may consequently facilitate the establishment of exotic vectors. In addition, the disruption of ecosystem processes may lead to increased populations of reservoir hosts or vectors of human pathogens. Ostfeld and Keesing (2000ab) and Ostfeld et al. (2002) discussed how reduction in species diversity can directly lead to increased Lyme disease risk by boosting populations of the most competent reservoir hosts. Although the factors leading to Lyme disease resurgence may vary to a certain extent in different areas, the authors have nonetheless suggested that similar models may be appli-

cable to other vector-borne diseases that have comparable elements in their cycle. For example, according to Chivian and Sullivan (2002), a severe reduction in the population of the natural predators of the native deer mouse in the southwest USA, associated with certain climatic conditions, lead to an exponential increase in population numbers of the latter species. There was, as a result, a major increase in the exposure of people to a hantavirus carried by the mouse (Chivian and Sullivan, 2002); a subsequent outbreak in 1993 led to 17 confirmed clinical cases of hantavirus pulmonary syndrome in humans, 13 of which resulted in the death of the patients (Duchin et al., 1994).

NEW ZEALAND SCENARIO

New Zealand is still relatively free of exotic vectors that can transmit introduced parasites/pathogens to humans. There are at least two emerging exotic pathogens known to cause zoonoses in humans in New Zealand as part of an introduced disease cycle: *Rickettsia typhi* and *Bartonella henselae* (Kelly et al., 2004, 2005a,b; Roberts and Ellis-Pegler, 2001). Exotic rats (*Rattus* spp.) are the main reservoir hosts of *R. typhi* (causative agent of murine typhus), with the exotic oriental rat flea, *Xenopsylla cheopsis*, believed to be the primary vector (Kelly et al., 2005a; Roberts and Ellis-Pegler, 2001). Introduced domestic cats (*Felis domesticus*) are the major reservoir hosts of *B. henselae* (an agent of bartonellosis) and can transmit the pathogen directly to humans, but the exotic cat flea, *Ctenocephalides felis*, is also a vector (Kelly et al., 2004, 2005a). Human cases of both diseases are still somewhat rare and, so far, only 20 or so cases of infection with *R. typhi* and approximately five with *B. henselae* have been officially reported (Kelly et al., 2005a). However, it is possible that the actual incidence of human infection with these pathogens is considerably more common than indicated by the reported cases (Kelly et al., 2005b).

Nonetheless, to date, there has not been a confirmed, indigenously acquired arboviral infection in humans in New Zealand (Derraik and Maguire, 2005). This appears to be entirely fortuitous, as there are no particular characteristics that make the country intrinsically refractory to these viruses (Weinstein, 1994; Weinstein et al., 1997). It is predicted that it is just a matter of time before an arboviral outbreak occurs, most likely from Ross River virus (Weinstein et al., 1995; Weinstein, 1996; Kelly-Hope et al., 2002; Derraik and Calisher, 2004).

Daszak et al. (2004) pointed out that one of the ultimate goals of the evolving field of “conservation medicine” is to predict the emergence of pathogens. In such a context, New Zealand is a textbook example where human-induced changes will most likely lead to disease emergence. A number of components are necessary for an arboviral disease to pose a public health problem: the virus, its reservoir, the vector, the human population, and the local environment (Weinstein, 1994). Outbreaks of mosquito-borne disease often result from the nonsimultaneous introduction of vector and pathogen, and such has been the case, for example, in the avian malaria and dengue outbreaks in Hawaii (Juliano and Lounibos, 2005). Similarly, this article discusses a possible human disease scenario in New Zealand, whose exotic components have been gradually added to the country’s environment by human activities.

New Zealand’s Mosquito Fauna

There were only 12 mosquito species before the arrival of humans, and Laird (1990) suggested that this mosquito fauna was unusually limited, as New Zealand offers a temperate climate and adequate environments for mosquitoes. England and Japan, for instance, both of similar size and latitude, have 32 and 67 mosquito species, respectively (Holder et al., 1999). The New Zealand Simuliidae (black flies and sandflies), another blood-feeding family, is also species-poor with 13 species present (Macfarlane and Andrew, 2001), compared to 65 in Japan [Lee Rogers, personal communication, 2002].

There are four exotic mosquitoes established in New Zealand, all of which are potential disease vectors (Weinstein et al., 1997; Holder et al., 1999; Derraik, 2004a): *Culex quinquefasciatus*, *Aedes notoscriptus*, *Aedes australis*, and *Aedes camptorhynchus*. The cosmopolitan *Cx. quinquefasciatus* was the first exotic mosquito to establish in New Zealand (1840s), but it seems to be mostly restricted to northern New Zealand due to its climatic requirements. The other three exotic mosquitoes are Australian species. *Aedes notoscriptus* is the second most abundant and widespread species in the North Island (Laird, 1990; Hearnden et al., 1999), and it is particularly well-established in urban and peri-urban areas in northern New Zealand. *Aedes australis* seems to be restricted to the southern half of the South Island, where it breeds in saline rock pools along the shore (Snell, 2005). The last exotic mosquito to arrive in New Zealand was the Southern saltmarsh mosquito, *Ae. camptorhynchus*, one of the main arbovirus vectors in

Australia (Russell, 1995). This species was discovered in New Zealand in 1998, and it has since spread to a number of sites in the North Island and the northern tip of the South Island (Derraik and Calisher, 2004). *Aedes camptorhynchus* is currently the target of a government-funded program attempting to eradicate it.

At least 30 other exotic culicid species have been intercepted at national entry ports, including the Asian tiger mosquito, *Aedes albopictus*, and other important disease vectors such as *Aedes aegypti* and *Culex annulirostris* (Derraik, 2004a, 2006a). The establishment of other exotic vectors such as *Ae. albopictus* could increase the likelihood of a disease outbreak in New Zealand (Derraik, 2006a).

Anthropogenic Environmental Change

The New Zealand landscape has suffered dramatic changes since the arrival of humans c.800 years ago (Higham et al., 1999; McGlone and Wilmshurst, 1999), leading to extensive habitat destruction, extinction of native species, and the introduction of exotic ones (Cook et al., 2002). It is estimated that over 60% of the country’s land area has been converted into farms, exotic forests, settlements, and roads (Department of Conservation and Ministry for the Environment, 2000). Native forests and woodlands in New Zealand covered approximately 21 million ha (c.78% of total land area) in pre-human times (King, 1990). By 1840 (in early years of European settlement), this had been reduced to c.14 million ha (53%), and now just over 6 million ha (23%) remain (King, 1990). Such extensive reduction and modification of indigenous ecosystems has led to the extinction of numerous species, and New Zealand has one of the worst records of indigenous biodiversity loss (Department of Conservation and Ministry for the Environment, 2000).

Although one third of New Zealand’s land area is now conservation estate, most of it is in mountainous and upland areas (Department of Conservation and Ministry for the Environment, 2000). In general terms, the mid-altitudes and lowlands (below 800 m) have become freehold land, as they have the greatest agricultural value and, as a result, tend to be highly modified (Watt, 1979). Human activities have turned New Zealand’s unique environment into a framework of isolated fragments, and most lowland and mid-altitude patches of native ecosystems are now within or on the edge of farms or exotic forestry blocks (Department of Conservation and Ministry for the Environment, 2000).

Human-induced alterations of native ecosystems and exotic species introductions seem to be occurring at a more reduced scale; however, the cessation of all anthropogenic-related disturbances would unlikely halt the cycle of degradation. The disturbance process would still be driven by numerous established exotic species, which can alter ecosystem processes and disturbance regimes (Mack et al., 2000), and compete with, and/or consume, native species (Vitousek et al., 1997a).

Disturbance, Exotic Mammals, and Mosquitoes

There is accumulating evidence of mosquito species replacement occurring in New Zealand, at least for the Auckland region, where native species appear to be nearly absent from anthropic habitats where exotic mosquitoes thrive (especially in urban areas), in comparison to the opposite pattern occurring in relatively undisturbed indigenous ecosystems. Habitat modification in New Zealand seems to favor exotic mosquitoes, while negatively impacting on native species. An exception is the native *Culex pervigilans*, which seems to be a synanthropic species and the only native mosquito capable of inhabiting highly modified habitats, particularly urban areas.

A number of investigations using oviposition traps and dry ice-baited light traps have been recently carried out in a variety of habitats in the Auckland region. Sampling in relatively pristine native habitats indicated a mosquito fauna comprised almost entirely of native species (Derraik et al., 2005ab). The only exotic mosquito recorded was *Ae. notoscriptus*, but at very low numbers and only close to the forest edge. In contrast, sampling in urban and peridomestic habitats indicated that exotic mosquitoes were dominant (e.g., Derraik, 2004b, *in press*; Derraik and Slaney, 2005). *Aedes notoscriptus* is the dominant species, most likely as a result of its extensive utilization of container habitats. This species is the predominant peridomestic mosquito in Australia (Foley et al., 2004), and the same pattern is being observed in northern New Zealand. *Culex quinquefasciatus* is the other exotic mosquito commonly found, but it appears to have a more restricted distribution (Derraik and Slaney, 2005). *Culex pervigilans* is the only native species that can be regularly found in urban areas and anthropic habitats, particularly due to its wide environmental tolerance and ability to breed in all sorts of larval habitats (Derraik and Slaney, 2005). All other native mosquitoes that breed in freshwater appear to be absent from urban areas in northern New Zealand, although some

species seem able to occur in areas adjacent to native forests. At least one native mosquito species, *Maorigoeldia argyropus* (the single representative of this monospecific endemic genus), appears to have become endangered as a result of anthropogenic environmental change (Snell et al., 2005).

It should be noted that New Zealand's evolutionary history and its early separation from the rest of Gondwanaland led to an absence of indigenous terrestrial mammals, the dominant nonflying terrestrial animals in the rest of the world (Diamond, 1990), apart from three species of bats (King, 1990). As a result, New Zealand mosquitoes appear to be primarily bird-feeders (Derraik and Snell, 2004), although there is little experimental evidence supporting this assumption. The endemic *Coquillettidia iracunda* seems to be the only native mosquito species breeding in freshwater that will aggressively feed on humans (Derraik and Snell, 2004; Derraik, 2006a). However, this is a sylvan species, which breeds in ground pools on the forest floor, and is therefore absent from anthropic habitats, except those immediately adjacent to sections of native forest.

There are a number of exotic mammals in New Zealand, which are causing major impacts on native ecosystems that evolved in the absence of terrestrial mammal browsers and predators. The introduced mammal causing the most substantial impact is the Australian brushtail possum (*Trichosurus vulpecula*), which directly preys on fauna and feeds on flora (Cowan, 1990; Montague, 2000). These animals are estimated to be as many as 70 million (Parliamentary Commissioner for the Environment, 2000) and now occupy over 97% of the country's land area (Derraik, 2005b), thriving particularly well in modified habitats, especially at the forest/pasture interface (Cowan, 2000). Possums cause considerable habitat disturbance and could, as a result, potentially displace native mosquitoes, while in theory favoring invading species.

The presence of numerous exotic mammals provide a large supply of mammalian blood meals previously unavailable in New Zealand. Livestock provide abundant blood meals in rural areas where the availability of other hosts such as humans and birds are somewhat reduced, while brushtail possums are abundant throughout the country, even in very remote areas. There are, therefore, favorable conditions for the establishment of exotic mosquitoes, such as *Ae. albopictus* (Derraik, 2006a), which not only breeds in artificial and natural containers, but also prefers mammalian hosts (Hawley, 1988). This situation

could probably characterize an “invasional meltdown,” which according to Simberloff and Von Holle (1999) is a “process by which a group of nonindigenous species facilitate one another’s invasion in various ways, increasing the likelihood of survival and/or ecological impact” (p. 22). Furthermore, the presence of exotic mammals can boost vector populations so that these will seek additional hosts, consequently increasing the likelihood of pathogen transmission to humans (Patz and Wolfe, 2002).

The consequent species replacement that appears to be occurring as a result of anthropogenic environmental change in New Zealand means that a primarily bird-feeding native mosquito fauna (whose vector status is virtually unknown) is being replaced by an anthropophilic or opportunistic exotic mosquito fauna of known disease vectors. This situation is particularly pronounced in urban areas in northern New Zealand, where two anthropophilic exotic species are abundant (*Ae. notoscriptus* and *Cx. quinquefasciatus*) and the only native species present is *Cx. pervigilans*, which seems to be primarily a bird-feeder and will very rarely feed on humans.

There is evidence that larval mosquito habitats in New Zealand ecosystems are underutilized (Laird, 1990; de Wet et al., 2001; Derraik, 2005a), which may provide vacant niches for exotic vector species, in particular container breeders, and consequently enhance their likelihood of establishment (Derraik, 2005a, 2006a). The evidence also suggests that susceptibility to invasion is higher in species-poor communities (Fox and Fox, 1986), and this situation could be compounded by an apparent lack of effective predators of mosquito larvae in New Zealand (Weinstein et al., 1997).

In the case of *Ae. albopictus*, under current climatic conditions, the species is predicted to have a potential distribution covering the northern region of New Zealand’s North Island (Fig. 1) (de Wet et al., 2005a). This region includes Auckland and contains over a quarter of New Zealand’s population. The predicted distribution correlates well with a mean annual temperature above 14°C, and includes some isolated marginal sites on the northeast coast (not shown on Fig. 1), whereas *Ae. aegypti* would be unlikely to establish in New Zealand under current climatic conditions (de Wet et al., 2005a). De Wet et al. (2005ab) have modeled the potential distribution of a number of exotic mosquito species that are disease vectors, and suitable environmental conditions exist in northern New Zealand for the establishment of *Aedes polynesiensis*, *Aedes vigilax*, *Culex annulirostris*, *Aedes japonicus*, and *Aedes*

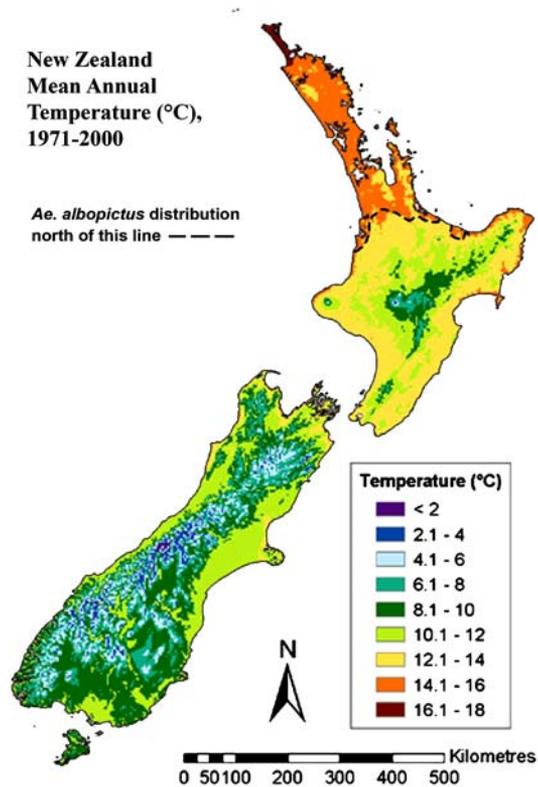


Figure 1. Predicted distribution of *Aedes albopictus* in New Zealand. Temperature data and map from National Institute of Water and Atmospheric Research (NIWA), and mosquito distribution data from de Wet et al. (2005a).

camptorhynchus (the latter is already established in the country).

Mosquito-borne Pathogens

The main limiting factor for the establishment of exotic pathogens in New Zealand is likely to be the climate, which appears to be relatively cold for the establishment of many tropical human diseases. No known human arbovirus of public health importance seems to be currently circulating endemically in New Zealand (Weinstein et al., 1995), however, there is a regular influx of viremic travelers, particularly from Australia (Kelly-Hope et al., 2002; Derraik and Calisher, 2004). Some important mosquito-borne pathogens could potentially become established in New Zealand, in particular, Japanese encephalitis virus, Barmah Forest virus, and especially Ross River virus (RRV) and West Nile virus (WNV).

West Nile virus is one of the mosquito-borne pathogens most likely to arrive in New Zealand, but a recent report outlined that the distribution of WNV in the country would be most likely determined by the distribu-

tion of suitable vectors (Spurr and Sandlant, 2004). The latter is potentially limited as the only known WNV vector currently established in New Zealand is *Cx. quinquefasciatus* (Turell et al., 2001), whose distribution is relatively sparse. However, since most native mosquitoes in New Zealand are most likely ornithophilic and some appear to occasionally feed on humans (Holder et al., 1999), their potential role as WNV vectors certainly needs investigation.

Ross River virus is the most common mosquito-borne pathogen affecting humans in Australia, annually causing at least 5000 illnesses (Russell, 2002), and is also the pathogen most likely to cause a mosquito-borne disease outbreak in New Zealand (Derraik and Calisher, 2004). The scenario for an outbreak of RRV (or other arboviruses) in New Zealand could resemble the major epidemic of RRV that occurred in the South Pacific in 1979 (Aaskov et al., 1981; Miles, 1984). The latter was a good example of disease emergence of major human health consequences, as a result of the introduction of an exotic disease system. This RRV epidemic seems to have started with the arrival of an infected human in Fiji, with the virus thought to have been transmitted by two introduced mosquito vectors, *Aedes vigilax* and *Culex annulirostris* (Miles, 1984). There were an estimated 50,000 clinical cases of RRV in Fiji, and more than 300,000 human infections (nearly half of the population) (Miles, 1984). The explosive nature of the Fijian outbreak is believed to have been a result of the low level of antibody to RRV in the community (Aaskov et al., 1981). Eventually the epidemic spread to Samoa, Cook Islands, New Caledonia, and Wallis and Futuna Islands (Miles, 1984). By 1981, however, there were no more reported cases in the islands (Miles, 1984). However, over the last 10 years, cases of RRV infection in travelers to Fiji have been sporadically reported, and RRV is likely to be still circulating there (Klapsing et al., 2005) [David Slaney, unpublished data].

There are no recognized alphaviruses or flaviviruses that affect humans in New Zealand, and it is unlikely that any immunity exists among the general population (Derraik and Calisher, 2004). Consequently, a similar “virgin soil” outbreak could occur in New Zealand, most likely in the Auckland region, the country’s largest city and main port of entry for people arriving from overseas and where most reported cases of imported mosquito-borne disease occur (Derraik and Calisher, 2004). Kelly-Hope et al. (2002) estimated that each year more than 100 people enter New Zealand from Queensland (Australia) alone with clinical and sub-clinical infections of RRV, for example;

Weinstein et al. (1995) pointed out that the number of circulating virus particles in humans in Auckland would likely initiate an outbreak if a competent mosquito vector were present.

Two of the established exotic mosquitoes, *Ae. camptorhynchus* and *Ae. notoscriptus*, are competent vectors of RRV (Doggett and Russell, 1997; Watson and Kay, 1998; Russell, 2002), and could potentially initiate an outbreak. *Aedes camptorhynchus*, in particular, is an important RRV vector in Australia (Russell, 2002), and although its actual distribution in New Zealand is still unknown, the species appears to be rare as a result of an ongoing eradication program. In contrast, *Ae. notoscriptus* is very abundant in anthropic habitats in the Auckland region, and although it seems to be one of the lesser vectors of RRV in Australia, there is increasing evidence that *Ae. notoscriptus* is an important vector of this virus in urban areas (Russell, 1995, 1998b; Doggett and Russell, 1997; Watson and Kay, 1997).

Miles (1984) pointed out that, during the South Pacific epidemic, there were 30 clinically diagnosed cases of humans reaching New Zealand from Fiji incubating RRV disease, but many more are believed to have gone unreported. John Miles (1984) believed that “had efficient vectors been present, spread would inevitably have occurred” (p. 221). He went further to state that “if this [*Ae. notoscriptus*] were an efficient vector, we would have expected indigenous cases,” but pointed out that species’ efficiency as a vector of RRV was unknown. Since *Ae. notoscriptus* was the only competent RRV vector known to be present in New Zealand at the time, based on Miles’ assumption, *Ae. notoscriptus* populations in New Zealand are either inefficient vectors of RRV or the local population was not dense enough at the time to initiate an outbreak. In the Fijian outbreak, an unusually large population of *Ae. vigilax* seems to have been important for the outbreak of RRV (Miles, 1984), and it is possible that in the absence of this unusually large density of *Ae. vigilax*, an outbreak might never have occurred. Therefore, it is plausible to assume that, at the time, the local populations of *Ae. notoscriptus* in New Zealand were not numerous enough to initiate a disease epidemic. Even though this species has been in New Zealand since, at least, the 1920s, the evidence suggests that this species distribution in the country is still expanding (Laird and Easton, 1994; Laird, 1995). Recent investigations have indicated the *Ae. notoscriptus* now occurs at high densities in the Auckland region, and appears to have surpassed the native *Cx. pervigilans* as the main mosquito species breeding in artificial and natural

containers (e.g., Derraik, 2004b, [in press](#); Derraik and Slaney, 2005).

Despite the very high level of human immunity to RRV in Fiji following the major 1979–1980 epidemic, it was thought that large populations of *Rattus* spp. and domestic pigs would have been able to maintain RRV as an enzootic infection. However, despite recent reported cases, RRV has apparently failed to become established in Fiji, most likely due to the absence of a suitable reservoir host (Miles, 1984; Weinstein, 1994). This situation could be somewhat different in New Zealand, due to the widespread and abundant brushtail possums that are competent hosts of RRV (Boyd et al., 2001; Boyd and Kay, 2001), and are suggested to be maintaining RRV epidemics in urban areas in Australia (Boyd and Kay, 2001). It should also be noted that RRV transmission from human to mosquito to human without the involvement of another animal host is believed to occur during periods of intense virus activity (Russell, 2002).

It is important to highlight that exotic mosquito-borne pathogens are not only a threat to human health, but also to New Zealand's unique native bird fauna (Derraik, 2006b). The introduction of *Cx. quinquefasciatus* and the *Plasmodium* parasite into Hawaii led to severe consequences, and it is estimated that nearly half of the country's endemic bird species have gone extinct as a result (van Riper et al., 1986). New Zealand's native birds could suffer a similar fate, and outbreaks of avian malaria have decimated some captive rearing populations of endangered birds (Derraik, 2006b). The threat may be aggravated by the fact that some widespread exotic bird species are believed to be asymptomatic carriers of the parasite (reservoir hosts) (Derraik, 2006b).

CONCLUSIONS AND RECOMMENDATIONS

Global warming is likely to favor mosquito populations and extend the areas susceptible to mosquito-borne diseases (Reeves et al., 1994; Russell, 1998a; Githeko et al., 2000; Reiter, 2001). The increase in average temperatures in New Zealand due to climate change would likely increase the likelihood of disease outbreaks occurring, as it would extend the areas of suitable climate for invading vector species such as *Ae. albopictus* and *Ae. aegypti*, and increase the rate of pathogen/parasite transmission (Weinstein et al., 1995; Hales et al., 1997; Watson et al., 1997; de Wet et al., 2001; Woodward et al., 2001). Likewise, in the event that Ross

River virus, for instance, becomes established in New Zealand, computer models predict a substantial increase in the number of reported cases under a global warming scenario [Knol et al., unpublished data].

The control of exotic mammals, both predators and browsers, is one of the most important measures to reduce disturbance in native ecosystems. The control of brushtail possums, particularly in the Auckland region, may also be a proactive approach to reduce the risk of a RRV epidemic and could become a necessary public health measure (Derraik, 2005b), especially since these animals are not only competent hosts of Ross River virus (Boyd et al., 2001; Boyd and Kay, 2001), but in Australia have also yielded antibodies to other arboviruses such as Barmah Forest virus (Boyd et al., 2001), Sindbis virus, and Murray Valley encephalitis virus (Azuolas, 1997).

The arrival in New Zealand of mosquito species such as *Ae. albopictus*, that are aggressive human biters, could aggravate the likelihood of an arboviral outbreak occurring, in particular, of RRV and WNV (Derraik, 2006a), as this species is a competent vector of these viruses (Russell, 2002; Sardelis et al., 2002). New invading species that are anthropophilic or opportunistic are therefore a major reason for concern, and border controls need to work to minimize the risk of other exotic vectors arriving and establishing in New Zealand (Derraik, 2004a, 2006a).

The only component of a mosquito-borne disease cycle affecting humans yet to become established in the country is an exotic pathogen. Therefore, New Zealand needs self-sufficiency with regard to arboviral testing in laboratories (Weinstein, 1994; Derraik and Calisher, 2004). Furthermore, there is no doubt that considerable work needs to be done to adequately assess the vector status of both native and exotic mosquitoes in New Zealand to a variety of human pathogens, especially those most likely to occur here such as Ross River virus, Barmah Forest virus, West Nile virus, and dengue viruses. It seems that New Zealand will eventually have to establish an effective vector control strategy, while also educating the general public on basic mosquito control and avoidance measures.

ACKNOWLEDGMENTS

Thanks to Cathy Rufaut and Gerry Closs (University of Otago), Bill Lee (Landcare Research), Sandy Toy and Sarah Clinehens (Biosecurity NZ), and two anonymous reviewers for valuable feedback on previous versions of this

manuscript. Thanks also to Lee Rogers (The National History Museum, London) for relevant information.

REFERENCES

- Aaskov JG, Mataika JU, Lawrence GW, Rabukawaqa V, Tucker MM, Miles JAR, et al. (1981) An epidemic of Ross River virus infection in Fiji, 1979. *American Journal of Tropical Medicine and Hygiene* 30:1053–1059
- Allan BF, Keesing F, Ostfeld RS (2003) Effect of forest fragmentation on Lyme disease risk. *Conservation Biology* 17:267–272
- Azuolas JK (1997) Arboviral diseases of horses and possums. *Arbovirus Research in Australia* 7:5–7
- Boyd AM, Hall RA, Gemmell RT, Kay BH (2001) Experimental infection of Australian brushtail possums, *Trichosurus vulpecula* (Phalangeridae: Marsupialia), with Ross River and Barmah Forest viruses by use of a natural mosquito vector system. *American Journal of Tropical Medicine and Hygiene* 65:777–782
- Boyd AM, Kay BH (2001) Solving the urban puzzle of Ross River and Barmah Forest viruses. *Arbovirus Research in Australia* 8:14–22
- Brown C (2004) Emerging zoonoses and pathogens of public health significance—an overview. *Revue Scientifique et Technique (International Office of Epizootics)* 23:435–442
- Center TD, Frank JH, Dray FA (1995) Biological invasions—stemming the tide in Florida. *Florida Entomologist* 78:45–55
- Chivian E, Sullivan S (2002) Biodiversity and human health. In: Conservation Medicine: Ecological Health in Practice, Aguirre AA, Ostfeld RS, Tabor GM, House CA, Pearl MC (editors), New York: Oxford University Press, pp 182–193
- Cook A, Weinstein P, Woodward A (2002) The impact of exotic insects in New Zealand. In: Pimentel D (editor), *Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal, and Microbe Species* Boca Raton, FL: CRC Press, pp 217–239
- Cowan P (2000) Factors Affecting Possum Re-infestation—Implications for Management. Science for Conservation 144, Wellington, NZ: Department of Conservation
- Cowan PE (1990) Brushtail possum. In: King CM (editor), *The Handbook of New Zealand Mammals* Auckland, NZ: Oxford University Press, pp 68–98
- Daszak P, Cunningham AA, Hyatt AD (2000) Emerging infectious diseases of wildlife—threats to biodiversity and human health. *Science* 287:443–449
- Daszak P, Tabor GM, Kilpatrick AM, Epstein J, Plowright R (2004) Conservation medicine and a new agenda for emerging diseases. *Annals New York Academy of Sciences* 1026:1–11
- de Wet N, Slaney D, Ye W, Warrick R, Hales S (2005a) Hotspots: Exotic Mosquito Risk Profiles for New Zealand. International Global Change Institute, University of Waikato, and Ecology and Health Research Centre, University of Otago. Available: <http://www.waikato.ac.nz/igci/hotspots/> [accessed November 28, 2006]
- de Wet N, Slaney D, Ye W, Warrick R, Hales S (2005b) Hotspots—Capacity for the Analysis of Mosquito-borne Disease Risks in New Zealand. A Case Study of *Ochlerotatus campitorhynchus* Incursions in New Zealand. International Global Change Institute, University of Waikato, and Ecology and Health Research Centre, University of Otago. Available: <http://www.waikato.ac.nz/igci/hotspots/> [accessed November 28, 2006]
- de Wet N, Ye W, Hales S, Warrick R, Woodward A, Weinstein P (2001) Use of a computer model to identify potential hotspots for dengue fever in New Zealand. *New Zealand Medical Journal* 114:420–422
- Department of Conservation and Ministry for the Environment (2000) New Zealand Biodiversity Strategy, Wellington, NZ: Department of Conservation and Ministry for the Environment
- Derraik JGB (2004a) Exotic mosquitoes in New Zealand: a review of species intercepted, their pathways and ports of entry. *Australian and New Zealand Journal of Public Health* 28:433–444
- Derraik JGB (2004b) A survey of the mosquito (Diptera: Culicidae) fauna of the Auckland Zoological Park. *New Zealand Entomologist* 27:51–55
- Derraik JGB (2005a) Mosquitoes breeding in phytotelmata in native forests in the Wellington region, New Zealand. *New Zealand Journal of Ecology* 29:185–191
- Derraik JGB (2005b) Brushtail possums (*Trichosurus vulpecula*) may pose a threat to public health in New Zealand. *Australian and New Zealand Journal of Public Health* 29:91
- Derraik JGB (2006a) A scenario for invasion and dispersal of *Aedes albopictus* (Diptera: Culicidae) in New Zealand. *Journal of Medical Entomology* 43:1–8
- Derraik JGB (2006b) Bitten birds: piecing together the avian malaria puzzle. *Biosecurity* 65:16–17
- Derraik JGB (in press) Larval mosquito (Diptera: Culicidae) survey in modified habitats in the Auckland Region. *Entomotropica*
- Derraik JGB, Calisher CH (2004) Is New Zealand prepared to deal with arboviral diseases?. *Australian and New Zealand Journal of Public Health* 28:27–30
- Derraik JGB, Maguire T (2005) Mosquito-borne diseases in New Zealand: has there ever been an indigenously acquired infection?. *New Zealand Medical Journal* 118:1670
- Derraik JGB, Slaney D (2005) Container aperture size and nutrient preferences of mosquitoes (Diptera: Culicidae) in the Auckland region, New Zealand. *Journal of Vector Ecology* 30:73–82
- Derraik JGB, Snell AE (2004) Notes on daytime biting catches of mosquitoes (Diptera: Culicidae) in native forest sites in the Auckland region. *The Weta* 28:14–19
- Derraik JGB, Snell AE, Slaney D (2005a) An investigation into the time of activity of adult mosquitoes (Diptera: Culicidae) seeking host-cues in West Auckland. *New Zealand Entomologist* 28:85–90
- Derraik JGB, Snell AE, Slaney D (2005b) Vertical distribution of mosquitoes in native forest in Auckland, New Zealand. *Journal of Vector Ecology* 30:334–336
- Diamond JM (1990) New Zealand as an archipelago: an international perspective. In: Towns DR, Daugherty CH, Atkinson IAE (editors), *Ecological Restoration of New Zealand Islands* Wellington, NZ: Department of Conservation, pp 3–8
- Doggett SL, Russell RC (1997) *Aedes notoscriptus* can transmit inland and coastal isolates of Ross River and Barmah Forest viruses from New South Wales. *Arbovirus Research in Australia* 7:79–81
- Duchin JS, Koster FT, Peters CJ, Simpson GL, Tempest B, Zaki SR, et al. (1994) Hantavirus pulmonary syndrome: a clinical description of 17 patients with a newly recognized disease. *New England Journal of Medicine* 330:949–955

- Foley DH, Russell RC, Bryan JH (2004) Population structure of the peridomestic mosquito *Ochlerotatus notoscriptus* in Australia. *Medical and Veterinary Entomology* 18:180–190
- Forattini OP, Massad E (1998) Culicidae vectors and anthropic changes in a Southern Brazil natural ecosystem. *Ecosystem Health* 4:9–19
- Fox MD, Fox BJ (1986) The susceptibility of natural communities to invasion. In: Groves RH, Burdon JJ (editors), *Ecology of Biological Invasions* Cambridge, UK: Cambridge University Press, pp 57–66
- Frankie GW, Ehler LE (1978) Ecology of insects in urban environments. *Annual Review of Entomology* 23:367–387
- Githeko AK, Lindsay SW, Confalonieri UE, Patz JA (2000) Climate change and vector-borne diseases: a regional analysis. *Bulletin of the World Health Organization* 78:1136–1147
- Gratz NG (1997) Dengue and dengue hemorrhagic fever: a spreading pandemic. *Public Health* 14:20–29
- Gratz NG (1999) Emerging and resurging vector-borne diseases. *Annual Review of Entomology* 44:51–75
- Gubler D (1998) Resurgent vector-borne diseases as a global health problem. *Emerging Infectious Diseases* 4:442–450
- Hales S, Weinstein P, Woodward A (1997) Public health impacts of global climate change. *Reviews on Environmental Health* 12:191–200
- Hawley WA (1988) The biology of *Aedes albopictus*. *Journal of the American Mosquito Control Association* 4:1–39
- Hearnden M, Skelly C, Weinstein P (1999) Improving the surveillance of mosquitoes with disease-vector potential in New Zealand. *New Zealand Public Health Report* 6:25–32
- Higham T, Anderson AJ, Jacomb C (1999) Dating the first New Zealanders: the chronology of Wairau Bar. *Antiquity* 73:420–427
- Holder P, Browne G, Bullians M (1999) The mosquitoes of New Zealand and their animal disease significance. *Surveillance* 26:12–15
- Holstein MH (1954) *Biology of Anopheles gambiae*, Geneva: World Health Organization
- Jones N (2003) Diseases are running rife in forest remnants. *New Scientist* 2381:15
- Juliano SA, Lounibos LP (2005) Ecology of invasive mosquitoes: effects on resident species and on human health. *Ecology Letters* 8:558–574
- Kelly PJ, Meads N, Theobald A, Fournier P-E, Raoult D (2004) *Rickettsia felis*, *Bartonella henselae*, and *B. clarridgeiae*, New Zealand. *Emerging Infectious Diseases* 10:967–968
- Kelly PJ, Roberts S, Fournier P-E (2005a) A review of emerging flea-borne bacterial pathogens in New Zealand. *New Zealand Medical Journal* 118:U1257
- Kelly P, Rolain JM, Raoult D (2005b) Prevalence of human pathogens in cat and dog fleas in New Zealand. *New Zealand Medical Journal* 118:U1754
- Kelly-Hope LA, Kay BH, Purdie DM, Williams GM (2002) The risk of Ross River and Barmah Forest virus disease in Queensland: implications for New Zealand. *Australian and New Zealand Journal of Public Health* 26:69–77
- King CM (editor) (1990) *The Handbook of New Zealand Mammals*. Auckland, NZ: Oxford University Press
- Klapsing P, MacLean JD, Glaze S, McClean KL, Drebot MA, Lanciotti RS, et al. (2005) Ross River virus disease reemergence, Fiji, 2003–2004. *Emerging Infectious Diseases* 11:613–615
- Laird M (1990) New Zealand's northern mosquito survey, 1988–89. *Journal of the American Mosquito Control Association* 6:287–299
- Laird M (1995) Background and findings of the 1993–94 New Zealand mosquito survey. *New Zealand Entomologist* 18:77–90
- Laird M, Easton JM (1994) *Aedes notoscriptus* (Diptera: Culicidae) in Wellington Province. *New Zealand Entomologist* 17:14–17
- Li W, Shi Z, Yu M, Ren W, Smith C, Epstein JH, et al. (2005) Bats are natural reservoirs of SARS-like coronaviruses. *Science* 310:676–679
- Longbottom H (1997) Emerging infectious diseases. *Communicable Diseases Intelligence* 21:89–93
- Macfarlane RP, Andrew IG (2001) New Zealand Diptera identification diversity and biogeography: a summary. *Records of the Canterbury Museum* 15:33–72
- Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA (2000) Biotic invasions: causes, epidemiology, global consequences, and control. *Ecological Applications* 10:689–710
- McGlone MS, Wilmshurst JM (1999) Dating initial Maori environmental impact in New Zealand. *Quaternary International* 59:5–16
- Miles JAR (1984) On the spread of Ross River virus in the islands of the South Pacific. In: Laird M (editor), *Commerce and the Spread of Pests and Disease Vectors* New York: Praeger Publishers, pp 209–224
- Molyneux DH (2002) Vector-borne infections and health related to landscape changes. In: Aguirre AA, Ostfeld RS, Tabor GM, House CA, Pearl MC (editors), *Conservation Medicine: Ecological Health in Practice* New York: Oxford University Press, pp 194–206
- Montague TL (editor) (2000) *The Brushtail Possum—Biology, Impact and Management of an Introduced Marsupial*. Lincoln, NZ: Manaaki Whenua Press
- Mooney HA, Hofgaard A (1999) Biological invasions and global change. In: Sandlant OT, Schei PJ, Viken A (editors), *Invasive Species and Biodiversity Management* Dordrecht, The Netherlands: Kluwer Academic Publishers, pp 139–148
- Nelson BC (1978) Ecology of medically important arthropods in urban environments. In: Frankie GW, Koehler CS (editors), *Perspectives in Urban Entomology* New York: Academic Press, pp 87–124
- Norris DE (2004) Mosquito-borne diseases as a consequence of land use change. *EcoHealth* 1:19–24
- Ostfeld RS, Keesing F (2000a) Biodiversity and disease risk: the case of Lyme disease. *Conservation Biology* 14:722–728
- Ostfeld RS, Keesing F (2000b) The function of biodiversity in the ecology of vector-borne zoonotic diseases. *Canadian Journal of Zoology* 78:2061–2078
- Ostfeld RS, Keesing F, Schaub EM, Schmidt KA (2002) The ecological context of Lyme disease—biodiversity, habitat fragmentation, and risk of infection. In: Aguirre AA, Ostfeld RS, Tabor GM, House CA, Pearl MC (editors), *Conservation Medicine: Ecological Health in Practice* New York: Oxford University Press, pp 207–219
- Parliamentary Commissioner for the Environment (2000) *Caught in the Headlights: New Zealander's Reflections on Possums, Control Options and Genetic Engineering*, Wellington, NZ: Parliamentary Commissioner for the Environment
- Patz JA, Wolfe ND (2002) Global ecological change and human health. In: Aguirre AA, Ostfeld RS, Tabor GM, House CA, Pearl

- MC (editors), Conservation Medicine: Ecological Health in Practice New York: Oxford University Press, pp 167–181
- Peterson G, Allen CR, Holling CS (1998) Ecological resilience, biodiversity, and scale. *Ecosystems* 1:6–18
- Reeves WC, Hardy JL, Reisen WK, Milby MM (1994) Potential effect of global warming on mosquito-borne arboviruses. *Journal of Medical Entomology* 31:323–332
- Reiter P (2001) Climate change and mosquito-borne disease. *Environmental Health Perspectives* 109(Suppl 1):141–161
- Roberts S, Ellis-Pegler R (2001) Murine typhus in New Zealand. *New Zealand Public Health Report* 8:73–75
- Russell RC (1995) Arboviruses and their vectors in Australia: an update on the ecology and epidemiology of some mosquito-borne arboviruses. *Review of Medical and Veterinary Entomology* 83:141–158
- Russell RC (1998a) Mosquito-borne arboviruses in Australia: the current scene and implications of climate change for human health. *International Journal for Parasitology* 28:955–969
- Russell RC (1998b) Vectors vs humans in Australia—who is on top down under? An update on vectorborne disease and research on vectors in Australia. *Journal of Vector Ecology* 23:1–46
- Russell RC (2002) Ross River virus: ecology and distribution. *Annual Review of Entomology* 47:1–31
- Sardelis MR, Turell MJ, O’Guinn ML, Andre RG, Roberts DR (2002) Vector competence of three North American strains of *Aedes albopictus* for West Nile virus. *Journal of the American Mosquito Control Association* 18:284–289
- Shea K, Chesson P (2002) Community ecology theory as a framework for biological invasions. *Trends in Ecology and Evolution* 14:170–176
- Simberloff D, Von Holle B (1999) Positive interactions of non-indigenous species: invasional meltdown?. *Biological Invasions* 1:21–32
- Snell AE (2005) The discovery of the exotic mosquito *Ochlerotatus australis* and the endemic *Opifex fuscus* (Diptera: Culicidae) on North East Island, Snares Islands. *The Weta* 30:10–13
- Snell AE, Derraik JGB, McIntyre M (2005) *Maorigoeldia argyropus* Walker (Diptera: Culicidae): is this another threatened endemic species?. *New Zealand Entomologist* 28:95–99
- Solomon T, Mallewa M (2001) Dengue and other emerging flaviviruses. *Journal of Infection* 42:104–115
- Spurr EB, Sandlant GR (2004) *Risk Assessment for the Establishment of West Nile Virus in New Zealand*. Lincoln, NZ: Manaaki Whenua Press
- Tadei WP, Thatcher BD (2000) Malaria vectors in the Brazilian Amazon: *Anopheles* of the subgenus *Nyssorhynchus*. *Revista do Instituto de Medicina Tropical de São Paulo* 42:87–94
- Tadei WP, Thatcher BD, Santos JMM, Scarpassa VM, Rodrigues IB, Rafael MS (1998) Ecologic observations on anopheline vectors of malaria in the Brazilian Amazon. *American Journal of Tropical Medicine and Hygiene* 59:325–335
- Taylor LH, Latham SM, Woolhouse ME (2001) Risk factors for human disease emergence. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 356:983–989
- Turell MJ, Sardelis MR, Dohm DJ, O’Guinn ML (2001) Potential North American vectors of West Nile virus. *Annals of the New York Academy of Sciences* 951:317–324
- van Riper C III, van Riper SG, Goff ML, Laird M (1986) The epizootiology and ecological significance of malaria in Hawaiian land birds. *Ecological Monographs* 56:327–344
- Vasconcelos PFC, Travassos da Rosa APAT, Rodrigues SG, Travassos da Rosa ES, Dégallier N, Travassos da Rosa JFS (2001) Inadequate management of natural ecosystem in the Brazilian Amazon region results in the emergence and reemergence of arboviruses. *Cadernos de Saúde Pública* 17:155–164
- Vitousek PM, Dantonio CM, Loope LL, Rejmanek M, Westbrooks R (1997a) Introduced species: a significant component of human-caused global change. *New Zealand Journal of Ecology* 21:1–16
- Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997b) Human domination of Earth’s ecosystems. *Science* 277:494–499
- Waltner-Toews D (2001) An ecosystem approach to health and its applications to tropical and emerging diseases. *Cadernos de Saúde Pública* 17:7–36
- Watson RT, Zinyowera MC, Moss RHE (1997) The Regional Impacts of Climate Change: an Assessment of Vulnerability, Geneva: International Panel on Climate Change
- Watson TM, Kay BH (1997) Is *Aedes notoscriptus* (Skuse) an urban vector of Ross River virus in Southeast Queensland?. *Arbovirus Research in Australia* 7:305–307
- Watson TM, Kay BH (1998) Vector competence of *Aedes notoscriptus* (Diptera: Culicidae) for Ross River virus in Queensland, Australia. *Journal of Medical Entomology* 35:104–106
- Watt JC (1979) New Zealand invertebrates. In: A Vanishing Heritage: The Problem of Endangered Species and Their Habitat Wellington, NZ: Nature Conservation Council, pp 140–146
- Weinhold B (2004) Infectious disease: the human costs of our environmental errors. *Environmental Health Perspectives* 112:A32–A39
- Weinstein P (1994) The Real and Potential Risks of Human Arboviral Disease in New Zealand, Porirua, NZ: Communicable Disease Centre, Institute of Environmental Science and Research Ltd
- Weinstein P (1996) When will mosquitoes strike?. *New Zealand Science Monthly* 7:6–7
- Weinstein P, Laird M, Browne G (1997) Exotic and Endemic Mosquitoes in New Zealand as Potential Arbovirus Vectors, Wellington, NZ: Ministry of Health
- Weinstein P, Laird M, Calder L (1995) Australian arboviruses: at what risk New Zealand?. *Australian and New Zealand Journal of Medicine* 25:666–669
- Woodward A, Hales S, de Wet N (2001) Climate Change: Potential Effects on Human Health in New Zealand, Wellington, NZ: Ministry of Environment