Exotic mosquitoes in New Zealand: a review of species intercepted, their pathways and ports of entry

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Abstract

A review was carried out to identify the exotic mosquito species intercepted in New Zealand to 2004, together with their origins, pathways and ports of entry into the country. A total of 171 interceptions have been recorded since 1929. There was little or no taxonomic information available for many, but at least 27 exotic species not yet established in New Zealand have been intercepted, including important disease vectors such as *Aedes albopictus*, *Aedes aegypti* and *Culex annulirostris*. Of 152 interception records with a described origin, 100 (66%) have originated from the South Pacific, 42 (28%) from Australia alone, while Japan was the likely source for 22 (15%) interceptions and has become the main source of exotic mosquitoes since the 1990s. Aircraft have clearly been the main vessel for invading mosquitoes with 94 (62%) of 151 cases with a described entrance pathway, but that pattern has changed greatly in the past 15 years, with 51 (82%) of 62 interceptions occurring on ships. Auckland, New Zealand's largest city, has been the main port of entry for invaders (75/93; 81%). The data indicate that it is somewhat fortunate that New Zealand has only four exotic mosquito species established. It is necessary, therefore, to adopt comprehensive exotic species monitoring and border surveillance, with particular emphasis on incoming ships and their cargo, in order to stop further mosquito invasions that could potentially lead to future outbreaks of mosquito-borne diseases.

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New Zealand, together with Hawaii, is recognised for its remarkable biota.[1,2] Hawaii was free of mosquitoes until the ship-borne arrival of *Culex (Culex) quinquefasciatus* Say in 1826.[3] In New Zealand, there were only 12 indigenous mosquito species before the arrival of humans (see Table 1). Laird suggested that this mosquito fauna was unusually limited, as the country offers a temperate climate and adequate environments for mosquitoes.[4] England and Japan, for instance, both of similar size and latitude, have 32 and 67 mosquito species, respectively.[5] New Zealand's species-poor mosquito fauna and high level of anthropogenic environmental disturbance make it particularly vulnerable to invasion by exotic mosquitoes. This susceptibility is worsened by the likely underutilisation of larval breeding containers for mosquitoes in New Zealand.[6]

Since the arrival of humans c.800 years ago,[7,8] the New Zealand environment has been plagued by the invasion of a very large number of exotic species. The rate of invasion has been aggravated since European settlement and the ever-increasing arrival of goods and passengers. The problem of invading species became considerably worse during the 20th century, which brought an exponential rise in the number of ships (and later aircraft) moving around the world, greatly increasing the opportunities for the spread of plants and animals, including mosquitoes.[3] Commerce became the most important medium for species invasion,[9] and the volume and frequency of commercial shipments continues to increase (both via sea and air), making the risk of new invasions higher than ever. The interception of important disease vectors has consequently become commonplace throughout the Pacific.[6,10] In the case of New Zealand, a large number of exotic invertebrate species are now established in the country, with the count at approximately 2,200 in 1997.[11]

The threat to the public health of New Zealand posed by invading vector mosquitoes has been acknowledged for over half a century. In the 1950s, for instance, Laird warned about the likelihood of the introduction of anophelines into the malaria-free zone of the South Pacific.[10,12] Thirty years later, Laird's fears had subsequently become a reality with the establishment of anophelines in several South Pacific areas.[3] Global travel has therefore become pivotal in the emergence of infectious diseases, including those that are mosquito-borne.[13]

Although no outbreaks of mosquito-borne human diseases have ever been recorded in New Zealand,[14] one *Alphavirus* (Whataroa virus) has been isolated from the endemic *Culiseta (Climacura) tonnoiri* (Edwards) and *Culex (Culex) pervigilans* Bergroth in South Westland.[15-17] Hogg et al. provided some evidence of arbovirus infection in man in Westland,[18] but there has been no subsequent confirmation of the latter and it may have been mistakenly identified as such. None the less, the situation could change because of

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the tide of species introductions, which pose a serious threat to New Zealand's economy, public health and conservation estate. This study therefore aimed at identifying the exotic mosquito species that are a threat to New Zealand, as well as their respective origins, invasion pathways and ports of entry.

Materials and Methods

To carry out a comprehensive review of the mosquito interception records in New Zealand, I have accessed data from three different sources:

1. Peer-reviewed literature.
2. Interception records published and/or released to the public domain by biosecurity and health authorities.
3. Unpublished interception records kept by biosecurity and health authorities.

In order to obtain the above material, the entomological library and the reprint collection of the Museum of New Zealand Te Papa Tongarewa were thoroughly searched. Whenever a relevant publication was encountered, its list of references was searched for other articles and reports that could provide further information. Note that since almost all interception records described in the peer-reviewed literature were published in the first half of the 20th century, these are largely unavailable in searchable electronic databases.

The New Zealand's Ministry of Health (MoH) website (www.moh.govt.nz) was searched for media releases and other publications concerning mosquito interceptions. To ensure that the data were comprehensive, I contacted the MoH to obtain all remaining and yet unpublished records. For the same reason, the Ministry of Agriculture and Forestry (MAF, New Zealand's main biosecurity authority) and the New Zealand Armed Forces (in charge of military airports) were also contacted.

The data were cross-checked to ensure the same interceptions described in different publications would not be mistakenly cited more than once.

Results and Discussion

The interception records

There is an overall paucity of published accounts on all aspects relating to mosquitoes in the country, and I am confident I accessed all peer-reviewed literature describing interceptions of exotic mosquitoes. Information from the first decades of 1900s was very scarce, and data could only be gathered from a few entomological publications, in particular those by Graham.[19,20] Mosquito interceptions only started to be given some relevance with Marshall Laird's publications dealing specifically with insect interceptions in the 1940s and 1950s. His accounts, however, mostly covered interceptions at New Zealand's military base in Whenuapai (Auckland), from the middle of the Second World War until the early 1950s.[12,21,22]

Official interception records seem to have only started to be catalogued since 1955, which was the first year covered in a series of volumes describing insect interceptions published by the New Zealand Plant Quarantine Service (Department of Agriculture).[23] These publications covered a period from 1955 until 1982.[24] During the subsequent years archiving of interception data was not well managed, and it seems that culicid data covering the period from 1982 to 1993 is not easily retrievable at the present time (Alan Flynn, personal communication 2004). None the less, thanks to Alan Flynn (National Plant Pest Reference Laboratory) I was able to obtain internal records from MAF covering the period from 1993 to 1999. Moreover, some significant interceptions that occurred in the early 1990s (including post-border detections) have come to light in a peer-reviewed article by Marshall Laird.[6]

Table 1: List of established mosquito species in New Zealand, their origins and associated pathogens.

Origin	Species	Associated pathogens
Endemic	*Coquillettidia (Austromansonia) tenuipalpis* (Edwards)	unknown
	Coquillettidia (Coquillettidia) iracunda (Walker)	unknown
	Culex (Culex) asteliae Belkin	unknown
	Culex (Culex) pervigilans Bergroth	WH
	Culex (Culex) rotoruae Belkin	unknown
	Culiseta (Climacura) novaezealandiae Pillai	unknown
	Culiseta (Climacura) tonnoiri (Edwards)	WH
	Maorigoeldia argyropus (Walker)	unknown
	Ochlerotatus (Nothoskusea) chatamicus (Dumbleton)	unknown
	Ochlerotatus (Ochlerotatus) antipodeus (Edwards)	unknown
	Ochlerotatus (Ochlerotatus) subalbirostris (Klein & Marks)	unknown
	Opifex fuscus Hutton	unknown
Exotic	*Culex (Culex) quinquefasciatus* Say	AM AP BF CH JE KUN LF MVE RR SIN SLE WNV
	Ochlerotatus (Finlaya) notoscriptus (Skuse)	BF CH DEN JE RR RVF
	Ochlerotatus (Halaedes) australis (Erichson)	CH DEN RR WH
	Ochlerotatus (Ochlerotatus) camptorhynchus (Thomson)	BF KOK RR SIN

Note:
Arboviruses: BF (Barmah Forest), DEN (dengue), JE (Japanese encephalitis), KOK (Kokobera), KUN (Kunjin), MVE (Murray Valley encephalitis), RR (Ross River), RVF (Rift Valley fever), SIN (Sindbis), SLE (St. Louis encephalitis), WH (Whataroa), WNV (West Nile). Other pathogens: AM (Plasmodium relictum, avian malaria), AP (avian pox viruses), CH (Dirofilaria immitis, canine heartworm), LF (Wuchereria bancrofti, lymphatic filariasis).

Table 2: List of unidentified and already established exotic mosquito species intercepted in New Zealand, with respective ports of entry and details of the findings.

Species	Entrance pathway	Location of interception	Country of origin[b]	Year of record[a]
Aedes sp.	aircraft	–	Norfolk Island	1951[21]
	aircraft	–	Australia	(1955-65)[23]
	aircraft	–	Fiji	(1955-65)[23]
	aircraft	–	France	(1955-65)[23]
	aircraft	–	Fiji/Samoa	2x (1966-72)[101]
	aircraft	–	–	(1979-82)[24]
	bananas (?)	–	Ecuador	(1979-82)[24]
Culex sp.	aircraft	–	Australia	7x (1955-65)[23]
	aircraft	–	Fiji	5x (1955-65)[23]
	aircraft	–	–	(1966-72)[101]
	aircraft	–	Australia	2x (1966-72)[101]
	aircraft	–	Hong Kong	(1966-72)[101]
	tent (?)	–	India	(1973-78)[116]
	aircraft	–	Australia	(1979-82)[24]
	container (ship)	–	Australia	(1979-82)[24]
	used tyres (ship)	–	Australia	1995 (MAF, unpublished data)
	aircraft	Auckland	–	1997 (MAF, unpublished data)
	aircraft	Auckland	Tonga	1997 (MAF, unpublished data)
	aircraft	Auckland	Sri Lanka	1998 (MAF, unpublished data)
	aircraft	Auckland	Malaysia	1998 (MAF, unpublished data)
	aircraft	Auckland	Fiji	1998 (MAF, unpublished data)
	cargo (ship)	Tauranga	Papua New Guinea	2001 (MAF, unpublished data)
	cargo (ship)	Tauranga	–	2001 (MAF, unpublished data)
	cargo (ship)	Tauranga	Papua New Guinea	2002 (MAF, unpublished data)
	cargo (ship)	Auckland	–	2002 (MAF, unpublished data)
	used tyres (ship)	Auckland	England	2003[117]
Culex sp. (*pipiens* or *pervigilans*)	aircraft	–	Fiji	(1955-65)[23]
Culex sp. (*pipiens* or *quinquefasciatus*)	aircraft	–	Australia	(1955-65)[23]
Culex (Culex) quinquefasciatus Say	aircraft	Auckland	Australia	1950[12]
	aircraft	Auckland	Fiji	2x 1950[12]
	aircraft	Auckland	New Caledonia	1943-44[22]
	aircraft	Auckland	Australia	4x (1955-65)[23]
	aircraft	–	Australia	(1966-72)[101]
	aircraft	–	Hawaii	(1966-72)[101]
	produce (?)	–	Tonga	(1979-82)[24]
	cargo (ship)	Auckland	Samoa	1997 (MAF, unpublished data)
	cargo (aircraft)	Auckland	Indonesia	1997 (MAF, unpublished data)
	used tyres (ship)	Auckland	Japan	1998 (MAF, unpublished data)
	cargo (ship)	Auckland	Philippines	2x 1998 (MAF, unpublished data)
	cargo (aircraft)	Auckland	USA	2000 (MAF, unpublished data)
	used machinery (ship)	Auckland	Japan	2003[118]
Ochlerotatus sp.	used tyres (ship)	Auckland	USA	2002 (MoH, unpublished data)
Ochlerotatus (Finlaya) notoscriptus (Skuse)	used tyres (ship)	Auckland	Australia	2003[119]
	used machinery (ship)	Auckland	Australia	2003 (MoH, unpublished data)
	used tyres (ship)	–	Australia	1995 (MAF, unpublished data)
Unidentified genus	aircraft	–	Australia	(1950-53)[120]
	aircraft	Auckland	New Hebrides	(1943-44)[118]
	aircraft	Auckland	New Caledonia	2x (1943-44)[118]
	aircraft	Auckland	Fiji/New Caledonia	(1943-44)[118]
	aircraft	–	Australia	(1955-65)[23]
	pineapple (?)	–	Australia	(1955-65)[23]
	aircraft	–	Fiji	(1955-65)[23]

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Species	Entrance pathway	Location of interception	Country of origin	Year of record
Unidentified genus	aircraft	–	USA	(1955-65)[23]
(cont. from previous page)	aircraft	–	Australia	(1966-72)[101]
	aircraft	–	Australia/USA	(1966-72)[101]
	aircraft	–	–	2x (1966-72)[101]
	aircraft	–	Hong Kong	(1966-72)[101]
	aircraft	–	American Samoa	(1966-72)[101]
	aircraft	–	Singapore	(1966-72)[101]
	plants (?)	–	Tonga	(1966-72)[101]
	–	–	–	(1973-78)[116]
	aircraft	–	–	(1973-78)[116]
	aircraft	–	Australia	(1973-78)[116]
	aircraft	–	Tahiti	(1973-78)[116]
	container (ship)	–	–	(1973-78)[116]
	effects (?)	–	Papua New Guinea	(1973-78)[116]
	effects (?)	–	Singapore	(1973-78)[116]
	orchids (?)	–	–	(1973-78)[116]
	tent (?)	–	Australia	(1973-78)[116]
	grapes (?)	–	USA	(1973-78)[116]
	aircraft	–	Fiji	(1973-78)[116]
	aircraft	–	Australia	(1979-82)[24]
	melons (?)	–	Australia	(1979-82)[24]
	effects (?)	–	Indonesia	(1979-82)[24]
	bananas (?)	–	Cook Islands	(1979-82)[24]
	dried seafood (?)	–	Hong Kong	(1979-82)[24]
	aircraft	–	–	1998 (MAF, unpublished data)
	cargo (ship)	Auckland	USA	2001 (MAF, unpublished data)

Notes:
(a) In many cases the year of interception was not recorded, but rather the period in which it occurred. In the case of identical interceptions in a particular year or period, the number of times it occurred is given.
(b) The country of origin is assumed to be the last port of call of ship or aircraft prior to its arrival in New Zealand.
?=entrance pathway unknown.

Eventually, with scientists warning about the risks of an arboviral disease outbreak in New Zealand,[25-28] public health authorities seem to have become aware of the importance of border control. From 1998 onwards, the MoH started to periodically report cases of mosquito interceptions through media releases, which provided detailed description of species and the circumstances relating to their interceptions. I was also able to obtain the remaining unpublished data from the MoH since 1998, which was provided by Annie Coughlan and Sally Gilbert.

Most of the interception records described in this review consisted of data from biosecurity and health authorities, mainly official media releases and published interception records. These records were, however, largely incomplete and had relevant data missing, and with few exceptions they did not state whether adults or larvae were intercepted. Moreover, most of the data available prior to the 1990s provided little or no taxonomic information and offered limited information about the circumstances surrounding individual interceptions.

Overall, the records on the interceptions of mosquitoes in New Zealand were uneven in their coverage, indicating an apparent absence of records for certain periods of the 20th century. Nevertheless, this survey is, to the best of my knowledge, comprehensive and clearly demonstrates the real threat posed by exotic mosquitoes to the public health of New Zealand.

Exotic mosquitoes already established in New Zealand

There are four exotic mosquito species established in New Zealand, which represent 25% of the country's culicid fauna (see Table 1). All four species are potential disease vectors.[5,29]

The first exotic mosquito species to become established in New Zealand was *Culex quinquefasciatus*. It was recorded in 1848,[6] and probably arrived on an American whaling vessel.[30] This species is cosmopolitan throughout the warmer regions of the world,[31] most likely as a result of international commerce.[32] It is an efficient vector of West Nile virus (WNV),[33] St Louis Encephalitis virus (SLE),[34] *Wuchereria bancrofti* (lymphatic filariasis, LF)[35] and *Dirofilaria immitis* (canine heartworm, CH).[31] *Culex quinquefasciatus* is also a vector of Japanese encephalitis (JE),[36] Murray Valley encephalitis (MVE), Kunjin (KUN) and Sindbis (SIN) viruses.[37,38] Lindsay et al. described the isolation of Ross River virus (RR) from this species,[39] but the authors believe that the species is likely to have little or no role in the transmission of the virus, as did Kay et al.[40] Barmah Forest virus (BF) has also been isolated from this mosquito species in Australia.[58] *Culex quinquefasciatus* is also a vector of *Plasmodium relictum* (avian malaria) and avian pox viruses, and its introduction to Hawaii led to the extinction of native bird species.[41] Avian malaria has been recorded in New Zealand,

and the species is likely to have been the vector responsible for the outbreaks.[42]

The Australian *Ochlerotatus (Finlaya) notoscriptus* (Skuse) has been in New Zealand since at least 1920.[43] It is at present one of the most abundant and widespread species in the North Island,[4,44] and it seems particularly well established in urban and peri-urban areas. This species is a vector of CH,[45] a potential vector of BF,[46] a laboratory vector of Rift Valley Fever (RVF),[47] dengue (DEN)[25] and JE viruses.[36] *Ochlerotatus notoscriptus* is most likely a vector of RR in urban areas.[38,48-50]

Ochlerotatus (Halaedes) australis (Erichson) was first reported in 1962,[51] and it seems to be restricted to the southern half of the South Island. The species breeds in saline rock pools along the shore.[52] It is a laboratory vector of DEN and RR,[25] Whataroa virus[15] and CH.[53]

The last species to arrive in New Zealand was the Southern salt-marsh mosquito *Ochlerotatus (Ochlerotatus) camptorhynchus* (Thomson). This Australian species was discovered in 1998 near Napier, on the east coast of the North Island,[54] and it has since been found in several other localities, most recently near Blenheim in the South Island.[55] Although eradication programs are under way, it is unlikely that this species will be eradicated from New Zealand.[56] *Ochlerotatus camptorhynchus* is regarded as a vicious biter[53] and it is one of the most important arbovirus vectors in Australia.[38] In New Zealand, *Oc. camptorhynchus* may become a serious public health hazard[56] as an efficient vector of RR,[57] a vector of BF,[58,59] Kokobera (KOK) and SIN viruses.[38]

The invading species

There were at least 171 interceptions of exotic mosquitoes in New Zealand since 1929 (75 years) (see Tables 2 and 3). For most interceptions, however, there was little or no taxonomic data on the species concerned (see Table 2). As a result, the majority of specimens listed in Table 2 are unidentified, with some identified as *Culex* or *Aedes* species. *Culex quinquefasciatus* and *Oc. notoscriptus* were two of the species recorded yet were already known to be established.

The list of interceptions in Table 3 includes the taxa not yet established in New Zealand, and adds to at least 27 new species. The actual number of such species is likely to be higher, since not even the genera involved in 35 interceptions have been identified (see Table 2).

Post-border interceptions

There were four recorded cases of post-border interceptions (see Table 3), but none of the species involved has become established in New Zealand. The first post-border interception was of *Culex (Culex) annulirostris* Skuse, initially discovered breeding in the hold of a ship from Fiji, in Auckland in 1929.[20] Live larvae were subsequently found in a barrel on the nearby waterfront and destroyed. This same species was intercepted on at least nine other occasions, the latest one in 1999.[60] *Culex annulirostris* is probably Australia's main arbovirus vector, involved in the transmission of LF and CH,[53] and of BF,[37] JE,[36] KOK,[61] Gan Gan (GG), Alfuy (ALF), Edge Hill (EH), SIN and Trubanaman (TRU) viruses.[38,62] The species is a primary vector of KUN and MVE,[63] RVF,[47] and RR.[57,64]

Also in 1929, larvae of a species described as *Aedes (Aedimorphus) vexans* Meigen were found in a tin can among rocks in Russell, Bay of Islands.[20] However, both Laird[30] and Belkin[65] agree that it is likely to have been a misidentification of the Fijian *Aedes (Aedimorphus) nocturnus* (Theobald), a species not known to be a vector of diseases.[65]

The last post-border interceptions (excluding that of *Oc. camptorhynchus*) were of the Asian tiger mosquito *Aedes (Stegomyia) albopictus* (Skuse) and *Ochlerotatus (Finlaya) japonicus* (Theobald) in 1993, in Auckland suburbs. The cases were well described by Laird et al.,[6] as they were part of several interceptions of mosquitoes in used tyres over a relatively short period of time. The fact that neither of these species became established in New Zealand is very fortunate.

Aedes albopictus, in particular, has already spread to many countries,[66-70] and it has been listed as one of the world's worst invasive alien species by the World Conservation Union (IUCN).[71] This species has been intercepted in New Zealand at least 12 times, usually as larvae in used tyres (see Table 3), its main mode of invasion worldwide.[72-76] Laird et al. believe that cold-hardy strains of *Ae. albopictus* coming from Japan could become established in New Zealand.[6]

Aedes albopictus is a serious public health hazard as a vector of yellow fever (YF), DEN, RR,[57,76] Chikungunya (CHIK),[77] La Crosse encephalitis (LAC)[78] and Eastern equine encephalitis (EEE)[79] viruses, and possibly JE and CH.[73] This species has also been found to be a very efficient laboratory vector of WNV.[80] Apart from being a vector of many diseases, *Ae. albopictus* is a particularly vicious biter, and its public health impacts as a general nuisance can be substantial. According to some dermatologists, this species' bites are painful and provoke wheals that are particularly troublesome when victims are not used to its toxin, which can often lead to a haemorrhagic appearance.[81]

Ochlerotatus japonicus utilises invasion pathways similar to *Ae. albopictus*, with incoming ships from Japan being involved in the nine recorded interceptions, including three in used tyres (see Table 3). Interestingly, the species was not recorded in New Zealand until 1993, and all interceptions occurred in the last 11 years (see Table 3). *Ochlerotatus japonicus* seems capable of becoming established in New Zealand, being adapted to colder conditions and able to survive snowy winters.[82] The species is a vector of JE[83] and it is an efficient laboratory vector of WNV.[84]

Other interceptions

Ochlerotatus (Ochlerotatus) vigilax (Skuse) and *Culex (Culex) bitaeniorhynchus* Giles have each been intercepted four times in aircraft entering New Zealand. Both species readily bite humans and a variety of other animals, and are of public health significance.[53] *Ochlerotatus vigilax* is widespread in the South Pacific[65] and it is an important arbovirus vector in Australia.[38] This species is a vector of RR,[57] BF[59,85] and possibly JE.[36] It is

Table 3: List of exotic mosquito species intercepted in New Zealand, and the respective ports of entry and details of the findings. (Does not include those species already established in New Zealand.)

Species[d]	Associated pathogens[g]	Entrance pathway	Location of interception	Country of origin[f]	Year of record and reference[e]
Aedes (Aedimorphus) vexans Meigen[a]	CH EEE RVF WNV	–	Russell (PB)	–	1929[20]
Aedes (Scutomyia) albolineatus (Theobald)	–	aircraft	Auckland	Singapore	1950?[12]
Aedes (Stegomyia) sp.	–	used tyres (ship)	Auckland	American Samoa	2003[121]
Aedes (Stegomyia) aegypti (Linnaeus)	CH CHIK DEN MVE RR WNV YF	aircraft	Auckland	Fiji	1950[12]
		used machinery (ship)	Auckland	Tonga	1999[60]
		rubbish hopper (ship)	Auckland	–	2001[122]
		used machinery (ship)	Auckland	Futuna Island	2004[123]
Aedes (Stegomyia) albopictus (Skuse)	CH CHIK DEN EEE JE LAC RR WNV YF	cargo (ship)	–	Hong Kong	(1979-82)[24]
		used tyres (ship)	Auckland	Japan	1993[6]
		used tyres (ship)	Auckland (PB)	Japan	1993[6]
		used tyres (ship)	Lyttleton	Japan	1993[6]
		used machinery (ship)	Auckland	Japan	1998[60]
		used cars (ship)	Wellington	Japan	1998[60]
		used machinery (ship)	Tauranga	–	1999[124]
		used machinery (ship)	Auckland	Japan	2001[60]
		used tyre (ship)	Auckland	Japan	2001[125]
		concrete truck (ship)	Auckland	Japan	2001[126]
		sewer truck (ship)	Auckland	Japan	2003[127]
		used machinery (ship)	Auckland	Japan	2004[128]
Aedes (Stegomyia) polynesiensis Marks	DEN LF RR	used machinery (ship)	Auckland	Futuna Island	2004[123]
Aedes (Stegomyia) scutellaris (Walker)	DEN	aircraft	Auckland	New Hebrides/ New Caledonia	(1943-44)[22]
Aedes (Stegomyia) tongae *Edwards*	LF	aircraft	Auckland	Tonga	1946[12]
Anopheles sp.	–	aircraft	–	Australia	2x (1955-65)[23]
		cargo (ship)	Auckland	USA	2001 (MAF, unpublished data)
Anopheles (Anopheles) maculipennis Meigen[b]	MA	ship	Auckland	East Indies	1929[20]
		ship	Auckland	Indonesia	1929[20]
Anopheles (Anopheles) stigmaticus Skuse	MA	cargo (aircraft)	Christchurch	Australia	2001 (MAF, unpublished data)
Coquillettidia (Coquillettidia) crassipes (Van der Wulp)	LF	aircraft	Auckland	Fiji	1951[21]
Coquillettidia (Coquillettidia) xanthogaster (Edwards)	DEN RR SIN	aircraft	Auckland	New Hebrides	(1943-44)[22]
Culex (Culex) annulirostris Skuse	ALF BF CH EH GG JE KOK KUN LF MVE RR RVF SIN TRU	ship hold	Auckland	Fiji	1929[20]
		–	Auckland (PB)	–	1929[20]
		aircraft	Auckland	Australia	1950[12]
		aircraft	Auckland	Fiji	2x 1950[12]
		aircraft	Auckland	Norfolk Islands	1950[12]
		aircraft	Auckland	Fiji	1951[21]
		aircraft	–	Fiji	(1955-65)[23]
		aircraft	–	USA	(1955-65)[23]
		aircraft	–	–	(1966-72)[101]
		dirty containers (ship)	Napier	–	1999[60]
Culex (Culex) ?australicus Dobrotworsky & Drummond	KUN MVE RR SIN	cargo (ship)	Wellington	Australia	1998 (MAF, unpublished data)
Culex (Culex) bitaeniorhynchus Giles	DEN JE LF MVE RR	aircraft	–	Fiji	(1966-72)[101]
		aircraft	–	Hong Kong	(1966-72)[101]
		aircraft	–	New Caledonia	(1966-72)[101]
		aircraft	–	Samoa/Fiji	(1966-72)[101]

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also associated with the transmission of CH, MVE and LF,[53] Stratford virus (STR),[49] GG, EH, KOK and SIN.[38,62] *Culex bitaeniorhynchus*, widespread in many regions of the world, is a vector of LF[86] and a potential vector of JE,[87] RR, MVE and DEN.[53]

Culex (Culex) sitiens Wiedemann was also intercepted on four occasions, three times in aircraft, and more recently (2003) in used tyres from American Samoa (see Table 3). This species is a vector of JE,[36] LF,[53] RR and BF,[38] SIN,[88] and possibly DEN and CH.[53]

The cosmopolitan yellow-fever mosquito *Aedes (Stegomyia) aegypti* (Linnaeus) was also recorded in New Zealand on four occasions, as recently as 2004 (see Table 3). The species seems to be the only known vector involved in urban epidemics of YF,[70]

Species[d]	Associated pathogens[g]	Entrance pathway	Location of interception	Country of origin[f]	Year of record and reference[e]
cont. from previous page					
Culex (Culex) gelidus Theobald	JE RR	imported flowers (?)	Auckland	India	2003[129]
Culex (Culex) pipiens pallens Coquillett	LF WNV	vessel refuse drum (ship)	Auckland	Hong Kong	2001[60]
Culex (Culex) sitiens Wiedemann	BF CH DEN	aircraft	Auckland	New Caledonia	1943-44[22]
	JE LF RR SIN	aircraft	Auckland	Fiji/Norfolk Islands	1950?[12]
		aircraft	–	Australia	(1979-82)[24]
		used tyres (ship)	Auckland	American Samoa	2003[121]
Culex (Lutzia) halifaxii Theobald	–	cargo (ship)	Tauranga	Australia	2002 (MAF, unpublished data)
Culex (Neoculex) sp.	–	aircraft	–	Fiji	(1955-65)[23]
Ochlerotatus (Finlaya) japonicus (Theobald)	JE, WNV	used tyres (ship)	Auckland (PB)	Japan	1993[6]
		used tyres (ship)	Lyttleton	Japan	1993[6]
		used tyres (ship)	Dunedin	Japan	1993[6]
		used machinery (ship)	Auckland	Japan	1998 (MAF, unpublished data)
		used machinery (ship)	Auckland	Japan	1999[60]
		water tanker (ship)	Auckland	Japan	2001[60]
		used machinery (ship)	Auckland	Japan	2002[130]
		used machinery (ship)	Auckland	Japan	2002 (MoH, unpublished data)
		used machinery (ship)	Auckland	Japan	2003[131]
Ochlerotatus (Muscidus) alternans (Westwood)	BF RR SIN	aircraft	Christchurch	Australia	2003 (MoH, unpublished data)
Ochlerotatus (Ochlerotatus) vigilax (Skuse)	BF CH EH GG JE	tent (?)	–	Fiji	(1979-82)[24]
	KOK LF MVE RR	aircraft	Auckland	New Caledonia	2x (1943-44)[22]
	SIN STR	aircraft	Christchurch	Australia	2001[132]
		aircraft	Christchurch	Australia	2002[132]
Ochlerotatus (Ochlerotatus) vittiger (Skuse)	MVE RR SIN	aircraft	–	South Pacific	?[5]
Toxorhynchites sp.	[c]	cargo (ship)	Auckland	–	2002 (MAF, unpublished data)
Tripteroides (Polylepidomyia) tasmaniensis (Strickland)	–	used tyres (ship)	Lyttleton	Australia	1993[6]
Tripteroides (Tripteroides) bambusa (Yamada)	–	used tyres (ship)	Lyttleton	Japan	1993[6]
Verrallina (Verrallina) lineata (Taylor)	RR	aircraft	Auckland	New Hebrides	(1943-44)[22]

Notes:
(a) Both [30] and [65] agree that it is likely to have been a misidentification of Aedes (Aedimorphus) nocturnus (Theobald), which is not a disease vector.
(b) Both [30] and [65] believe it was also a misidentification, but it was not possible to identify the likely species involved.
(c) Toxorhynchites species do not blood feed.
(d) Species names from original records were substituted for the most recent nomenclature.
(e) In many cases the year of interception was not recorded, but rather the period in which it occurred. In the case of more than one identical interception in a particular year or period, the number of times it occurred is given.
(f) The country of origin is assumed to be the last port of call of ship or aircraft prior to its arrival in New Zealand.
*(g) Arboviruses: ALF (Alfuy), BF (Barmah Forest), CHIK (Chikungunya), DEN (dengue), EEE (Eastern equine encephalitis), EH (Edge Hill), GG (Gan Gan), JE (Japanese encephalitis), KOK (Kokobera), KUN (Kunjin), LAC (La Crosse encephalitis), MVE (Murray Valley encephalitis), RR (Ross River), RVF (Rift Valley Fever), SIN (Sindbis), STR (Stratford), TRU (Trubanaman), WNV (West Nile) and YF (yellow fever). Other pathogens: MA (*Plasmodium falciparum*, malaria), CH (*Dirofilaria immitis*, canine heartworm) and LF (*Wuchereia bancrofti* or *Brugia malayi*, lymphatic filariasis).*
PB=post-border interceptions.
?=entrance pathway is unknown.

and it is the world's main vector of the four virus strains causing dengue fever and a vector of RR.[57] It is also a potential vector of CHIK,[77] MVE,[133] WNV[134] and CH.[89] A suitable climate for *Ae. aegypti* exists in the northern tip of the country,[90] and establishment of the virus cycle (human to human via infected mosquitoes) could become a reality.

The list of mosquito species intercepted at least once includes the following disease vectors: *Aedes (Stegomyia) scutellaris* (Walker), a vector of DEN;[91] *Aedes (Stegomyia) polynesiensis* Marks, a vector of LF,[86] RR[92] and DEN;[93] *Aedes (Stegomyia) tongae* Edwards, a vector of LF;[86] *Coquillettidia (Coquillettidia) crassipes* (Van der Wulp), also a vector of LF, but of the filaria *Brugia malayi*;[86] *Coquillettidia (Coquillettidia) xanthogaster* (Edwards), a potential vector of SIN,[38] DEN[53] and RR;[64] *Culex (Culex) australicus* Dobrotworsky & Drummond, a potential vector of KUN, MVE, RR and SIN;[37,38] *Culex (Culex) gelidus* Theobald, a vector of JE[36] and possibly RR;[94] *Culex (Culex) pipiens pallens* Coquillett, a vector of LF[95] and WNV;[96] *Ochlerotatus (Mucidus) alternans* (Westwood), a vector of RR,[37,38] SIN,[38] and possibly BF;[64] *Ochlerotatus (Ochlerotatus) vittiger* (Skuse), a potential vector of RR,[57,64] MVE[53,133] and SIN;[38] and *Verrallina (Verrallina) lineata* (Taylor), a possible vector of RR.[94]

There were also five cases involving the interception of *Anopheles*, including one of *Anopheles (Anopheles) maculipennis* Meigen, a world-wide vector of malaria. However, according to both Belkin[65] and Laird[30] it was most likely misidentified as such. The only identified species in this genus was *Anopheles (Anopheles) stigmaticus* Skuse, a potential vector of malaria.[53] Two other unidentified and possibly distinct species from the same genus were intercepted in aircraft originated from Australia in the 1950s. There are 16 *Anopheles* species in Australia, many of which are vectors of *Plasmodium* spp. (malaria) and *Wuchereria bancrofti* larvae (filariasis).[53]

Other nuisance but non-vector species intercepted were *Tripteroides (Polylepidomyia) tasmaniensis* (Strickland), *Tripteroides (Tripteroides) bambusa* (Yamada) and *Aedes (Scutomyia) albolineatus* (Theobald). *Culex (Lutzia) halifaxii* Theobald was also recorded, but the species is not anthropophilic and rarely bites humans.[53] A *Toxorhynchites* sp. was also recorded, but species from this genus are not capable of blood feeding and consequently are not pests or vectors.[97,98] The remaining taxon was a *Culex (Neoculex)* sp. intercepted in an aircraft from Fiji, even though there are no species from this particular subgenus in New Zealand or in Fiji.

Although the majority of interception records did not state whether specimens were found dead or alive, most recent records such as those released by New Zealand's Ministry of Health often related to detection of live larvae. None the less, detailed unreleased records from the Ministry of Agriculture and Forestry (unpublished data) described interceptions of live adults both in aircraft and ships. These interceptions highlight that New Zealand is also at risk from localised disease outbreaks such as 'airport malaria', which is often described overseas.[99,100]

Interception origins, pathways and ports of entry

In many cases, it is not possible to be entirely certain of the exact origin of an invading species. As a result, the origin is assumed to be the last port of call of ship or aircraft prior to its arrival in New Zealand, as this appears to be the standard practice.[101] The South Pacific region has been the most common source of exotic mosquito invaders, accounting for 100 (66%) of the 152 interceptions shown in Table 4. This is not surprising as New Zealand's greatest amount of trade and travel were likely to be with its nearest neighbours. As such, Australia has been the main source with 42 interceptions (28%), as New Zealand's closest neighbour, economic partner and main international source and destination for tourists.[102] Note that three of the four exotic species already established in New Zealand are native to Australia. The second most important source of invading mosquitoes was Fiji, identified as the origin of 22 (15%) interceptions (see Table 4).

The second most important region in relation to invaders was Asia, which was the source of 40 interceptions (26%; see Table 4). Japan topped the list of Asian countries as the origin of 22 (15% of all interceptions; see Table 4). There were surprisingly no records of invaders from China, one of New Zealand's largest

Table 4: Origin of the exotic mosquito species intercepted in New Zealand.

Region of	Country of origin	Number of interceptions	% of total
Asia	Hong Kong	6	3.9
	India	2	1.3
	Indonesia	3	2.0
	Japan	22	14.5
	Malaysia	1	0.7
	Philippines	2	1.3
	Singapore	3	2.0
	Sri Lanka	1	0.7
Total Asia		**40**	**26.3**
South Pacific	American Samoa	5	3.3
	Australia	42	27.6
	Cook Islands	1	0.7
	Fiji	22	14.5
	Futuna Island	2	1.3
	New Caledonia	7	4.6
	New Hebrides	3	2.0
	Norfolk Island	2	1.3
	Papua New Guinea	3	2.0
	Tahiti	1	0.7
	Tonga	5	3.3
	Uncertain	7	4.6
Total South Pacific		**100**	**65.8**
Other areas	East Indies	1	0.7
	Ecuador	1	0.7
	England	1	0.7
	France	1	0.7
	Hawaii	1	0.7
	USA	7	4.6
Total other areas		**12**	**7.9**
World-wide total		**152**	**100.0**

Table 5: The entrance pathway of exotic mosquitoes intercepted in New Zealand.

	Aircraft	Ships						Unknown	Overall total
		Containers and large recipients	Used machinery	Used tyres	Vehicles	Non-specified and others	Total		
Number of interceptions	94	17	14	17	4	5	57	20	171
% of identified pathway	62.3	11.3	9.3	11.3	2.6	3.3	37.7	–	–
% of total	55.0	9.9	8.2	9.9	3.3	2.9	33.3	11.7	100.0

trading partners. The remaining records corresponded to mosquito invasions from other regions of the world, which accounted for only 12 interceptions or 8% of the total (see Table 4). It is important to point out that Japan has become the main source of exotic mosquitoes since the 1990s, during which time it has been the origin of at least 22 (35%) of 62 interceptions recorded in this period. All of those cases involved used machinery or tyres imported to New Zealand in ships.

The main entrance pathway for invading mosquitoes has clearly been aircraft. Of the 151 interceptions with an identified entrance pathway, 94 (62%) occurred in airplanes and respective cargo, with the remaining 57 (38%) in ships (see Table 5). This pattern, however, has largely shifted towards ships and their cargo since the 1990s, which accounted for 51 (82%) of 62 described interceptions since January 1990 (see Tables 2 and 3).

Information relating to New Zealand's ports of entry for invading mosquitoes was available for only 93 (54%) of all 171 interception records. Based on these data, Auckland stood out as the port of entry for 75 interceptions (81%; see Table 6). Auckland is New Zealand's largest city with approximately 1.3 million people (nearly one-third of the country's population), and the main entryway for both goods and people.[44] Christchurch, South Island's largest city and sea port, accounted for only nine cases (9%; see Table 6).

Conclusions and recommendations

The records of mosquito interceptions indicate that New Zealand is at high risk from invading exotic species. Considering the many species intercepted, including the four cases of post-border detection, it is somewhat surprising that to date there are only four exotic mosquito species established in New Zealand. The data stressed the continuing need for routine aircraft disinfection, as the vast majority of specimens have been intercepted inside airplanes. Aircraft have also been the source of numerous mosquito interceptions in other countries, such as the United States[103] and Australia.[104]

The importance of aircraft disinfection is well acknowledged,[105] and the World Health Organization has published guidelines to avoid outbreaks of 'airport malaria' and the introduction of exotic mosquito vectors.[106] The biggest threat of arboviral disease importation would come from Australia, where there are endemic diseases[37,38,107] and frequent traveller exchange with New Zealand.[1] In this country, however, preventive disinfection work is mandatory, and it is carried out in civilian aircraft by the flight crew under Ministry of Agriculture and Forestry guidelines, or, in some cases, by MAF quarantine officers.[108] Recently, the New Zealand Armed Forces have taken the responsibility for disinfecting military airplanes at Whenuapai airbase in Auckland (Timothy Hopkins, personal communication 2003). It seems disinfection is working, and it could be accounting for the low number of mosquito interceptions from aircraft in the past 15 years.

The dominance of invasive species coming from the South Pacific region demonstrates that incoming ships and aircraft from neighbouring countries are the main source of exotic invaders. Australia was for a long period of time the main source of incoming specimens to New Zealand. However, ships arriving from Japan with used machinery and tyres have become the most important pathway for exotic mosquitoes, and the threat is considerable since they were responsible for all recorded interceptions of *Oc. japonicus* and most of *Ae. albopictus*.

A problem for New Zealand biosecurity authorities is the difficulty in adequately controlling for invading organisms aboard ships. Ideally, all vessels should be intercepted before docking in New Zealand, where thorough examination and disinfection could be carried out. Unfortunately, the present system is less stringent, and ships are only searched after docking, and the inspection procedures seem below the necessary standards to safeguard New Zealand's borders against exotic mosquitoes. The sea containers pathway has been identified as the least well controlled of all

Table 6: Ports of entry for exotic mosquitoes into New Zealand.

	Location of interception							
	Auckland (NI)	Bay of Islands (NI)	Christchurch and Lyttleton (SI)	Dunedin (SI)	Napier (NI)	Tauranga (NI)	Wellington (NI)	Total
Number of interceptions	75	1	8	1	1	5	2	93
Percentage of the total	80.6	1.1	8.6	1.1	1.1	5.4	2.2	100.0

Note:
(NI)=North Island. (SI)=South Island.

ports of entry in New Zealand,[109] and a recent survey of standard container door inspections indicated that approximately 96% of invading insects and spiders were not detected under current procedures.[110] Ships therefore pose a serious threat to New Zealand's biosecurity, and used tyres and machinery in particular seem to be rapidly becoming the main means of invasion, especially for container-breeding mosquitoes.

Aedes albopictus seems to pose the greatest threat to New Zealand's biosecurity. One very important factor that must be considered when designing adequate border control programs is that eggs of the species may remain viable, but dry, in larval habitats for months or even years.[111] As a result, it is not enough simply to inspect and treat with larvicide only water-filled larval habitats. Significantly more effort would be necessary to effectively stop *Ae. albopictus* from entering the country, which means treating all possible larval mosquito habitats, whether or not they are water-filled, especially used tyres.

New Zealand is under a serious risk of arboviral infection outbreaks,[56] and it is predicted that the human-induced climate change will further facilitate the survival and establishment of new exotic disease vectors in the country.[90,112,113] Under these circumstances, adequate monitoring and border surveillance, and inspections of all incoming goods and crafts are of utmost importance to safeguard the public health of New Zealand's population.

Effort must be concentrated in the Auckland region where most interceptions occur, and where the climate is likely to suit many of the species that manage to escape undetected. The New Zealand Government plans to spend close to $US20 million over four years in an attempt to eradicate *Oc. camptorhynchus*.[114] It would be much safer, easier and cheaper to stop invading mosquitoes and other organisms at the border, rather than to try eradicating them after their establishment in the New Zealand environment.[115] It is also worth developing multilateral strategies with trading partners and neighbouring countries in order to minimise the spread of disease vectors.

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