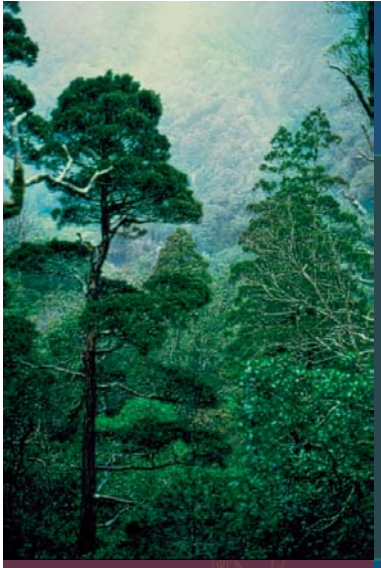

Risk Assessment for the Establishment of West Nile Virus in New Zealand

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Landcare Research Science Series No. 25

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Contents

Summary

An assessment of the risk that West Nile virus (WNV) might establish in New Zealand was conducted by comparing the taxonomic relatedness of potential vectors and hosts in New Zealand to known WNV vectors and hosts overseas, and assessing whether WNV might survive and spread after arriving. We also reviewed surveillance strategies currently used in North America to detect outbreaks of WNV, and assessed whether they are relevant to New Zealand or whether other strategies should be used. We obtained our information by conducting a literature search using the Internet search engine Google™ and the Internet version of CAB Abstracts® (1973–2004), for the terms 'West Nile virus' and 'West Nile virus vector'.

One species of mosquito (*Culex quinquefasciatus*) and a bird tick (*Ornithodoros capensis)* known to be WNV vectors overseas are present in New Zealand. At least another 10 species of mosquitoes present in New Zealand are in the same genus (and same subgenus) as species infected with WNV overseas. Two other mosquitoes not established in New Zealand but regularly intercepted at New Zealand ports and airports (*Aedes albopictus* and *Ochlerotatus japonicus*) are also known WNV vectors overseas. Three other mosquitoes not established in New Zealand but also regularly intercepted at New Zealand ports and airports (*Cx. annulirostris*, *Cx. australicus*, and *Cx. pipiens pallens*) are likely to become WNV vectors should they and WNV become established in New Zealand.

At least 30 bird species present in New Zealand have been infected with WNV overseas. These include the introduced mallard duck, domestic chicken, rock pigeon, blackbird, song thrush, chaffinch, goldfinch, house sparrow, and starling, all of which are widespread and common throughout New Zealand. A large number of other birds in New Zealand, including native species, occur in the same genus as those infected with WNV overseas, and an even larger number occur in the same family.

At least 16 mammal species in New Zealand have been infected with WNV overseas, including humans, horses, cattle, sheep, dogs, cats, mice, and rabbits. No reptiles or amphibians in New Zealand are the same as species infected with WNV overseas, but WNV in these groups has not been extensively studied.

Two surveillance strategies are used for the detection of WNV in the USA and elsewhere: passive and active. Passive programmes sample only animals reported sick or dead, viz. hosts (birds, horses, and humans). Active programmes sample animals 'captured' alive, including both vectors (at this stage only mosquitoes) and hosts (birds, horses, and humans).

If introduced into New Zealand, WNV is likely to become established and persist in both mosquito (and tick) vectors and vertebrate hosts (such as birds and mammals). The consequences of establishment for vertebrate hosts will depend on the strain of WNV that is introduced. The distribution of the virus within New Zealand would most likely be determined by vector distribution (which is potentially limited) rather than host distribution (which is widespread). Passive reporting and testing of any unexplained clusters of dead birds (or other animals) is the most relevant surveillance strategy for New Zealand at present. If resources permit, samples of mosquitoes and birds should be tested proactively to see if there is currently any evidence of WNV in New Zealand.

Introduction

West Nile virus (WNV) (family Flaviviridae, genus *Flavivirus*) is an RNA virus. It was first isolated from a human in the West Nile province of Uganda in 1937 (Garmendia et al. 2001; Murgue et al. 2002; CDC 2003). Subsequently, it has been recorded in humans in other parts of Africa, Europe, Asia, and, most recently, North America. The almost identical Kunjin virus (KUN) occurs widely in Australia (Hall et al. 2001; Mackenzie et al. 2003). Other related viruses include the Japanese, Murray Valley, and St Louis encephalitis viruses. WNV is generally non-symptomatic, but can cause mild fever, encephalitis (inflammation of the brain) and/or meningitis (swelling of the tissue that encloses the brain and spinal cord), and may result in death of animals contracting it. In this study, we assess the risk that WNV might establish in New Zealand, review surveillance strategies used in North America to detect outbreaks of WNV, and assess whether they are relevant to New Zealand or whether other strategies should be used.

WNV has been present in Europe since at least the 1960s (Hubálek & Halouzka 1999; Hubálek 2000; Komar 2000; Garmendia et al. 2001; Crook et al. 2002; Malkinson et al. 2002; Murgue et al. 2002; Rappole & Hubálek 2003). Before 1994, only a small number of WNV outbreaks were reported, isolated in both space and time, and WNV was considered to have little effect on human health. WNV also had little effect on wildlife. Since 1994, however, outbreaks have been more frequent, larger, and the cause of increasing numbers of human, equine, and bird deaths (see references above). As yet there have been no outbreaks in any species in the UK. WNV is present in both migratory and resident UK birds, but has not caused mortality, perhaps because it is an avirulent strain and/or because the local birds have been exposed to it for many years and have become immune (Buckley et al. 2003; Higgs et al. 2004).

WNV was first detected in North America in 1999, in the state of New York, USA, and by 2003 had spread rapidly across North America, west into the state of California, north into Canada, and south into Mexico and the West Indies (Drebot et al. 2003; Dupuis et al. 2003; Estrada-Franco et al. 2003; Fernandez-Salas et al. 2003; Peterson et al. 2003; Rappole & Hubálek 2003; Quirin et al. 2004). WNV has been much more virulent in North America than in Europe, perhaps because it was newly arrived and there was no or little host immunity (Buckley et al. 2003). As at 31 December 2003, WNV had caused the death of 566 humans, hundreds of horses, many other mammals and reptiles, and tens of thousands of birds in the USA (www.cdc.gov/ncidod/dvbid/westnile/background.htm, accessed 10 June 2004). The human fatality rate has been about 4% of reported cases.

WNV is an arbovirus (i.e. an arthropod-borne virus). At least 75 species of mosquitoes in 11 genera have been found infected with the virus, including species active during the day, and species active at dawn and dusk (Hubálek & Halouzka 1999; Bernard & Kramer 2001; Crook et al. 2002; Goddard et al. 2002; Drebot et al. 2003; Fonseca et al. 2004; Higgs et al. 2004). At least eight species of ticks have been found infected with WNV (Hubálek & Halouzka 1999; Komar 2000; Higgs et al. 2004), and mites also could be vectors (Buckley et al. 2003). However, the detection of WNV in a particular species does not necessarily mean that the species is a competent vector of WNV (CDC 2003). Vector competence (i.e. the ability of the vector to become infected with, replicate, and transmit the virus), feeding preferences, longevity, and density are all important factors determining the relative importance of different species in the transmission cycle (Bernard & Kramer 2001; Goddard et al. 2002). The predominant (primary) vectors are mosquitoes, especially those in the genus *Culex* (subgenus *Culex*): *Cx. univittatus* in Africa and the Middle East, *Cx. pipiens*, *Cx. modestus*, and *Coquillettidia richiardii* in Europe, *Cx. quinquefasciatus* and *Cx. tritaeniorhynchus* in Asia, *Cx. pipiens* and *Cx. restuans* in northern North America, and *Cx. quinquefasciatus* in southern North America (see references above). Infectious adult mosquitoes carry the virus in their salivary glands and infect susceptible hosts while feeding on blood. The period of infectiousness lasts for up to 2

weeks. In some species of mosquito (e.g. *Cx. pipiens* in North America), the adults are able to transmit WNV vertically to their progeny (Dohm et al 2002). In addition, some infected adult *Cx. pipiens* are able to survive over winter, and become a WNV source the following spring (Dohm et al 2002; Drebot et al. 2003).

Birds are the principal hosts for WNV, although mammals, reptiles, and amphibians can also be infected (Hubálek 2000). Competent hosts are those that attain high levels of infectious virus in the bloodstream (viraemia) and retain these levels for sufficiently long (1–4 days) to infect biting mosquitoes (www.cdc.gov/ncidod/dvbid/westnile/birds&mammals.htm, accessed 26 February 2004). Birds can do this, and therefore act as amplifying hosts, whereas mammals (including humans), reptiles, and amphibians usually cannot, and therefore are termed incidental, spill-over, or dead-end hosts (Hubálek & Halouzka 1999; Crook et al. 2002; Drebot et al. 2003; Huhn et al. 2003; Rappole & Hubálek 2003; Fonseca et al. 2004). Thus, the virus cycles principally between birds (amplifying hosts) and bird-biting mosquitoes (maintenance vectors) in an enzootic transmission cycle.

Mammal (including human) infection requires mosquitoes that bite both birds and mammals (bridge vectors). In Europe, there are two types of cycles, a rural cycle between birds, usually migratory wetland birds such as white storks (*Ciconia ciconia*), and bird-biting mosquitoes such as *Cx. pipiens*, and an urban cycle between birds, usually resident terrestrial birds such as house sparrows (*Passer domesticus*), and mosquitoes such as *Cx. modestus* that bite both birds and mammals (Hubálek & Halouzka 1999; Hubálek 2000; Buckley et al. 2003; Drebot et al. 2003; Higgs et al. 2004). In North America, hybrids between bird-biting and mammal-biting mosquitoes have arisen, and may be the bridge vectors contributing to the unprecedented severity and range of the WNV epidemic in North America (Fonseca et al. 2004). It has also been suggested that a more virulent strain of the virus may have emerged (Buckley et al. 2003; Drebot et al. 2003). Seroprevalence of the virus (indicating background immunity) in humans can be greater than 50% in endemic areas in Africa, but only 2–4% in outbreak areas in Europe and North America, suggesting that most of the population in these areas was not immune to WNV, resulting in a large number of cases of human illness (Buckley et al. 2003; Drebot et al. 2003).

WNV in North America, unlike in Africa, Europe, and Asia, has been characterised by the mortality of tens of thousands of birds from a wide range of species (CDC 2003). To date, deaths have been recorded in at least 225 bird species (in at least 55 families). The highest mortality rate has been in American crows (*Corvus brachyrhynchos*), which suffered about 40% mortality of marked birds in one study and 68% mortality in another study (Caffrey et al. 2003; Yaremych et al. 2004). The impacts of WNV on populations of other bird species are not known. About 50% of all dead birds tested have been WNV positive, most having the virus or viral RNA but some having only antibodies reported (USGS 2003). However, most birds that carry the disease survive WNV infection, as indicated by the high seroprevalence in live birds (CDC 2003).

Possible ways in which WNV was introduced into North America include via infected migratory birds, infected imported birds, infected people arriving from overseas, and infected mosquitoes hitch-hiking in imported second-hand tyres (Rappole et al. 2000; Zwerdling 2001; CDC 2003; Rappole & Hubálek 2003). Although infected migratory birds are likely to have spread WNV from Africa to Europe (Rappole et al. 2000; Malkinson & Banet 2002; Malkinson et al. 2002; Higgs et al. 2004), they are considered unlikely to have been responsible for the introduction of WNV into North America because of the level and duration of viraemia required (Rappole & Hubálek 2003). Rappole & Hubálek (2003) considered that the importation of infected birds (perhaps for a zoo or private collection) was the most likely mode of entry of WNV into the USA. As unlikely as it may seem, they suggested that a local mosquito could have bitten an infected imported bird during transport from the aeroplane to the quarantine site. Once established, WNV is postulated to have spread within North America in two ways: long-distance, lineal (north–south) spread via migratory birds such as American

crows (Rappole et al. 2000; Peterson et al. 2003; Rappole & Hubálek 2003), and/or radial spread via non-migratory birds such as house sparrows (Rappole & Hubálek 2003).

As in the USA, migratory birds are considered doubtful as a possible method of introduction of WNV to Australia, because of the route and length of migration (Mackenzie et al. 2003). The same is likely to be true for New Zealand. Possible sources of new infectious diseases in New Zealand include incoming humans, animals, and cargo (Crump et al. 2001; Heath 2001; Derraik & Calisher 2004). The absence of indigenously acquired arboviral infections in New Zealand to date seems to be entirely fortuitous (Weinstein et al. 1997; Derraik & Calisher 2004), and it is probably only a matter of time before this situation changes. The Ministry of Agriculture and Forestry (MAF) has recently commissioned a review (not yet completed) of the risk of exotic diseases (including WNV) arriving in New Zealand with migratory birds. For this reason, our review focuses on issues relating to WNV establishment once here. Several earlier studies have also considered the risk of WNV establishment in other countries: e.g. Australia (Hall 2000; Mackenzie et al. 2003), Canada (Drebot et al. 2003), UK (Crook et al. 2002; Buckley et al. 2003; Higgs et al. 2004), and the Scandinavian countries (Knudsen et al. 2003).

Methods

Information on WNV was obtained by conducting a literature search using the Internet search engine Google™ and the Internet version of CAB Abstracts® (1973–2004), for the terms "West Nile virus" and "West Nile virus vector". Key web sites located included (in alphabetical order):

environmentalrisk.cornell.edu/WNV/
www.aphis.usda.gov/lpa/issues/wnv/wnv.html
www.audubon.org/bird/wnv/
www.cdc.gov/ncidod/dvbid/westnile/index.htm
www.epa.gov/oppsrrd1/op/malathion/index.html
www.nlm.nih.gov/medlineplus/westnilevirus.html
www.nwhc.usgs.gov/research/west_nile/west_nile.html
www.promedmail.org/
www.wildlifeinformation.org/

Information on the distribution of New Zealand mosquitoes was obtained from Laird (1995), Weinstein et al. (1997), and Holder (1999), ticks from Dumbleton (1958, 1961, 1963), Ramsey (1968), Austin (1984), Heath (1977, 1987), and Bishop & Heath (1998), birds from Bull et al. (1985), Heather & Robertson (1996), and Robertson & Heather (1999), amphibians and reptiles from Pickard & Towns (1988), and mammals from King (1990).

Results

Potential vectors of WNV in New Zealand

Mosquitoes

One introduced species of *Culex* (subgenus *Culex*) mosquito (*Cx. quinquefasciatus*) present in New Zealand is known to carry and transmit WNV in Pakistan (Akhter et al. 1982), India and Madagascar (Hubálek & Halouzka 1999), and the USA (Bernard & Kramer 2001; Goddard et al. 2002). It is thought to have arrived in New Zealand in the 1830s on American sailing ships bringing sealers and whalers to these shores (Laird 1995). In New Zealand it has been found in the North Island, and also Nelson, Picton (Weinstein et al. 1997), and around Christchurch (M. Disbury, Biosecure, Napier, pers. comm.) in the South Island. It may still be spreading southwards. *Cx. quinquefasciatus* bites a wide variety of birds and mammals, both overseas (Bernard & Kramer 2001) and in New Zealand (Holder 1999), and as such has been called a bridge vector because as well as passing the virus to birds in an enzootic cycle, it also passes the virus to dead-end mammal hosts (Huhn et al. 2003). A related species overseas, *Cx. pipiens*, bites frogs (Hubálek & Halouzka 1999), and other species of mosquitoes overseas bite reptiles (Klenk & Komar 2003), but it is not known if *Cx. quinquefasciatus* does, although there is no reason to think that it does not. Compared with other vectors of WNV, *Cx. quinquefasciatus* is less susceptible to infection and quite variable in its efficiency as a vector (Goddard et al. 2002). Nevertheless, it is one of the main vectors in Asia and in the southern states of the USA (Hubálek & Halouzka 1999; Bernard & Kramer 2001; Goddard et al. 2002). Where *Cx. pipiens*, the main ornithophilic vector in the northern states of the USA, and *Cx. quinquefasciatus* are sympatric in North America, hybrid populations have developed (Fonseca et al. 2004). All USA populations of both species now have some hybrid genetic material. The current limited distribution of *Cx. quinquefasciatus* in New Zealand indicates that its role as a vector in this country would be limited to the North Island and northern South Island, although this may change if it spreads southwards.

Three other species of mosquitoes present in New Zealand (*Cx. pervigilans*, *Cx. asteliae*, and *Cx. rotoruae*, all endemic) are in the same genus (and subgenus) as *Cx. quinquefasciatus* and many other species of mosquitoes known to carry and transmit WNV overseas. The three New Zealand species are closely related to each other, and *Cx. pervigilans* is found throughout New Zealand. Their potential role in the transmission of WNV is unknown, although Whataroa virus (an endemic alphavirus of birds) has been isolated from *Cx. pervigilans* in Westland (Holder 1999). If *Cx. pervigilans* is able to become infected and transmit WNV it could become a maintenance vector because it primarily feeds on birds (Belkin 1968). Hybridisation between *Cx. pervigilans* and *Cx. quinquefasciatus* has been hypothesised (Belkin 1968), but was not occurring in one population of *Cx. pervigilans* sympatric with *Cx. quinquefasciatus* (Smith & Fonseca 2004).

Two endemic species of *Coquillettidia*, two endemic species of *Culiseta*, and three endemic and three introduced species of *Ochlerotatus* mosquitoes present in New Zealand are in the same genera as species known to carry WNV overseas (Holder 1999; Higgs et al. 2004). Their potential role in the transmission of WNV is unknown. Whataroa virus has been isolated from *Culiseta tonnoiri*, *Ochlerotatus australis*, and *Oc. notoscriptus* (Holder 1999). The three introduced species of *Ochlerotatus* established in New Zealand, *Oc. australis*, *Oc. notoscriptus*, and *Oc. camptorhynchus*, all occur in Australia. None of them have had the WNV sub type KUN isolated from them, but the latter two have been infected experimentally in the laboratory with the Murray Valley encephalitis flavivirus (Russell 1993).

Four species of *Culex* (subgenus *Culex*) mosquitoes not established in New Zealand have been intercepted at New Zealand ports and airports: *Cx. annulirostris*, *Cx. australicus*, *Cx pipiens pallens*,

and *Cx. gelidus* (www.moh.govt.nz/media.html, accessed 13 May 2004). *Cx. annulirostris* is a major pest in the Murray/Darling River basin of south-eastern Australia. It bites both birds and mammals, is an efficient laboratory vector of the WNV sub type KUN, and has been implicated as a vector in field studies (Russell 1993). *Cx. australicus* from the Murray Valley also carries the KUN virus. It is not attracted to feed from humans, but probably plays a role in maintaining KUN in other vertebrates (Russell 1993). *Cx. pipiens pallens* from Japan and Korea is part of the *Cx. pipiens* complex and would likely be a vector of WNV as are other members of this complex. *Cx. gelidus* from S.E. Asia is established in coastal tropical Australia. Its vector competence for WNV is unknown, and it is unlikely to establish in New Zealand.

Two other mosquitoes not established in New Zealand, *Aedes albopictus* and *Ochlerotatus japonicus*, are also regularly intercepted at New Zealand ports and airports (Sandlant 2003; www.moh.govt.nz/media.html, accessed 13 May 2004). Both are highly susceptible to WNV infection and can transmit the virus by bite (Sardelis & Turell 2001; Turell et al. 2001). Once established, either of these artificial container-breeding mosquitoes could disperse within New Zealand, aided by our transport systems, to provide a nationwide vector.

Ticks

One cosmopolitan species of soft tick, *Ornithodoros capensis* (family Argasidae), known to carry WNV on islands of the Baku Archipelago, Republic of Azerbaijan (Heath 1987; Hubálek & Halouzka 1999; Higgs et al. 2004) is present on a number of species of birds, mainly seabirds, and in seabird nests on the Kermadec Islands and the North Island and South Island of New Zealand (Appendix 1). In addition, it has been found on the brown booby (*Sula leucogaster*), a seabird in the Pacific, and the turnstone (*Arenaria interpres*), a land bird from the high Arctic (Heath 1977). Both species visit or migrate to New Zealand during the northern winter, and could bring the tick with them. Typically, ticks of this family feed quickly and then leave the host, and all stages are commonly found in the nest, not on the host (Dumbleton 1958, 1963). However, despite leaving the host after feeding, *O. capensis* is found in both hemispheres, and it is generally thought to have a cosmopolitan distribution due to transportation on migrating birds (Austin 1984; Heath 1977, 1987). *O. capensis* has been shown experimentally to be capable of transmitting WNV (Hubálek & Halouzka 1999), and other arboviruses such as the Johnson Atoll virus and Hughes group viruses have been isolated from *O. capensis* in colonies of migratory seabirds in New Zealand (Austin 1984). However, its vector competence for WNV transmission in the wild is unknown. If *O. capensis* moved between nests in a seabird colony it could transmit WNV from bird to bird, and also to any other bird (or mammal) venturing into that colony. As well as biting seabirds, *O. capensis* readily bites humans (Heath 1987). Thus, not only could *O. capensis* be a pathway for the virus coming to New Zealand, it could also become a maintenance vector and a bridge vector once the virus is here.

The brown dog-tick (*Rhipicephalus sanguineus*), a hard tick in the family Ixodidae, has been the most common tick intercepted at New Zealand ports and airports over a 20-year period (Heath 2001). It is capable of experimental transmission of WNV (Hubálek & Halouzka 1999; Higgs et al. 2004). It bites mammals, and is reported to have a very wide host range (Sheals 1973), so could be a bridge vector if it bites birds and became established in New Zealand.

Mosquitoes and ticks together

A primarily ornithophilic vector is required to build up the viraemic levels in birds, in order for the virus to persist in the wild (Dohm et al. 2002). Whether *Cx. quinquefasciatus* could fulfil the role of a maintenance vector in the primary enzootic cycle between birds and mosquitoes in New Zealand is unknown, but it certainly appears to play this role in Asia and the southern USA. If not *Cx. quinquefasciatus*, then another species or group of species would be required, such as the endemic *Cx. pervigilans* complex. *Cx. quinquefasciatus* is a competent bridge vector that could transmit the

virus from birds to mammals (including humans). As noted above, the bird tick, *Ornithodoros capensis*, could also become a maintenance and bridge vector. Thus, any introduction of WNV to New Zealand has every likelihood of being transmitted to potential hosts.

Potential hosts of WNV in New Zealand

Birds, mammals, reptiles, and amphibians

At least 30 bird species present in New Zealand have been found infected with WNV overseas (Appendix 2). These include the mallard duck (see Appendices for scientific names of bird species), domestic chicken, rock pigeon, blackbird, song thrush, chaffinch, goldfinch, house sparrow, and starling, all of which are widespread and common throughout New Zealand (Bull et al. 1985; Heather & Robertson 1996; Robertson & Heather 1999). All are introduced, non-migratory resident, farm, or cage birds, except for the cosmopolitan black shag (native resident), little egret (uncommon Australian migrant), glossy ibis (uncommon Australian vagrant), cosmopolitan Australian coot (common native resident), turnstone (common Arctic migrant), eastern common tern (rare Arctic migrant), and barn owl (rare Australian vagrant). A large number of other birds in New Zealand, including native species, occur in the same genus as those infected with WNV overseas (Appendix 3), and an even larger number occur in the same family (Appendix 4).

At least 16 mammal species in New Zealand have been found infected with WNV overseas, including humans, horses, cattle, sheep, dogs, cats, mice, and rabbits (Appendix 5). Most of these species are widespread and common in New Zealand (King 1990).

No reptiles or amphibians in New Zealand are the same as the few species found infected with WNV overseas (Hubálek & Halouzka 1999; Hubálek 2000; Klenk & Komar 2003; Miller et al. 2003; Steinman et al. 2003; USGS 2003). Reptiles and amphibians reported infected with WNV overseas include captive alligators, crocodiles, iguanas, monitors, snakes, turtles, and frogs. This does not mean that reptiles and amphibians in New Zealand could not become infected with WNV. Reptiles and amphibians are thought to serve as a reservoir of other arboviruses, but their role in the life cycle and epidemiology of WNV has not been extensively evaluated (see references above).

Risk of WNV establishment in New Zealand

Given that New Zealand has many proven avian and mammalian hosts of WNV, the risk of their infection with WNV should it arrive in this country must be high, provided the virus can survive here, and there are enough competent vectors and competent hosts to maintain (cycle) the virus in the environment.

WNV survives over winter in temperate regions of Europe and North America at similar or higher latitudes to New Zealand (Murgue et al. 2002; Drebot et al. 2003; Rappole & Hubálek 2003). For example, the virus has been found in overwintering female mosquitoes (*Cx. pipiens*) in Canada, and it has been suggested that these mosquitoes were able to establish localised foci of enzootic amplification the following spring (Drebot et al. 2003). The virus is also considered to have overwintered in north-eastern USA (Rappole & Hubálek 2003). This implies that WNV would also survive over winter in New Zealand.

As noted above, New Zealand has at least one species of mosquito, *Cx. quinquefasciatus*, that is both a primary and a bridge vector overseas. Despite low densities of mosquitoes in the UK, successful transfer of WNV from infected migrant to local resident birds has occurred, and, furthermore, a relatively high proportion of resident birds in the UK have become infected (Buckley et al. 2003). Thus, even if mosquito densities in New Zealand are low, as in the UK, there must be a reasonable chance that birds in New Zealand would become infected if WNV arrived in this country.

Some species of birds present in New Zealand, such as the house sparrow, attain high levels of viraemia for a sufficient length of time (up to 6 days) for them to be competent (infectious) hosts overseas (Komar et al. 2003; Rappole & Hubálek 2003). Generally, Passeriformes (such as house sparrows and finches) and Charadriiformes (such as plovers, turnstones, knots, godwits, gulls, and terns) are the most infectious (competent) hosts, and Anseriformes (swans, geese, and ducks), Psittaciformes (parrots and parakeets), Galliformes (pheasants, turkeys, domestic chickens, etc.), and Columbiformes (pigeons) the least (Komar et al. 2003).

It is difficult to predict which native bird species in New Zealand might become infected if WNV arrived in this country. It is not necessarily true that species in the same genus, or even species in the same family, are more at risk than others. Totally unrelated species may prove to be highly susceptible to WNV. Antibody of Whataroa virus, transmitted by *Cx. pervigilans*, was found in about 20% of birds sampled in Westland, including tui (*Prosthemadera novaeseelandiae*), bellbird (*Anthornis melanura*), and silvereye (*Zosterops lateralis*) (Ross et al. 1964). Based on overseas experience, it is likely that most native New Zealand birds would become infected with WNV.

The effect of WNV infection on vertebrate hosts (such as birds and mammals) may depend upon which strain or lineage of the virus becomes introduced – a less virulent strain as in Africa, or a more virulent strain as in parts of Europe and North America (Murgue et al. 2002; Buckley et al. 2003; Drebot et al. 2003; Fonseca et al. 2004). Immunity to WNV is likely to be low, or nil, in New Zealand, so the effect of a virulent strain of WNV on humans, horses, and birds in this country may be similar to that in the USA. It would be disastrous if the high levels of mortality observed in American crows occurred in our native birds, such as the kokako (*Callaeas cinerea*) – both are in the order Passeriformes although they are in different families (Corvidae cf. Callaeidae).

Surveillance strategies for WNV

There are two surveillance strategies used for the detection of WNV in the USA (and elsewhere): passive strategies (relying on the reporting of sick or dead animals for testing) and active strategies (involving 'capture' of live animals for testing) (Table 1). Passive programmes sample only hosts (sick or dead birds, horses, and humans). Active programmes sample both vectors (at this stage only mosquitoes) and hosts (birds, horses, and humans). In general, programmes using passive strategies are viewed as the most feasible and affordable, but have lower case ascertainment, and programmes using active strategies provide a better measure of disease occurrence if there are sufficient resources for their implementation (Eidson 2001). However, for diseases such as WNV, which occur in only a few vector or host species, active surveillance programmes have to be extraordinarily thorough and extensive to find the few positives (Eidson 2001). The major surveillance programmes in the USA involve mosquito (vector), dead bird, live bird, sentinel bird, horse, and human (host) surveillance (CDC 2003).

Table 1. WNV surveillance programmes in the USA

Mosquitoes:	Active capture and testing of mosquitoes, regularly, at specific locations.
Birds – found dead:	Passive reporting and testing of wild or captive birds found dead (or sick).
– captured live:	Active capture, bleeding, and testing of wild birds at specific locations.
– held captive:	Active bleeding and testing of captive (sentinel) birds (e.g. chickens), regularly, at specific locations.
Other captive animals:	Passive reporting and testing of other animals (e.g. horses) found dead (or sick), and active bleeding and testing of live animals.
Humans:	Passive and active testing of humans.

Mosquito surveillance

Mosquito-based surveillance is the primary tool for quantifying the intensity of virus transmission in an area (CDC 2003). A minimal mosquito-based surveillance programme involves collecting adult mosquitoes regularly at representative sites, using a variety of trapping techniques, and rapid testing of samples of sufficient size to detect low virus infection rates (White 2001; CDC 2003). The data can be used to estimate adult mosquito abundance (numbers caught per trap night) and infection rate (estimated number of infected mosquitoes per 1000 tested). This information can be used to assess the threat of human disease, identify geographic areas of high risk, and assess the need for and timing of interventions (e.g. mosquito control). A more comprehensive mosquito-based surveillance programme will include sampling larval as well as adult mosquitoes (White 2001; CDC 2003). Larval mosquitoes are collected by taking dip samples from a variety of aquatic habitats to identify the species present and the location of potential sources of adult mosquitoes. This information can be used for planning larval control, or if this is not feasible, for predicting future adult mosquito abundance.

Dead bird surveillance

Dead bird surveillance has proved to be the most sensitive method of detecting WNV presence in the USA (Eidson et al. 2001a, 2001b; Komar 2000, 2001; Julian et al. 2002; CDC 2003; Guptill et al. 2003; Mostashari et al. 2003). Corvids, especially American crows, have been the most sensitive species for surveillance. However, WNV has been detected in dead birds from at least 225 species, including species common in New Zealand such as rock pigeons, house sparrows, and starlings. Dead bird surveillance comprises two components; the reporting of sightings of dead birds, and the testing of samples of dead birds for WNV, viral RNA, or antigens (CDC 2003). The success of such a programme relies on public participation and the timely reporting of dead bird sightings to the appropriate authorities. A potential disadvantage of this type of surveillance is that the public may not participate equally in all areas of the country or at all times. Nevertheless, the US experience is that the reporting of dead birds, and especially the reporting of WNV-positive dead birds, has usually provided the earliest indication of viral activity in an area, preceding reports of human illness by about a month on average (CDC 2003). The pros and cons of dead bird surveillance were summarised by CDC (2003).

Live wild bird surveillance

Live wild bird surveillance has not been used consistently for detecting WNV in the USA, or elsewhere, although Australia is considering such a programme. It involves the capture and blood sampling of free-living wild birds, and then testing the blood samples for WNV virus, RNA, or antibodies (Komar 2001; CDC 2003). The captured birds may be banded with uniquely numbered leg bands before being released so that recaptures can be recognised. One advantage of free-living birds over captive birds (see below) is that they have the freedom to move about, increasing the probability that they will come into contact with the virus. A disadvantage is that it is impossible to know the travel history of each wild bird sampled. In this context, the most suitable species include relatively sedentary species such as the rock pigeon and house sparrow (Komar 2001). Another disadvantage is that free-living birds are seldom recaptured, so seroconversion (change from negative to positive antibody status) may not be observed, and seropositive birds may not provide information on which year the infection took place. However, seropositive ‘hatching year’ (juvenile) birds indicate recent infection.

Live captive (sentinel) bird surveillance

Live captive birds (usually chickens or rock pigeons) have been used as sentinels in WNV surveillance programmes in the USA (and elsewhere), although the term sentinel is sometimes also used to refer to free-living wild birds or even dead birds (Eidson 2001; Komar 2001; Langevin et al. 2001; CDC 2003). Chickens and rock pigeons are considered suitable species for captive bird

surveillance programmes because they develop antibodies after infection without becoming highly infectious to mosquito vectors. In the USA, seroconversions (change from negative to positive antibody status) were detected in captive sentinel birds but they were rarely the earliest indicators of WNV activity (CDC 2003). Successful application of captive sentinel bird surveillance requires extensive knowledge of local transmission dynamics (Komar 2001), and the CDC (2003) recommended that further research be done before relying on this strategy as a primary means of WNV surveillance. Despite this, several countries use live captive birds as sentinels. For example, Australia has a sentinel chicken surveillance programme to provide early warning of increased levels of the WNV sub type KUN and Murray Valley encephalitis viruses (Broom 2003), and is considering extending this for the detection of WNV.

Horse and other captive mammal surveillance

The passive reporting and testing of dead (or sick) horses has been used for WNV surveillance in areas in the USA where horses are present (Komar 2000, 2001; CDC 2003). In theory, sentinel horses and other mammals might be better than sentinel birds as an indicator of risk of WNV transmission to humans (Komar 2001). However, WNV disease in horses was the first indication of WNV activity in only 16% of US counties where WNV disease in humans was reported in 2002 (CDC 2003). Active surveillance of horses could also be implemented because horses are routinely bled and tested for other pathogens (CDC 2003). New Zealand currently has an active surveillance programme for arboviruses that affect livestock, such as Akabane disease, bluetongue, and Palyam group viruses, using sentinel cattle herds (Horner 2002). This could be extended to include testing for WNV.

Human surveillance

Passive human surveillance, viz. testing for WNV infection in hospitalised cases of encephalitis, and milder symptoms as resources allow, is undertaken in the USA in areas with potential WNV activity (CDC 2003). Active human surveillance is considered only in areas with known WNV activity. However, because the primary objective of surveillance systems is the prevention of human infection, human case surveillance alone is not used in areas where WNV activity is likely to be present.

Discussion

Whether WNV establishes in New Zealand depends on its arriving here (not extensively considered in the main part of this study, but discussed briefly below), survival in vectors and hosts, and spread and distribution after arriving.

Introduction to New Zealand

The most likely mode of introduction of WNV to New Zealand is by the importation of an infected bird (perhaps for a zoo or private collection), although we have not ascertained how frequently birds are imported. This is the favoured explanation for how WNV arrived in the USA (Rappole & Hubálek 2003). The second most likely mode of introduction of WNV to New Zealand is the inadvertent importation of infected mosquitoes in cargo, although again we do not know how often this occurs. Mosquitoes are occasionally found in imported second-hand tyres (Sandlant 2003; Derraik & Calisher 2004), for example, but all such arrivals are unlikely to be detected. If any of these arriving mosquitoes were infected with WNV before they left their home country, and they took less than 2 weeks to get here, thus retaining their infectiousness, they could be a source of the virus establishing in New Zealand.

Infected migratory birds are unlikely to be the source of WNV introduction to New Zealand, because of the routes and duration of migration. The same conclusion was reached for the USA and Australia (Mackenzie et al. 2003; Rappole & Hubálek 2003). Most (if not all) of our migratory birds do not come from or go to areas where WNV is known to occur at present (see below). Furthermore, the duration of migration is longer than the length of time birds remain viraemic. The only way infected migrating birds could introduce WNV to New Zealand would be for a WNV-infected vector, such as the tick *Ornithodoros capensis*, to be attached to them. The infected migratory bird and attached infected tick would have to continually reinfect each other during migration. However, whether infected ticks on migratory birds could infect local birds remains to be resolved (Murgue et al. 2002). There has been some debate in the literature about the possible distribution of arthropod-borne viruses in New Zealand by migrating birds (Ross et al. 1964; Heath 1977, 1987; Austin 1984; Pharo et al. 2000).

Most birds migrating to New Zealand are shorebirds (Charadriiformes) that breed in Arctic regions of Europe, Asia, and North America, and migrate south for the northern winter. The most numerous species that migrate to New Zealand are the bar-tailed godwit (*Limosa lapponica*), lesser knot (*Calidris canutus*), curlew sandpiper (*C. ferruginea*), red-necked stint (*C. ruficollis*), turnstone, and Pacific golden plover (Heather & Robertson 1996). We do not know whether any of these would encounter WNV in their homelands. However, WNV has been detected in the turnstone in the USA (USGS 2003), and the Pacific golden plover is in the same family as the turnstone. Presumably, an infected overwintering turnstone in the USA could return to the Arctic to breed and infect other turnstones that come to New Zealand to overwinter. Turnstones carry the tick *Ornithodoros capensis* (see above).

There are at least eight species of petrels (Procellariiformes) that breed in New Zealand and spend the winter in the North Pacific. Three, the wedge-tailed shearwater (*Puffinus pacificus pacificus*), black-winged petrel (*Pterodroma nigripennis*), and Kermadec petrel (*Pterodroma neglecta*) go to waters in the temperate North Pacific, while the remaining four, the sooty shearwater (*Puffinus griseus*), Buller's shearwater (*Puffinus bulleri*), flesh-footed shearwater (*Puffinus carneipes*), and mottled petrel (*Pterodroma inexpectata*) go to Arctic, subarctic, or North Pacific waters (Heather & Robertson 1996). We do not know whether any of these would encounter WNV on their travels, but some at least carry the tick *Ornithodoros capensis*.

Two land birds that breed in New Zealand, the long-tailed cuckoo (*Eudynamys taitensis*) and shining cuckoo (*Chrysococcyx lucidus*), migrate north for the New Zealand winter. The long-tailed cuckoo migrates to the Pacific Islands, from the Bismark Archipelago in the west to the Marquesas and Tuamotu Islands in the east, while the shining cuckoo migrates through eastern Australia to Indonesia, New Guinea, Bismark Archipelago, and Solomon Islands (Heather & Robertson 1996). WNV is not known to occur in these areas but KUN, an almost identical virus, occurs in Australia. The absence of KUN in New Zealand does not mean that WNV could not enter New Zealand from Australia.

Other potential methods of WNV introduction to New Zealand include the arrival of an infected person from overseas, as happened in France (Charles et al. 2003), and the importation of an infected horse, as happened in Australia (Studdert 2003). However, infected humans and horses are unlikely sources of WNV establishment because viraemia levels in mammals are too low and too short to allow infection of mosquito vectors and subsequent transmission to other hosts.

Persistence in New Zealand

If the virus is introduced into New Zealand in a competent host (e.g. an infected bird) or a competent vector (e.g. an infected mosquito), it is likely to become established and persist in an enzootic cycle between mosquitoes and birds, and be transmitted to susceptible mammalian hosts, as has happened in temperate regions of Europe and North America. Establishment of WNV in bird populations in the UK, which is at a higher latitude than New Zealand, was initially considered unlikely because of low mosquito densities (Crook et al. 2002; Higgs et al. 2004), but has nevertheless happened (Buckley et al. 2003). However, for unknown reasons it has yet to cause an outbreak in humans and other mammals. Immunity to WNV is likely to be low, or nil, in New Zealand, meaning that should WNV become established here it could cause human, equine, and avian mortality as in the USA.

Spread and distribution within New Zealand

Birds such as house sparrows are highly competent hosts, and are likely to disperse WNV within New Zealand, as in the USA (Rappole & Hubálek 2003). The distribution of the virus will likely be limited by the distribution and density of vectors (which are potentially limited by climate) rather than hosts (which are widespread). For example, *Cx. quinquefasciatus* is not known to occur south of about Christchurch, although it may be still spreading southwards. However, if *Cx. pervigilans* became a vector, then WNV could spread throughout New Zealand.

Surveillance in New Zealand

On the basis of overseas experience, surveillance for WNV in New Zealand should be passive, and involve testing any unexplained clusters of dead birds (or other animals), as recommended for the UK (Crook et al. 2002; Buckley et al. 2003; Duff 2003; Duff et al. 2003). The outbreak of salmonella (*Salmonella typhimurium*) in New Zealand in 1998, causing the death of large numbers of house sparrows, is a good example of what could happen with the introduction of WNV. It has not been determined how salmonella entered New Zealand, but possible means suggested include migratory birds, imported animal feed, and human travellers (MAF 2002). At the time, the Ministry of Agriculture and Forestry requested that unexplained deaths of more than 20 birds should be reported to their Exotic Disease Hotline. As well as being screened for salmonella, such birds should now also be screened for WNV. New Zealand currently does not have the necessary reagents for testing for WNV (G. Horner, MAF, Wallaceville, pers. comm.), so will have to either import such reagents or send samples overseas for testing. If resources permit, samples of mosquitoes and birds should be tested proactively to see if there is currently any evidence of WNV in New Zealand, as was done in the UK (Buckley et al. 2003; Duff 2003; Duff et al. 2003).

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Appendices

Appendix 1. Bird hosts for the tick *Ornithodoros capensis*

Common name (in checklist order)	Scientific name	Location
Wedge-tailed shearwater	*Puffinus pacificus pacificus*	Kermadec Is. [1]
Black-winged petrel	*Pterodroma nigripennis*	Kermadec Is. [1,8]
Kermadec petrel	*Pterodroma neglecta*	Kermadec Is. [1,8]
Red-tailed tropicbird	*Phaethon rubricauda*	? [2,8]
Australasian gannet	*Morus serrator*	Cape Kidnappers [3,7]
Spotted shag	*Stictocarbo puncatatus puncatatus*	Perpendicular Point, Punakaiki, West Coast [4] Birdlings Flat, Banks Peninsula, Canterbury [4,5]
Spotless crake	*Porzana tabuensis pulmbea*	Kermadec Is. [1,8]
Red-billed gull	*Larus novaehollandiae scopulinus*	Kaikoura, Sumner, and Karitane [3,7,8]; ? [6];
White-fronted tern	*Sterna striata*	Kaikoura, Sumner, and Karitane [3,7]
Sooty tern	*Sterna fuscata*	Kermadec Is. [1,8]
White-capped noddy	*Anous tenuirostris minutus*	Kermadec Is. [1]

[1]Ramsey (1968); [2]Museum of New Zealand Te Papa Tongarewa; [3]Austin (1984); [4]Dumbleton (1958); [5]Dumbleton (1961); [6]AgResearch, Wallaceville Animal Research Centre; [7]Heath (1987); [8]Bishop & Heath (1998).

Appendix 2. Bird species in New Zealand infected with WNV overseas

Common name (in checklist order)	Scientific name	Residency status
Ostrich[1]	*Struthio camelus*	Farmed
Emu[1]	*Dromaius novaehollandiae*	Farmed
Black shag[3]	*Phalacrocorax carbo novaehollandiae*	Resident
Little egret[3]	*Egretta garzetta*	Migrant
Glossy ibis[3]	*Plegadis falcinellus*	Vagrant
Domestic goose[1,3]	*Anser anser*	Resident
Canada goose[1,3]	*Branta canadensis*	Resident
Mallard duck[1,3]	*Anas platyrhynchos*	Resident
Mute swan[1]	*Cygnus olor*	Resident
Bobwhite quail[1]	*Colinus virginianus*	Resident
Chukor[1]	*Alectoris chukar*	Resident
Domestic chicken[1,2,3]	*Gallus gallus*	Resident
Ring-necked pheasant[1,3]	*Phasianus colchicus*	Resident
Turkey[1,2]	*Meleagris gallopavo*	Resident
Australian coot[3]	*Fulica atra australis*	Resident
Turnstone[1]	*Arenaria interpres*	Migrant
Eastern common tern[3]	*Sterna hirundo longipennis*	Migrant
Rock pigeon[1,3]	*Columba livia*	Resident
Barn owl[1]	*Tyto alba delicatula*	Vagrant
Zebra finch[1]	*Taeniophygia guttata*	Captive
Cockatiel[1]	*Nymphicus hollandicus*	Captive
Budgerigar[1]	*Melopsittacus undulatus*	Captive
Hedgesparrow[2]	*Prunella modularis*	Resident
Blackbird[2,3]	*Turdus merula*	Resident
Song thrush[2]	*Turdus philomelos*	Resident
Chaffinch[2,3]	*Fringilla coelebs*	Resident
Goldfinch[1,3]	*Carduelis carduelis*	Resident
House sparrow[1,3]	*Passer domesticus*	Resident
Starling[1,2,3]	*Sturnus vulgaris*	Resident
Rook[3]	*Corvus frugilegus*	Resident

[1]WNV detected in USA, [2]UK, [3]elsewhere in Europe.

Residency status key for appendices 2–4 (adapted from Heather & Robertson 1996):
Captive/farmed: Cage bird or farm animal.
Migrant: Moves annually and seasonally between breeding and non-breeding areas, either within New Zealand or between New Zealand and other countries.
Resident: Remains in roughly the same area throughout the year.
Straggler: Reaches New Zealand by going further than usual along normal migratory route, or by straying a little off course.
Vagrant: Wanders or is blown off course, arriving unexpectedly, from an unusual direction.
Visitor: Disperses from mating area, reaching New Zealand every year.

References for appendices 2–5:
Komar (2000); Rappole et al. (2000); Malkinson & Banet (2002); Murgue et al. (2002); Buckley et al. (2003); Rappole & Hubálek (2003); USGS (2003); Higgs et al. (2004).

Appendix 3. Bird species in New Zealand in the same genera as infected with WNV overseas

Common name (in checklist order)	Scientific name	Residency status
Australasian crested grebe	*Podiceps cristatus australis*	Resident
Magellanic penguin	*Spheniscus magellanicus*	Vagrant
Australian pelican	*Pelecanus conspicillatus*	Vagrant
Pied shag	*Phalacrocorax varius*	Resident
Little black shag	*Phalacrocorax sulcirostris*	Resident
Little shag	*Phalacrocorax melanoleucos*	Resident
White-faced heron	*Ardea novaehollandiae*	Resident
White-necked heron	*Ardea pacifica*	Vagrant
White heron	*Egretta alba*	Resident
Intermediate egret	*Egretta intermedia*	Vagrant
Reef heron	*Egretta sacra*	Resident
Nankeen night heron	*Nycticorax caledonicus*	Vagrant
Australasian bittern	*Botaurus poiciloptilus*	Resident
Australian little bittern	*Ixobrychus minutus dubius*	Vagrant
Black swan	*Cygnus atratus*	Resident
Grey duck	*Anas superciliosa*	Resident
Brown teal	*Anas aucklandica*	Resident
Australasian shoveler	*Anas rhynchotis*	Resident
Northern shoveler	*Anas clypeata*	Vagrant
White-eyed duck	*Aythya australis*	Vagrant
New Zealand scaup	*Aythya novaeseelandiae*	Resident
Australasian harrier	*Circus approximans*	Resident
New Zealand falcon	*Falco novaeseelandiae*	Resident
Nankeen kestrel	*Falco cenchroides*	Vagrant
Black falcon	*Falco subniger*	Vagrant
Red-legged partridge	*Alectoris rufa*	Resident?
Banded rail	*Rallus philippensis assimilis*	Resident
Brolga	*Grus rubicundus*	Vagrant
New Zealand dotterel	*Charadrius obscurus*	Resident
Banded dotterel	*Charadrius bicinctus*	Resident
Red-capped dotterel	*Charadrius ruficapillus*	Vagrant
Black-fronted dotterel	*Charadrius melanops*	Resident
Ringed plover	*Charadrius hiaticula*	Vagrant
Large sand dotterel	*Charadrius leschenaultia*	Migrant
Mongolian dotterel	*Charadrius mongolus*	Migrant
Oriental dotterel	*Charadrius veredus*	Migrant
Spur-winged plover	*Vanellus miles novaehollandiae*	Resident
Southern black-backed gull	*Larus dominicanus*	Resident
Red-billed gull	*Larus novaehollandiae*	Resident
Black-billed gull	*Larus bulleri*	Resident
Black-fronted tern	*Sterna albostriata*	Resident
Caspian tern	*Sterna caspia*	Resident
White-fronted tern	*Sterna striata*	Resident
Sooty tern	*Sterna fuscata serrata*	Vagrant
Antarctic tern	*Sterna vittata bethunei*	Resident
Fairy tern	*Sterna nereis davisae*	Resident

Common name (in checklist order)	Scientific name	Residency status
Eastern little tern	*Sterna albifrons sinensis*	Migrant
Arctic tern	*Sterna paradisaea*	Migrant
Crested tern	*Sterna bergii*	Vagrant
Bridled tern	*Sterna anaethetus*	Vagrant
Barbary dove	*Streptopelia roseogrisea*	Resident
Spotted dove	*Streptopelia chinensis*	Resident
Sulphur-crested cockatoo	*Cacatua galerita*	Resident
Welcome swallow	*Hirundo tahitica*	Resident
Australian tree martin	*Hirundo nigricans*	Vagrant
Fairy martin	*Hirundo ariel*	Vagrant?
Greenfinch	*Carduelis chloris*	Resident
Redpoll	*Carduelis flammea*	Resident

Residency status key same as in Appendix 2.
References same as in Appendix 2.

Appendix 4. Bird species in New Zealand in the same families as infected with WNV overseas

Common name (in checklist order)	Scientific name	Residency status
Dabchick	*Poliocephalus rufopectus*	Resident
Hoary-headed grebe	*Poliocephalus poliocephalus*	Vagrant
Australasian little grebe	*Tachybaptus n. novaehollandiae*	Resident
Emperor penguin	*Aptenodytes forsteri*	Vagrant
King penguin	*Aptenodytes patagonicus*	Vagrant
Yellow-eyed penguin	*Megadyptes antipodes*	Resident
Gentoo penguin	*Pygoscelis papua*	Vagrant
Adélie penguin	*Pygoscelis adeliae*	Vagrant
Chinstrap penguin	*Pygoscelis antarctica*	Vagrant
Blue penguin	*Eudyptula minor*	Resident
Rockhopper penguin	*Eudyptes chrysocome*	Straggler
Macaroni penguin	*Eudyptes chrysolophus*	Straggler
Fiordland crested penguin	*Eudyptes pachyrhynchus*	Resident
Snares crested penguin	*Eudyptes robustus*	Straggler
Erect-crested penguin	*Eudyptes sclateri*	Visitor
New Zealand king shag	*Leucocarbo carunculatus*	Resident
Stewart Island shag	*Leucocarbo chalconotus*	Resident
Spotted shag	*Stictocarbo punctatus*	Resident
Cattle egret	*Bubulcus ibis*	Migrant
White ibis	*Threskiornis molucca*	Vagrant
Royal spoonbill	*Platalea regia*	Resident
Yellow-billed spoonbill	*Platalea flavipes*	Vagrant
Grass whistling duck	*Dendrocygna eytoni*	Vagrant
Cape Barren goose	*Cereopsis novaehollandiae*	Vagrant
Paradise shelduck	*Tadorna variegata*	Resident
Australian wood duck	*Chenonetta jubata*	Vagrant
Blue duck	*Hymenolaimus malacorhynchos*	Resident
California quail	*Callipepla californica*	Resident
Grey partridge	*Perdix perdix*	Resident?
Brown quail	*Synoicus ypsilophorus*	Resident
Peafowl	*Pavo cristatus*	Resident
Tufted guineafowl	*Numida meleagris*	Resident
Weka	*Gallirallus australis*	Resident
Spotless crake	*Porzana tabuensis*	Resident
Marsh crake	*Porzana pusilla*	Resident
Black-tailed native hen	*Gallinula ventralis*	Vagrant
Dusky moorhen	*Gallinula tenebrosa*	Vagrant
Pukeko	*Porphyrio porphyrio melanotus*	Resident
Takahe	*Porphyrio mantelli*	Resident
Red-kneed dotterel	*Erythrogonys cinctus*	Vagrant
Shore plover	*Thinornis novaeseelandiae*	Resident
Wrybill	*Anarhynchus frontalis*	Resident
Pacific golden plover	*Pluvialis fulva*	Migrant
Grey plover	*Pluvialis squatarola*	Migrant
Kereru	*Hemiphaga novaeseelandiae*	Resident
Kakapo	*Strigops habroptilus*	Resident
Kaka	*Nestor meriodionalis*	Resident
Kea	*Nestor notabilis*	Resident
Crimson rosella	*Platycercus elegans*	Resident
Eastern rosella	*Platycercus eximius*	Resident
Red-crowned parakeet	*Cyanoramphus novaezelandiae*	Resident

Common name (in checklist order)	Scientific name	Residency status
Yellow-crowned parakeet	*Cyanoramphus auriceps*	Resident
Oriental cuckoo	*Cuculus saturatus*	Vagrant
Pallid cuckoo	*Cuculus pallidus*	Vagrant
Fan-tailed cuckoo	*Cacomantis flabelliformis*	Vagrant
Shining cuckoo	*Chrysococcyx lucidus*	Resident
Long-tailed cuckoo	*Eudynamys taitensis*	Resident
Channel-billed cuckoo	*Scythrops novaehollandiae*	Vagrant
Morepork	*Ninox novaeseelandiae*	Resident
Little owl	*Athene noctua*	Resident
Spine-tailed swift	*Hirundapus caudacutus*	Vagrant
Fork-tailed swift	*Apus pacificus*	Vagrant
Kookaburra	*Dacelo novaeguineae*	Vagrant
New Zealand kingfisher	*Halcyon sancta vagans*	Resident
Yellowhammer	*Emberiza citrinella*	Resident
Cirl bunting	*Emberiza cirlus*	Resident
Common myna	*Acridotheres tristis*	Resident

Residency status key same as in Appendix 2.
References same as in Appendix 2.

Appendix 5. Mammal species in New Zealand infected with WNV overseas

Common name (in checklist order)	Scientific name	Residency status
Hedgehog[3]	*Erinaceus europaeus occidentalis*	Wild
Rabbit[1,3]	*Oryctolagus cuniculus*	Wild
Hare[3]	*Lepus europaeus*	Wild
House mouse[2]	*Mus musculus*	Wild
Guinea pig[3]	*Cavia porcellus*	Pet
Dog[1,3]	*Canis familiaris*	Farm and pet
Cat[1]	*Felis catus*	Pet and feral
Horse[1,2,3]	*Equus caballus*	Farm and feral
Donkey[1]	*Equus asinus*	Farm
Pig[3]	*Sus scrofa*	Farm and feral
Cattle[1,3]	*Bos taurus*	Farm and feral
Goat[3]	*Capra hircus*	Farm and feral
Sheep[1,3]	*Ovis aries*	Farm and feral
Llama[1]	*Lama glama*	Farm
Alpaca[1]	*Lama pacos*	Farm
White-tailed deer[1]	*Odocoileus virginianus borealis*	Wild

[1]WNV detected in USA, [2]UK, [3]elsewhere in Europe.
Residency status: all species introduced.
References same as in Appendix 2.

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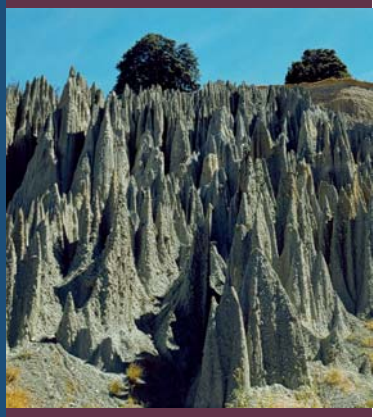

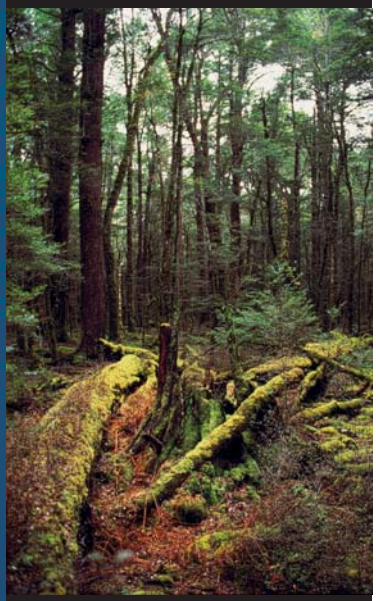

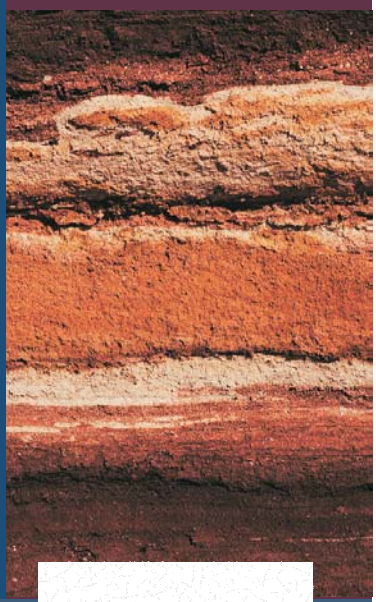

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