Impacts of wind farms on birds: a review

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Ralph G. Powlesland

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Cover: Vestas V90 turbine, Tararua Wind Farm stage III, near Palmerston North.
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Impacts of wind farms on birds: a review

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ABSTRACT

The impacts of wind farms on New Zealand bird species and populations are unknown. This document reviews available literature on the impacts of onshore wind farms on birds, based on studies in other countries. A key finding is that wind farms tend to have variable effects on bird populations, which can be species-, season- and/or site-specific. The impacts include collision fatalities, habitat loss and disturbance resulting in displacement. The main factors that contribute to collision fatalities are proximity to areas of high bird density or frequency of movements (migration routes, staging areas, wintering areas), bird species (some are more prone to collision or displacement than others), landscape features that concentrate bird movement, and poor weather conditions. In many instances, the numbers of carcasses reported are likely to be underestimates, as they are often based only on found carcasses, without accounting for scavenging and searcher efficiency. Habitat loss as a result of wind farm construction seems to have a minor impact on birds, as typically only 2–5% of the total wind farm area is taken up by turbines, buildings and roads. However, the cumulative loss of sensitive or rare habitats may be significant, especially if multiple large developments are sited at locations of high bird use. Disturbance of birds as a result of wind farm development may arise from increased activity of people at the site, and/or the presence, motion and noise of turbines. The level of disturbance to birds has been shown to vary, depending on the availability of alternative feeding or breeding habitat. Although some of the findings from this review may be relevant to the New Zealand situation, it is important to realise that each wind farm tends to be different as a result of topography, weather, habitats, land use, bird species and turbine characteristics.

Keywords: wind farm, turbine, review, collision fatalities, habitat loss, displacement, migration routes, weather, lighting, mitigation

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1. Introduction

The levels of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere have become the focus of international concern, being linked to observed and predicted climate change. Atmospheric CO_2 concentrations were approximately constant until the industrial era began in about 1750. Since then, they have risen by around 35% and are currently increasing at 0.4% per annum on average (Ashby 2004). Most of the increase is thought to have come from burning of fossil fuels. Most governments now accept that climate change is a reality and that it presents serious environmental threats, including threats to human health, food production and biodiversity. The Kyoto Protocol was established under the United Nations Framework Convention on Climate Change as an international response to the climate change issue. The New Zealand Government ratified the Kyoto Protocol in December 2002.

The Kyoto Protocol commits New Zealand to reduce greenhouse gas emissions by at least 5% of 1990 levels between 2008 and 2012. Renewable sources of energy offer an opportunity to reduce the deleterious environmental impacts of climate change arising from over-reliance on fossil fuels. Of the most advanced renewable technologies, wind energy is set to make a modest contribution to energy generation in many countries. Already, some state governments in the USA are setting targets for large utilities to purchase a minimum proportion of their electricity from renewable sources (Nijhuis 2006), and the UK Government has set a specific target to derive 10% of energy from renewable sources by 2010, of which 7–8% will be from wind energy, and has set a goal of doubling that by 2020 (Drewitt & Langston 2006; Morley 2006). In contrast, in 2007 the New Zealand Government said it aimed to have 90% of electricity generated from renewable resources, such as wind and hydro power, by 2025 (www.stuff.co.nz/print/4217358a7693.html; viewed 27 August 2008).

New Zealand probably has the best overall accessible wind resource of any nation (Ashby 2004). Large parts of New Zealand have good mean wind speeds for generation year round (Parliamentary Commissioner for the Environment 2006: figure 3.1). However, a wind turbine with a rated capacity of 1 MW will not produce that output all the time, due to variation in wind speeds. Worldwide in 2002, the average capacity factor was 23%, i.e. the amount of electricity produced by turbines was equivalent to them operating at 23% of their rated capacity. By comparison, capacity factors achieved so far in New Zealand are 40–50% (Ashby 2004). Major providers in the energy industry see wind as being able to supply up to 20% of New Zealand's energy needs safely, economically and reliably within the next 10 years (Rodgers 2006).

Unfortunately, although wind power is a cleaner option for energy production, its impact on wildlife remains unclear. In New Zealand and Australia, developers often voluntarily commission wildlife surveys before beginning construction, but studies often span inadequate time periods, details are rarely made public and robust results from impact surveys following construction have not been reported. Although some state governments in the USA have established permitting processes and guidelines for wind farm development, monitoring remains weak and haphazard (Nijhuis 2006). Thus, conservationists and scientists often find themselves in a difficult situation. As Nijhuis (2006) asked, 'How can they support and encourage the rapid spread of wind power, our most promising source of clean, renewable energy, while ensuring that the industry minimises its damage to birds and other wildlife?'.

As a result of concern over the negative impacts that wind-energy developments could have on wildlife, especially threatened species, efforts have been increasing to avoid establishing new developments at locations that are likely to pose significant risks to birds, and to accurately quantify the impacts of wind farms on birds at existing wind farm sites (Percival 2005; Morrison et al. 2007).

In New Zealand, energy production by wind farms is still in a much earlier stage of development than in Europe and North America. However, it is poised for rapid expansion, to make a significant contribution to total energy production. Thus, this is an opportune time to learn from the observed effects that wind farms have had on birds elsewhere. In some areas, wind farms have had adverse impacts on birds, e.g. 1143 carcasses of more than 40 species, including threatened species, were found following searches around 4075 turbines at the Altamont Pass Wind Resource Area, California, USA, during May 1998 – May 2003 (Smallwood & Thelander 2004). However, many wind farms exist where recorded bird mortality has been non-existent or minimal, including facilities in Africa, Asia, Europe, Australia, Canada, USA and South America (Kingsley & Whittam 2005). For example, in the UK, there have been no significant[1] ornithological problems reported at wind farms, despite there being some 101 wind farms in operation comprising about 1234 turbines with a capacity of 979 MW in 2005 (Drewitt & Langston 2006), mainly because they are sited away from important bird populations (Percival 2005). Therefore, the challenge in New Zealand is to identify which species are likely to be adversely affected by wind farms, the locations at which adverse impacts are most likely, and the particular features of the environment and wind farm structures that increase the risks to birds, so that adverse effects can be appropriately avoided, remedied or mitigated in a way that meets the purpose of the Resource Management Act (Anon. 1991).

This report reviews literature, both published and unpublished, about the impacts of wind farms on birds. The review was undertaken at the request of the Corporate Services Group of the Department of Conservation to provide background information on the topic for the Group and other Department staff dealing with consent applications for the building of wind farms by New Zealand wind energy generators. This report includes information about features of wind farms that may contribute to impacts on birds, collision fatalities, disturbance leading to displacement, loss of or damage to habitat, and barrier effects. It is restricted mainly to the impacts of onshore wind farms as, at present, most wind farms throughout the world are onshore facilities, and although offshore wind farms are likely to make up a significant part of the future wind farm development in Europe with further technological advances, no offshore facilities are currently present in New Zealand. Many reports referred to in this review were commissioned for particular purposes and have not been through a peer-review process. However, because of the paucity of published studies on the impacts of wind farms on bird populations, much information in this review emanates from these non-peer-reviewed unpublished reports. Thus, I recommend caution about drawing firm conclusions from the results provided in these reports.

Common and scientific names for New Zealand bird species used in this document follow those of Turbott (1990).

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[1] Throughout this report, 'significant' is used either in a statistical sense or to refer to an impact on a species that occurs at the population level.

2. Features of wind farms that may contribute to impacts on birds

A number of features of wind farms may contribute to their impacts on birds and their populations. These include the scale of wind farms, wind farm configuration, construction and operation, turbine design and dimensions, lighting, blade speed and motion smear, associated structures, and landscape features.

2.1 SCALE OF WIND FARMS

There is little relationship between the scale of a wind farm and the amount of bird mortality that has occurred (Kingsley & Whittam 2005; Percival 2005). A large, appropriately sited wind farm may kill fewer birds than a small, poorly sited one. Considered in isolation, it is unlikely that small numbers of fatalities per year at a wind farm would be considered significant, unless some of those fatalities were of threatened species, in which case impacts might occur at the population level (although it should be noted that cumulative effects of small numbers of fatalities at two or more wind farms may be sufficent to result in population impacts). In contrast, a large facility may kill many birds in total, thus impacting at the population level, especially when threatened species are involved. Even relatively small increases in mortality rates may be significant for populations of some birds, especially long-lived species with generally low annual productivity and slow maturity, and particularly when already rare (Percival 2000; Langston & Pullan 2003; Everaert & Stienen 2007), e.g. blue duck (*Hymenolaimus malacorhynchos*) and kaka (*Nestor meridionalis*). When considering potential impact, it is important to consider the average effect of each turbine, the cumulative effect of the total number of turbines and associated structures (overhead power lines, meteorological masts; see section 2.4) on a farm, and even the cumulative impact of other wind farms in the range of a bird population, particularly where rare or threatened species are concerned (Australian Wind Energy Association 2002; Everaert & Stienen 2007).

As the area of the farm increases (density of turbines remaining constant), the potential for adverse effects, other than fatalities, also increases. Large facilities may cause more bird habitat to be lost or compromised, so that foraging and breeding birds may be more inclined to avoid the area. Even in New Zealand, a large wind farm can occupy many square kilometres in area: e.g. Hawke's Bay wind farm near Napier—75 turbines, 30.0 km^2; Project West Wind near Wellington—62 turbines, 55.8 km^2; Project Hayes near the Lammermoor Range, Otago—176 turbines, 92 km^2. Percival (2005) considered that direct habitat loss from wind farm construction was usually small-scale and unlikely to have a significant impact on bird populations. However, a considerable proportion of habitat may be lost if a particularly scarce and important habitat type was affected, or if there was potential for the effects to extend into the wider area (e.g. through disrupting the hydrology of a wetland).

2.2 WIND FARM CONFIGURATION, CONSTRUCTION AND OPERATION

The configuration of turbines at onshore facilities is most often dictated by the wind resource, and thus far no one has examined how overall wind farm configuration may affect birds. Percival (2001) considered that, in general, spacing between turbines should be greater than 200 m in order to avoid inhibiting bird movement (barrier effect). This recommended distance is also often the amount of spacing required by industry to reduce wake effects of large turbines on neighbouring turbines (Kingsley & Whittam 2005). However, spacing turbines widely in an attempt to reduce the likelihood of blocking bird movement may potentially increase the area from which birds will be displaced by disturbance. Given that most New Zealand operational and planned wind farms occur on open/modified landscapes (habitat occupied mainly by common and widespread bird species), the displacement of such bird species from portions of a wind farm is unlikely to have population consequences.

Although it has been suggested that some species are more disturbed by clusters of turbines than strings, clusters may be more advantageous, as mortality could subsequently be reduced (Percival 2001). For large projects, a possible solution is to provide wide corridors between clusters of closely spaced turbines (Langston & Pullan 2003). Winkelman (1992b) also considered that wind farm layout was probably an important determinant of collision risk, arguing that a (dense) cluster of turbines was potentially less damaging for wintering, feeding and possibly breeding birds, because it tended to dissuade them from flying amongst the turbines. Larsen & Madsen's (2000) study of foraging geese supported this. However, for migrants, Winkelman (1992b) considered that a line formation parallel to the main flight direction or a loose cluster was the best arrangement.

The high degree of disturbance normally associated with construction of a wind farm is temporary. The time taken to construct a wind farm is dependent upon several factors, including the scale of the project, the terrain and climate. However, construction typically takes 9–18 months (Kingsley & Whittam 2005), making it likely that some of this time will coincide with bird breeding. Construction usually begins with the development of roads, followed by the excavation and pouring of the concrete foundations for the towers. Typically, this is followed by digging trenches and burial of underground electrical cables where soil conditions allow. Substations and any other buildings are then built, and lastly the turbines are assembled and tested. The erection of a turbine usually takes 1 day.

As most wind farms are completely automated, disturbance by people at a site is minimal once construction is complete, with only a few on-site personnel required on an occasional basis. However, some wind farms are promoted as tourist sites (e.g. Meridian Energy's Te Apiti wind farm on Saddle Road, near the Manawatu Gorge), which may result in substantial human disturbance. The activities associated with decommissioning of turbines could also disturb birds at the site.

Although wind energy is considered 'clean and green', it does produce waste materials during all phases of a facility's life (construction, operation and decommissioning). Potential pollutants include various lubricants that are used in the turbines, such as gearbox oils, hydraulic fluids and insulating fluids. These materials pose little threat to birds if handled appropriately, but contamination can arise from spills during routine maintenance and fluid leaks if the turbines are not regularly inspected. Decommissioning creates a great deal of waste, as all of the turbines must be dismantled, any above-ground wires removed, and any other equipment and waste removed from the site and disposed of appropriately.

2.3 TURBINES

2.3.1 Design and dimensions

Most commercial-scale wind turbines consist of a three-bladed rotor that rotates around a horizontal hub facing upwind in front of the generator and tower (Fig. 1). Most towers these days are of tubular steel construction and are bolted to a concrete foundation. Blades are made of fibreglass or wood epoxy. The hub is connected to a gearbox and generator, which are all located in the nacelle. The tower of a large wind turbine may have an internal elevator to transport workers to the nacelle for maintenance. The nacelle on top of the tower contains a generator turned by the blades, which in turn produces electricity.

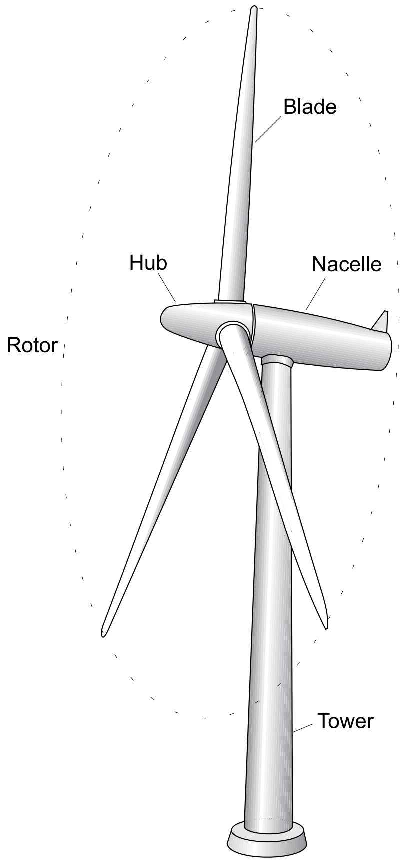

Figure 1. Basic features of a wind turbine.

As wind-power generation has developed and the associated technologies advanced, rotor diameters and tower heights have increased and are likely to continue to do so, as taller towers allow turbines to intercept wind that is less turbulent. During the 1980s, relatively short turbine towers were installed, with few exceeding 18 m in height (Kingsley & Whittam 2005). In contrast, typical tower heights today for commercial-scale turbines (1–2 MW capacity) are 80–100 m. The length of the blade is usually about half the height of the tower (Ashby 2004), making the tallest turbines in New Zealand about 150 m in total height (Meridian Energy Ltd 2007). Experience with communication towers and skyscrapers in the USA suggests that turbines of this height have the potential to interact more frequently with migratory birds (Kingsley & Whittam 2005). However, it is unknown whether turbines greater than 150 m in height in New Zealand would cause increased bird mortality.

Small turbines are often used in remote areas, where they meet the electricity needs of a settlement, field station or family. These turbines often have tubular or lattice towers, and range between 18 m and 40 m in height. They also tend to be variable speed turbines with quickly turning blades (usually 10–50 revolutions per minute (rpm), but can be as great as 300 rpm). Typically, the use of such turbines would be on a small scale, and their effect on birds is likely to be reduced if sited correctly.

Laboratory research has indicated that high contrast patterns on turbine blades (McIsaac 2001) or a single black blade paired with two white blades may reduce collision risk by increasing the visibility of the rotating blades (Hodos et al. 2001, cited in Sterner 2002). However, it is not known to what extent these features might avert collisions, especially in conditions of poor visibility. Furthermore, such measures may be unacceptable on landscape grounds.

Wind turbines can be mounted on either lattice or tubular steel towers. In the past, it was believed that lattice-type towers encouraged raptor perching, which led to increased mortality (Percival 2000). However, recent research suggests that the specific type of turbine does not influence the flight, perching behaviour or rate of collisions of raptors. Rather, it is the placement of turbines within the landscape that appears to be the major factor influencing raptor behaviour and death (Morrison et al. 2007).

2.3.2 Lighting

In general, turbines are required to have some form of lighting, either individually or collectively as a wind farm. The lighting specifications differ between countries. In New Zealand, the lighting required has been specified by the Civil Aviation Authority of New Zealand (CAA) on a case-by-case basis. Generally, each turbine in New Zealand at either end of a line has a light, but more may be required to have lights depending on factors such as proximity to an airport and low-level flight zones. The lights are usually medium-intensity obstruction lights, and they have to be installed and operated in a way that minimises their visibility at ground level. As a result, low-intensity steady red lights are used that are directed upwards (shielded downwards) and installed on top of the nacelle. To minimise the risk of the lighting causing problems for wildlife, white lighting is not allowed.

Lit turbines can attract birds, thereby potentially increasing the risk of collision, especially in conditions of poor visibility (Winkelman 1992b). There have been large mortality events at a variety of lit structures in the USA as a result of nocturnal-migrant songbirds being disorientated by lights when forced to fly at low altitude by rain and mist (Langston & Pullan 2003; Kingsley & Whittam 2005). Erickson et al. (2001) suggested that lighting was the single most critical attractant for nocturnal migrants[2], leading to collisions with tall structures. Various explanations have been put forward for the apparent attraction of birds, especially nocturnally migrating passerines, to artificial lights (Avery et al. 1976; Verheijen 1985), though none of these has been conclusively established. Perhaps the most plausible relates to a ‘trapping effect’ of light rather than actual attraction (Avery et al. 1976): on entering an illuminated area, especially on a foggy night, passing migrants are reluctant to leave; on approaching the edge of the illuminated area, they are hesitant to fly into the darkness beyond, and instead fly back towards

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[2] Migration refers to the regular seasonal journeys undertaken by many species of birds, often between breeding and wintering sites. It includes movements within national boundaries and between countries.

the light. Solid or blinking red lights seem to attract birds more than white strobes, which flash every 1–3 seconds (Ogden 1996; Sterner 2002). Therefore, the trapping effect could be minimised by reducing the intensity of the light to a minimum, and having the intervals between flashes as long as possible (Hotker at al. 2006; Huppop et al. 2006). It has been suggested that the hazard of lighting attracting or trapping nocturnally active birds could be reduced by shielding, but this needs to be tested to ensure that it meets the requirements of navigational safety and does not introduce an unacceptable collision risk for birds. The issue of these lights attracting or confusing nocturnally migrating birds and resulting in them colliding with turbines has been a concern for wildlife agencies, and therefore needs to be considered in detail when assessing risk.

Mass mortality of birds involving thousands during one night has occurred at some communication towers in the USA. For example, an estimated 30 000 birds representing 56 species were killed at the Eau Claire tower, Wisconsin, on the nights of 18 and 19 September 1963 (Kemper 1964). Generally, such large-scale mortality events have almost exclusively occurred at guyed and lit communication towers greater than 150–180 m (500–600 feet) in height (Avery et al. 1980; Kerlinger 2000). The number of nocturnal migrants reported dead at North American wind turbines is a small fraction of the number killed by communication towers (Kerlinger 2004). Similarly, none of the wind turbine studies in the USA listed in Erickson et al. (2002) reported large or significant numbers of nocturnal migrants colliding with wind turbines, and some reported no collisions; the reported fatality incidents mostly involved collisions of single birds. The reason so few nocturnal migrants have been found to collide with wind turbines to date compared with tall communication towers is likely related to the shorter height of wind turbines, their lack of guy wires and their minimal lighting (Avery et al. 1980; Kerlinger 2000).

2.3.3 Blade speed and motion smear

The rotor on a 1.5 MW capacity turbine turns at a speed of about 19 rpm. In contrast, smaller machines, such as the 225 kW Brooklyn turbine, turn at 40–45 rpm (Ashby 2004). To avoid damage, turbines automatically shut off when the wind reaches a speed of about 25 m/s (c. 90 km/h).

There are several reasons why birds may collide with wind turbines during conditions of good visibility, with the most obvious being that they are unable to detect the spinning blades. Two hypotheses, applying mainly to raptors, have been suggested to explain this. The first is motion smear, or motion blur, which occurs when an object moves with increasing speed, becoming progressively more blurred. This phenomenon is apparent at the tips of turbine blades because the speed at the tip is much greater than at the base of the blade, so that the eye is unable to detect the individual revolutions (although it is not clear whether this perceived problem is based on human vision or bird vision). The second hypothesis is the inability of birds to divide their attention between hunting and monitoring the horizon for obstacles. Hodos (2003) considered it likely that hunting raptors are able to focus on both the ground and the horizon, as their eyes have two foveal regions, one for frontal vision and the other for looking down. However, observations of hunting raptors by L. Barea (Department of Conservation, pers. comm. 15 February 2008) suggest that for at least some of the time birds cannot use the two fovea at the same time, as they become so focussed on the ground they are searching or prey they are pursuing that they sometimes fail to see objects in front of them, such as power lines, resulting in collisions. Therefore, although motion smear is considered by some to be the main reason birds collide with moving turbine blades during good visibility (McIsaac 2001; Hodos 2003), it is probably not the only reason.

To date, most studies of the effects of turbine blades on bird mortality have been based on older, variable-speed turbines. These turbines, which have c. 3-m-long blades, can have very high blade speeds of over 60 rpm, making motion smear an important issue. However, wind turbine technology has changed significantly, such that the c. 11-m-long blades of large turbines (> 1 MW) now rotate at a much slower speed of 15–30 rpm. Even though the tips of the 11-m blades revolve faster than those of 3-m blades, the longer blades seem to be more visible to birds (Kingsley & Whittam 2005), lessening the potential risk of collision. Nonetheless, no studies to date have examined the effect of slower blade revolution on birds (Kingsley & Whittam 2005).

All new wind energy developments should ensure that blade revolutions per minute are minimised, to avoid motion smear and promote blade visibility during the day. Laboratory research indicates that applying certain designs to turbine blades will enhance the ability of birds to see rotating blades, and thus potentially reduce fatalities (see McIsaac 2001: figure 9 for design examples).

2.4 ASSOCIATED STRUCTURES

The following structures, which may occur at wind farms, have been responsible for avian fatalities: overhead wires (power transmission and distribution lines), guy wires, lighting and uninsulated electrical equipment.

Based on fatality rates reported in other studies, Erickson et al. (2001) estimated that tens of thousands to 174 million bird fatalities occur in the USA each year due to collision with overhead wires. Several groups of birds appear to be susceptible to collision with wires, most notably waterfowl, shorebirds and raptors (Curtis 1977; Anderson 1978; Olsen & Olsen 1980). Although waterfowl and shorebirds seem to avoid turbines, as evident by the low recorded incidence of fatal collisions involving these groups of birds (Percival 2005), significant numbers have been known to collide with associated power lines, especially when located near wetlands (Anderson 1978; Moorehead & Epstein 1985, cited in Kingsley & Whittam 2005). At a power plant in Illinois, 200–400 waterfowl (0.2–0.4% of the peak number present) were killed each autumn during 1973–1975 as a result of colliding with overhead power lines (Anderson 1978). However, it is important to keep in mind the fact that impacts are site- and species-specific, and there are no data for New Zealand situations.

The maximum number of bird fatalities reported at a wind farm is a recently reported event that involved 27 birds at three turbines and a substation (Kerlinger 2003). The event occurred on a foggy night and was, in all probability, caused by four sodium vapour lamps that were mounted on the substation, which was near the middle of the turbines (Kerns & Kerlinger 2004), as once the substation lamps were turned off, no subsequent multiple fatalities occurred (Kerlinger 2003). At another wind farm, 14 fresh carcasses (all passerines) were found underneath two adjacent turbines (Johnson et al. 2002). Although carcass searches were conducted at 14-day intervals at the site, a severe thunderstorm during the night before the search was suspected to have forced the migrating birds to fly at a lower than normal altitude and into the turbines.

Although evidence from US studies suggests that nocturnal bird migration typically occurs at heights above most wind farm structures (see section 5.2.3), collisions still occur with structures less than 100 m in height (Avery et al. 1980). For example, Wylie (1977) found 73 dead birds representing 21 species at an unlit fire tower following a night of fog and rain. The 30-m tower stood on a ridge at c. 800 m a.s.l. It was considered that the inclement weather and the tower being on a ridge at high elevation contributed to the mortality, even though the tower was unlit and relatively short. This example emphasises the site- and weather-specific nature of some occurrences. Therefore, the altitude at which nocturnal migrants, such as waders, fly in New Zealand during different weather conditions needs to be determined for species of concern.

Another possible risk to birds is electrocution from perching on uninsulated equipment. For example, the 'Falcons for Grapes Project' in Marlborough released 19 young falcons (*Falco novaeseelandiae*) in vineyards of the Wairau Plain during 2005/06, of which five were electrocuted during their first few months of flight as a result of perching on uninsulated transformers (www.falconsforgrapes.org; viewed 4 September 2008). However, transformers on wind farms are large and insulated, and the conductors, which are uninsulated, are well spaced from anything that could earth them, making electrocution of a perched bird in such circumstances impossible (S. Faulkner, Connell Wagner Ltd, pers. comm. 30 January 2008).

Reducing the amount of above-ground wire at wind farms will reduce the potential risk of collision to birds in the area. However, it is not always practical to place cables underground. Furthermore, in areas where the risk of bird collision is low and where sensitive habitat exists, the placement of wires underground may cause more damage to local bird populations through habitat destruction than overhead wires would cause through collisions. Where it is unavoidable to have above-ground wires at a wind farm, bird deflectors (brightly coloured plastic balls) should be attached to wires, to alert birds to their presence. However, these will only work during the day.

2.5 LANDSCAPE FEATURES

Physical features on the landscape can strongly influence bird movement and behaviour. For example, diurnal migrants tend to follow coasts, shorelines of lakes, rivers, ridges and other linear features (Richardson 2000). During the day, peninsulas and islands can host concentrations of nocturnal migrants that have been migrating over large bodies of water, and coastal islands and headlands provide essential resting and feeding habitat during layover times for these birds. Islands of habitat (plantations) can act in a similar fashion, concentrating migrants in otherwise hostile environments, such as in open agricultural landscapes and in industrial areas. Thus, the placement of turbines close to prominent landscape features may positively or negatively influence the number of birds moving through a wind farm, particularly migrants and wetland species.

3. Weather conditions and collision fatalities

Many studies have shown that certain weather conditions (e.g. strong winds that affect the ability to control flight manoeuvrability, or reduced visibility) increase the occurrence of collisions with artificial structures, especially communication towers (Case et al. 1965; Seets & Bohlen 1977; Elkins 2004). The majority of collisions at wind farms have involved single birds (Kingsley & Whittam 2005), and even in poor weather conditions there have been very few multiple bird kills reported. The greatest mortality reported in North America on a single night was 27 birds, which occurred at the Mountaineer site in West Virginia on a foggy night, the birds being found at three turbines and a brightly lit substation (Kerlinger 2003). Another large mortality event at a North American wind farm was of 14 birds found at two adjacent turbines, which occurred during a severe thunderstorm (Erickson et al. 2001). Mortality events of such magnitude are rare phenomena, but can occur during periods of poor weather. Winkelman (1989, cited in Percival 2003; 1992a) showed that most collision fatalities at two sites in The Netherlands were found following nights with poor flight and visibility conditions.

4. Possible bird and wind turbine interactions

4.1 COLLISION FATALITIES

Direct mortality at wind farms results from birds striking revolving blades, towers, nacelles, and associated powerlines and meteorological masts. There is also evidence of birds being violently forced to the ground by turbulence behind the turbine created by the moving blades (Winkelman 1992a; Drewitt & Langston 2008).

Two wind farm areas have become synonymous with collision fatalities: Altamont Pass in California and Tarifa in southern Spain. Large numbers of raptors have collided with turbines at these sites, including substantial numbers of golden eagles (*Aquila chrysaetos*) at Altamont (Thelander et al. 2003), and griffon vultures (*Gyps fulvus*) at Tarifa (Barrios & Rodriguez 2004), both of which are long-lived species with low reproductive outputs. While the numbers of collisions per turbine at Altamont and Tarifa have been relatively low (considerably less than 1 bird per turbine per year for each), the total number of collisions has been significant, as a result of the large number of turbines (c. 7000 at Altamont and c. 700 at Tarifa). Also, and of particular importance, both sites support important food resources that attract raptors, resulting in birds of these species foraging within the collision-risk zone of turbines (Thelander et al. 2003). Thus, in both areas, the scale and siting of the wind farms are inappropriate given the species' behaviour (large soaring species with poor flight manoeuvrability), which makes them vulnerable to colliding with turbines, and their demographics, which make their populations vulnerable to small increases in mortality (Percival 2005).

Most other studies completed to date suggest low numbers of bird fatalities at wind farms (Australian Wind Energy Association 2002; Kingsley & Whittam 2005; Percival 2005). No other 'Altamont-type' problems have been reported elsewhere in North America (Erickson et al. 2001; Kingsley & Whittam 2005). Likewise, studies at upland sites in the UK have generally reported extremely low collision rates (< 0.1/turbine/year), with some finding no collisions at all (Meek et al. 1993; Percival 2005), probably reflecting the generally low bird densities present in these areas. In comparison, studies of bird collisions at coastal wind farms have generally reported higher numbers of collisions, which may reflect higher bird densities at coastal sites (Percival 2005), or greater frequency of bird movements at such sites. For example, studies at Blyth Harbour, Northumberland (Painter et al. 1999), and at Zeebrugger Harbour, Belgium (Everaert et al. 2002; Everaert & Stienen 2007), revealed collision rates greater than one bird per turbine per year, with most casualties at both sites being terns and gulls. Again, these results stress the importance of site characteristics.

Unfortunately, in many instances these numbers are likely to be underestimates, as they are often based only on found corpses, without accounting for scavenging and searcher efficiency. Several studies have indicated rapid removal of carcasses by scavengers (Langston & Pullan 2003). For example, in the USA, Kerlinger et al. (2000) found that most passerine carcasses disappeared within 3 days, but that large carcasses remained for at least 1–2 months. Search efficiency of observers was also shown to be variable, with only 25% of small birds (passerines) being found, but 75% of medium-sized carcasses (ducks) and all large carcasses (large raptors) being found (Kerlinger et al. 2000). In another study at Buffalo Ridge, USA, it was found that scavengers removed 39% of carcasses within 7 days (Osborn et al. 2000) and observers had a search efficiency of 79% in grasslands and cropped land. These and other studies highlight the potential for underestimating collision rates, particularly for passerines, and the consequent need to correct measures of collision rates for the confounding variables through experimental work (Smallwood 2007).

The following figures provide an indication of the range of collision fatalities per turbine per year from a variety of studies. Except for figures reported by the American National Wind Coordinating Committee (2004), it is not known whether these values have been corrected for scavenging rate and/or search efficiency. An estimated mean of 2.3 birds have been killed per turbine per year in parts of the USA outside California (based on 12 studies), with rates varying from 0.63 (agricultural site) to 10.00 (fragmented mountain forest site) (National Wind Coordinating Committee 2004). The number of collision fatalities in different onshore European wind farms has varied from less than one bird per turbine per year up to 125 birds per turbine per year (Langston & Pullan 2003; Percival 2005; Everaert & Stienen 2007). The results from 48 studies summarised by Percival (2005) indicated that most wind farms have resulted in less than one fatality per turbine per year: 10 studies resulted in no carcasses being found, 24 of < 0.1 fatalities/turbine/year, 7 of 0.1–1 fatalities/turbine/year, 5 of 1–10 fatalities/turbine/year, and two of > 10 fatalities/turbine/year.

Erickson et al. (2001) estimated that 33 000 birds would be killed by wind turbines in the USA in 2001 (based on an average of 2.2 fatalities/turbine/year where scavenging rate and searcher efficiency had been taken into account, and a projection of 15 000 operational turbines), 26 600 of which would be killed in California (where the Altamont Pass wind farms occur). These estimates were based on ten studies of 0.4 to 3.7 years' duration during 1988–2001. Although this may seem to be a large number of bird deaths, the impact is relatively small compared to the millions of birds that die annually due to collision with transmission lines, vehicles, buildings and communication towers. For example, it is estimated that 80 million birds are killed on US roads each year (Erickson et al. 2001, 2002). However, it should be remembered that this may be partially due to the relative scarcity of wind farms in the landscape at present compared with other structures (Evans 2004), as can be seen by breaking down mortality with other structures on a per structure basis. For example, using the numbers provided by Erickson et al. (2001), it appears that roads result in 9–12 bird deaths/km/year, buildings and windows result in 1–10 bird deaths/structure/year, and communication towers result in 50–625 bird deaths/tower/year. As wind power becomes more popular and wind farms become more abundant, collision numbers will increase. Indeed, given current documented average mortality rates of about 2 bird deaths/turbine/year, the projected impact of turbines in the USA could be in the range of 1–5 million birds per year by 2025, if large numbers of wind turbines become part of the landscape (Evans 2004). This makes proper siting imperative to help reduce bird mortality and therefore population effects.

An important issue is whether or not the collision fatalities at wind farms are sufficiently great in number to cause population declines. Even when collision rates per turbine are low, collision mortality at a wind farm may be considered high, especially when composed of hundreds or thousands of turbines (Langston & Pullan 2003). The cumulative mortality from multiple wind farms may also contribute to population declines in susceptible species, such as soaring raptors (Hunt et al. 1998). Furthermore, even relatively small increases in mortality rates may have a significant impact on some populations of birds, such as a threatened species, or a long-lived species with low annual productivity and slow maturity (Langston & Pullan 2003), such as many New Zealand waders, particularly when adults are killed.

The strongest evidence of collision mortality affecting populations comes from studies of particularly vulnerable species that are present in relatively high numbers in the vicinity of wind turbines. The most vulnerable species appear to be those highly susceptible to collision and with low productivity (e.g. large raptors, seabirds), making them less able to compensate for increased levels of adult mortality. For example, a long-term study of golden eagles at Altamont Pass, California, showed that the incidence of collision mortality had reduced productivity in the local population to the point were it had become a sink, dependent on immigration for its maintenance (Hunt & Hunt 2006). Similarly, evidence from a study of nesting terns at Zeebrugge, Belgium, estimated additional mortality of at least 1.5% for two species as a result of colliding with turbines as they returned to their nests (Everaert & Stienen 2006). Dierschke et al. (2003, cited in Drewitt & Langston 2008) suggested that such increases in mortality of greater than 0.5% could have serious population impacts.

There appear to be four main (and often interacting) factors that contribute to avian mortality at a particular wind farm site (Kingsley & Whittam 2005):

1. **Density of birds**: In general, there are more opportunities for birds to collide with turbines when there is an abundance of birds or high frequency of movements. This does not mean that high bird density or frequency of movements necessarily translates into greater bird mortality; a direct relationship between the number of birds in an area and collision rate has only been documented by one study (Everaert 2003).
2. **Bird species**: Particular species or groups of birds appear to be particularly prone to collision with structures such as wind turbines. These groups include swans and ducks (Anseriformes), raptors (Accipitridae), particularly large soaring species, owls (Strigiformes), and nocturnally migrating passerines (Thelander & Rugge 2000; Erickson et al. 2001; Langston & Pullan 2003; Stewart et al. 2004). See section 5 for further discussion.
3. **Landscape features**: Some landforms at wind farm sites, such as ridges, steep slopes, saddles and valleys, may increase the degree of interaction between turbines and birds using or moving through an area, although some debate exists around this point (Barrios & Rodriguez 2004; Smallwood & Thelander 2004; Drewitt & Langston 2008). The presence of other landforms, such as peninsulas and shorelines, can funnel diurnal bird movement, which may also affect collision rates, although this has yet to be studied. These features can combine with high bird abundance to create high collision risk.

4. **Poor weather conditions**: At many sites, collisions by nocturnal migrants tend to occur during episodes of poor weather with low visibility. Although most examples appear to be isolated incidents, weather conditions should be kept in mind if a wind farm is being proposed in an area that has a large number of poor visibility days (< 200 m visibility) during spring and autumn (periods of migration), and has other confounding factors (e.g. large numbers of nocturnal migrants and landform features such as ridges present). See section 3 for further discussion.

It is difficult to determine the potential magnitude of wind turbine-related bird fatalities at New Zealand wind farms by extrapolating from studies elsewhere, because there is no information available about the rate of collision fatalities at New Zealand wind farms where the removal of carcasses by scavengers or the efficiency of observers at locating carcasses have been quantified. Also, as far as I am aware, no studies have modelled collision risk for birds at New Zealand wind farms. Therefore, there is an urgent need for comparative data from New Zealand wind farms to determine the extent to which native species, particularly threatened species, are being killed. It is also important that the mistakes made at Altamont and Tarifa are not repeated in New Zealand, and that the characteristics of the bird populations at proposed wind farm locations are determined, and potential problem sites identified and avoided. This is crucial when planning New Zealand wind farms, given the infancy of the industry and lack of robust data from which to make predictions.

4.2 HABITAT LOSS

Wind farm development will result in habitat loss for birds (Percival 2000). Land will be taken up by turbine bases and access roads, and secondary effects, such as altered hydrology, are possible. In the UK, habitat loss or damage as a result of wind farm infrastructure is not generally perceived to be a major concern for birds outside designated sites of national and international importance for biodiversity (Percival 2005). Typically, actual habitat loss only amounts to 2–5% of the total development area (Fox et al. 2006), and careful positioning of turbine bases and routing of access roads, together with the use of proven restoration techniques, should ensure that any loss is minimised. However, the cumulative loss of or damage to sensitive habitats may be significant, especially if multiple large developments are sited at locations of high bird use. Furthermore, direct habitat loss may be additive to displacement.

The scale of habitat loss, together with the availability and quality of other suitable habitats that can accommodate displaced birds, and the conservation status of those birds, will determine whether or not there is an adverse impact on populations (Anon. 2006). The possibility that wintering birds might habituate to wind farm structures has been suggested (Langston & Pullan 2003), but there is little evidence and few studies of long enough duration to show this (Stewart et al. 2004; Drewitt & Langston 2006). Differences in behaviour between residents and migrants have been observed in some studies (Kingsley & Whittam 2005; Drewitt & Langston 2006), but not in others (Langston & Pullan 2003; Percival 2005). Unfortunately, very few conclusive studies are available because most lack well-designed procedures incorporating observations both before and after construction (e.g. Ketzenberg et al. 2002). Furthermore, very few studies have taken into account differences between diurnal and nocturnal behaviour, only assessing daytime activity (Anon. 2006). This is inadequate for those species, including many in New Zealand, that are active at night, and which may behave quite differently at night compared with by day.

4.3 DISTURBANCE AND DISPLACEMENT

Although collision rates have been the primary focus of research and monitoring in North America, the effects of disturbance may have a greater impact on birds (Stewart et al. 2004; Kingsley & Whittam 2005), and yet this is the least studied aspect of wind farm impacts on birds. Behavioural research on disturbance impacts is lacking for some bird groups. However, the available information suggests that some groups of birds (e.g. seaducks) may be more sensitive to disturbance from wind farms than others (Percival 2005; Drewitt & Langston 2006).

Disturbance and displacement may arise from increased activity by people at a wind farm during construction and maintenance, as well as from improved road access as a result of the wind farm development, especially in areas where there was little human activity before the wind farm existed. Roads may also improve access for predators of ground-dwelling or ground-nesting birds, such as wandering dogs (*Canis lupus*), possums (*Trichosurus vulpecula*) and hedgehogs (*Erinaceus europaeus*). The presence and noise of turbines may deter birds from using an area close to these.

Some studies appear to show little or no behavioural impact of wind turbines on various bird species. In some cases, this apparent lack of evidence may be an artefact of such things as the type and intensity of monitoring. However, in Britain the majority of recent studies have also found no disturbance effects (Percival 2000, 2005) and there is an increasing body of evidence that wind farms generally do not affect bird distribution. For example, no significant adverse effect was reported on birds breeding in upland sites at Bryn Tytli, Carno or Cemmaes in Wales, at Ovenden Moor in the south Pennines, or at Windy Standard in southwest Scotland (Percival 2000). The Ovenden study showed how useful longer term monitoring programmes can be, as the 23-turbine wind farm was constructed following 2 years of breeding-bird surveys that had shown that the site held good numbers of upland birds, particularly golden plover (*Pluvialis apricaria*). The wind farm was constructed in 1993 and further surveys were carried out in 1995 and again in 1997, to determine the effects on these birds and their populations. Whilst numbers in a nearby control area remained constant, numbers at Ovenden actually increased (Percival 2000). The distribution of the birds suggested that they were unaffected by the wind farm; there was no significant difference in distribution pattern in relation to the turbine positions, and no evidence of any disturbance zone. Similarly, Thomas (1999, cited in Percival 2005), who surveyed breeding birds at ten wind farms in England and Wales, found no significant disturbance effects on any species, including curlew (*Numenius arquata*), lapwing (*Vanellus vanellus*), meadow pipit (*Anthus pratensis*) and skylark (*Alauda arvensis*).

In other studies, a reduction in bird numbers has been reported as far as 600 m from turbines outside the breeding season, and up to 300 m from turbines during the breeding season (Percival 2005). Such variation was found during two studies on the barnacle goose (*Branta leucopsis*) population. The first study, which was carried out on the birds' spring staging grounds in Sweden, where they fed in close proximity to wind turbines (to within 25 m), found no significant disturbance effect (Percival 1998). However, the second study of the same population on their wintering grounds in Germany found that few geese fed within 350 m of turbines, and there was a reduction in numbers up to 600 m from the turbines (Kowallik & Borbach-Jaene 2001). The most likely explanation for such different results is that geese avoid turbines when there is easy access to alternative feeding habitat, but will be less selective when resources are limited (Percival 2005). Similar results of birds becoming more tolerant of disturbance as resources become scarcer have been found in other studies of disturbance of wintering waterfowl (Percival 1993), and studies to date have shown that substantial displacement by wind turbines seems to have occurred primarily in farmland habitats, where there would typically be alternative feeding areas within easy reach (Percival 2005). Other results suggest that disturbance can lead to reduced breeding productivity (Madsen 1995), reduced survival or a reduction in available habitat (Woodfield & Langston 2004, cited in Percival 2005), so disturbance may be significant for some species in certain situations.

Studies of birds' responses to turbines at night, using thermal and passive imaging equipment plus radar, revealed that more flight reactions occurred with headwinds (87%) than with tailwinds (29%) (Winkelman 1992b). Winkelman's (1992b) observations in daylight indicated that over 75% of all reactions took place within 100 m of the turbines, with ducks reacting at the greatest distance and passerines reacting closest to wind turbines. Flights were mainly at the height of turbines (up to 50 m) at sunrise during dispersal from nocturnal roosts to feeding areas, at the end of nocturnal and start of diurnal migrations and, to some extent, at sunset as flights to roost and nocturnal migration started (Winkelman 1995). In comparison, observed flight reactions to wind turbines in Schleswig-Holstein, Germany, indicated that waders, terns and waterfowl reacted 200–500 m from the turbines, whereas gulls reacted at a distance of 100–150 m (Koop 1997). Gulls and waders increased their flight height or changed direction to fly over or around turbines, whilst waterfowl manoeuvred to fly between turbines. Observations of diurnal flight behaviour by gulls and common terns (*Sterna hirundo*) at two sites found that they flew between the turbines to and from their breeding colonies and marine feeding areas (van den Bergh et al. 2002; Everaert 2003). Breeding adults tend to fly much closer to structures when making frequent flights to feed chicks than at other times, and they may sustain collisions as a consequence (Everaert 2003; Everaert & Stienen 2007).

Relatively long lines of turbines or large wind farms can become important barriers to the local or seasonal movements of birds (Langston & Pullan 2003). The effect of birds altering their local flight paths or migration routes to avoid a wind farm is a form of displacement. This effect is of concern because it may result in increased energy expenditure when birds have to fly further to avoid a large array of turbines, and it may disrupt linkages between distant feeding, roosting, moulting and breeding areas (Drewitt & Langston 2006). The magnitude of the effect will depend on species, type of bird movement, flight height, distance between rows of turbines, layout and operational status of turbines, time of day, and wind force and direction. The impact can range from a slight 'check' in flight direction, height or speed, through to significant diversions that may reduce the numbers of birds using areas beyond the wind farm (Drewitt & Langston 2006).

Several studies have shown that some species alter their route to avoid flying through wind farms, e.g. tufted duck (*Aythya fuligula*) and common pochard (*Aythya ferina*) at Lely in The Netherlands (Dirksen et al. 1998). While this may reduce collision risk, it could result in the wind farm acting as a barrier to bird movements. However, such effects are not universal; for example, at Zeebrugge, large numbers of birds regularly fly through a wind farm without diverting around it (Everaert et al. 2002), and van der Bergh et al. (2002) and Everaert & Stienen (2007) concluded that a line of turbines did not act as a barrier to the daily flight paths of breeding gulls and terns. In contrast, studies of bird movements in response to offshore developments have recorded waterfowl taking avoidance action between 100 m and 3000 m from turbines (Christensen et al. 2004; Kahlert et al. 2004a, b). These findings highlight the species- and site-specific nature of wind farm impacts on birds.

Some birds will fly between turbine rows, as seen with common eider (*Somateria mollissima*) at Nysted, where the turbines were 480 m apart (Kahlert et al. 2004b). However, their ability to do so will depend on the distance between turbines. Although evidence for this type of response is limited, these observations have implications for wind farm design. Generally, spacing between turbines at onshore wind farms is recommended to be a minimum of 200 m apart to avoid inhibiting bird movements (Percival 2001). This recommended distance is often the minimum spacing required by industry to reduce wake effects of large turbines on neighbouring turbines (Kingsley & Whittam 2005).

For a small wind farm (< 10 turbines), the ecological consequences of any barrier are unlikely to be a problem, with minimal diversion distances involved. For larger sites, however, the barrier effect has the potential to be more important. Thus, it is important to consider new wind farm proposals on a case-by-case basis, and to assess the patterns of resource availability and the potential loss through disturbance for each. However, it should be noted that a review of the literature suggests that none of the barrier effects identified so far have had significant impacts on populations (Drewitt & Langston 2006).

5. Observed impacts of wind farms on various groups of birds

5.1 HABITAT GROUPINGS

The following is a review of the impacts of wind farms on various groups of birds, largely in relation to the main habitat type they occupy. For each group, findings from other countries are related back to the New Zealand situation, particularly where relevant to a New Zealand species.

5.1.1 Waterbirds

Waterbirds include species that are typical of terrestrial wetland habitats, including ponds, lakes and rivers. This category excludes seabirds, waterfowl and shorebirds, which are discussed separately. Waterbirds of New Zealand include grebes, shags, herons, egrets, rails, gulls and terns.

There have been few reports of waterbird fatalities resulting from collision impacts at wind farms, but in many cases the methods used to detect them have been imprecise (see section 4.1). Gulls and terns have been identified as being especially vulnerable to mortality due to wind turbines because they often fly within the height of the rotor sweep zone (Langston & Pullan 2003). However, despite their perceived vulnerability, very low numbers of gulls and terns have been reported as colliding with turbines, with the exception of three sites in Belgium (Everaert 2003; Everaert & Stienen 2007). At one of these sites, Zeebrugge, Everaert & Stienen (2007) calculated that the mean number of collision fatalities (mainly gulls and terns) per turbine per year in 2004 and 2005 was 20.9 and 19.1 birds, respectively, after taking into account the number of dead birds found under turbines and the correction factors for available search area, search efficiency and scavenging.

There is little information available regarding the behavioural impacts of turbines sited near wetlands on waterbirds. Wind farms could have a marked negative impact on waterbirds where a significant proportion of a local resource, such as nesting or foraging habitat, is no longer available because turbines were placed on or too close to it (Percival 2001). Some species feed close to their breeding colonies, while others may forage some distance away (shags, gulls, terns). More research is needed to examine the potential effects of disturbance caused by wind turbines on waterbirds, particularly colonial nesting waterbirds.

The black shag (*Phalacrocorax carbo*) and cattle egret (*Bubulcus ibis*) are the only species of waterbirds occurring in New Zealand that were listed by Kingsley & Whittam (2005) as having been found fatally injured after colliding with a wind turbine. However, Kingsley & Whittam (2005) did list representatives from several genera that are represented in New Zealand: *Larus* (gulls), *Sterna* (terns), *Ardea* (herons) and *Nycticorax* (night heron). Three such waterbird species occasionally forage over pasture near wetlands and are threatened (Hitchmough et al. 2007): the red-billed gull (*Larus novaehollandiae*) (gradual decline), black-billed gull (*Larus bulleri*) (serious decline), and black-fronted tern (*Sterna albostriata*) (nationally endangered). Therefore, any wind farms sited in pastureland that may have deleterious impacts on the populations of these three species would be of concern.

5.1.2 Seabirds (order Procellariiformes)

I have not found any records of Procellariiformes being killed as a result of collision with wind turbines, or offshore wind farms resulting in their displacement. This probably reflects both the fact that in the Northern Hemisphere, where most wind farms occur, there is little overlap in the distribution of such seabirds and wind farms, and the difficulty of locating seabirds killed by collision at offshore wind farms. Even so, Procellariiformes, particularly the larger species, may be just as vulnerable to turbine collision fatalities as soaring raptors, because these seabirds are adapted to sustained high-speed flight with slow manoeuvrability in unobstructed environments. In addition, many have delayed maturity and low productivity, making their populations sensitive to increased mortality.

I am not aware of any applications to develop offshore wind farms about New Zealand. However, there have been applications and investigations for the establishment of wind farms at coastal sites (see Appendix 1). A few colonies of Procellariiformes remain on the main islands of New Zealand. Most occur on headlands or coastal cliffs, e.g. royal albatross (*Diomedea epomophora*) at Taiaroa Head near Dunedin; small colonies of the sooty shearwater (*Puffinus griseus*) on Banks Peninsula, Cape Wanbrow near Oamaru, and headlands along the Otago coast and west coast of the South Island; and small colonies of the grey-faced petrel (*Pterodroma macroptera*) on scattered headlands of the northern North Island as far south as New Plymouth on the west coast and Gisborne on the east coast. Birds from these coastal colonies are unlikely to be impacted by wind farms unless turbines are erected within a kilometre or so of their colonies. Two species fly some distance inland to their colonies: the nationally endangered Hutton's shearwater (*Puffinus huttoni*), which flies to the Seaward Kaikoura Range, and the range restricted Westland Petrel (*Procellaria westlandica*), which flies to the coastal foothills of the Paparoa Range. Obviously, any turbines erected in the flight paths of these two species, both of which have restricted colony distributions, would be highly likely to result in collision fatalities. In addition, both species fly to and from their colonies at night, particularly around dusk and dawn. It has been found that nocturnal seabirds, especially fledglings, can become disorientated, especially during periods of fog, and are then prone to being attracted to artificial lights, such as street lights. Thus, lighting on turbines would increase the risk of collision for these nocturnally active seabirds if wind farms were sited near their colonies or on routes between the sea and their colonies.

5.1.3 Waterfowl

The effects of wind turbines on waterfowl (e.g. ducks, shelducks, geese and swans) have been examined at a few wind farms, particularly in Europe. Even though waterfowl are regarded as prone to collision with turbines (Langston & Pullan 2003), the presence of large numbers of waterfowl near wind farms does not necessarily mean that large numbers of fatalities will eventuate (Erickson et al. 2002; Kingsley & Whittam 2005). In some cases, seaducks are believed to have learned to avoid turbines, resulting in fewer collisions over time (Percival 2001). Sites in the USA with year-round waterfowl use reported the most fatalities of dabbling ducks (Anatinae) (Erickson et al. 2002), and at these sites waterfowl made up 10–20% of all fatalities (Erickson et al. 2002). However, numbers of fatalities were still low, especially in relation to the number of ducks that used the areas. Moorehead & Epstein (1985, cited in Kingsley & Whittam 2005) identified large wetland birds, such as geese and cranes, as being especially susceptible to collisions with wind farm installations. They emphasised that collision potential varied with a number of factors (weather, terrain, turbine placement, and rotor design and speed), and identified the provision of visual cues and the selection of sites outside critical areas among their recommended mitigation measures.

Disturbance is an important factor to consider when siting a wind farm near significant waterfowl areas. The most comprehensive study of the effect of wind turbines on waterfowl took place in Denmark and involved a modern, 10-turbine offshore facility in an area where large numbers of common eider (*Somateria mollissima*) and black scoter (*Melanitta nigra*) fed. It was found that these diving ducks exhibited avoidance behaviour towards the turbines, which was accentuated in poor weather (Guillemette et al. 1999; Tulp et al. 1999). Eiders generally avoided flying or landing within 100 m of the turbines, and avoided flying between turbines that were spaced less than 200 m apart, preferring to fly around the outer turbines. Similarly, two diving duck species, common pochard and tufted duck, were tracked at night using radar and were found to avoid flying near turbines, passing around the outer turbines instead (Larsson 1994; Dirksen et al. 1998). In a meta-analysis of 19 studies into the effects of wind farms on bird abundance, Stewart et al. (2004) found that wind farms seemed to reduce the abundance of many bird species and that Anseriformes (swans, geese, ducks) experienced greater declines than other bird groups, suggesting that a precautionary approach should be adopted to wind farm developments near aggregations of Anseriformes.

The observations of avoidance behaviour are not restricted to studies at offshore wind farms. In the Yukon, a single turbine was placed at the edge of a river valley, past which large numbers of waterfowl migrated. No collisions were recorded, but the birds avoided flying close to the turbine (Mossop 1998). Amongst waterfowl, reactions to onshore wind turbines appear to be species-specific, with even closely related species showing very different reactions. For example, pink-footed geese (*Anser brachyrhynchus*) were reluctant to forage within c. 100 m of turbines in Denmark (Larsen & Madsen 2000), whereas barnacle geese (*Branta leucopsis*) in Sweden foraged to within 25 m of the structures (Percival 2005).

The Canada goose (*Branta canadensis*), domestic goose (*Anser anser*), mallard (*Anas platyrhynchos*) and mute swan (*Cygnus olor*) are waterfowl species that occur in New Zealand and were listed by Kingsley & Whittam (2005) as having been found fatally injured after colliding with wind turbines. In addition, the following genera are represented in the mortality list of Kingsley & Whittam (2005), all of which have members in New Zealand: *Podiceps* (Australasian crested grebe *P. cristatus*), *Tadorna* (paradise shelduck *T. variegata*) and *Aythya* (New Zealand scaup *A. novaeseelandiae*).

5.1.4 Shorebirds

In North America, observed mortality of shorebirds (waders) at wind farms has been low (Kingsley & Whittam 2005), possibly because few sites are located in shorebird habitat. In contrast, Stewart et al. (2004) found that wind farms can have a negative impact on the abundance of shorebirds, and advocated a precautionary approach to wind farm development at coastal sites where aggregations of shorebirds occur. This result was derived from a meta-analysis of six studies: two in the USA, and one each in Germany, The Netherlands, Scotland and England.

Each species of shorebird appears to have a different threshold to disturbance. For example, at Blyth Harbour wind farm in the UK, purple sandpipers (*Calidris maritima*) did not seem to be disturbed by either the construction process or the operation of wind turbines (Lowther 2000). In contrast, studies in The Netherlands and Denmark examining the effect of turbines near important staging areas for many shorebird species found that the birds avoided the turbines and were at a relatively low risk of collision (Pedersen & Poulson 1991, cited in Drewitt & Langston 2006; Dirksen et al. 1998). Some studies have shown that shorebirds avoid turbines up to 500 m away (Winkelman 1995), while others have shown no significant effect on shorebird distribution (Thomas 1999, cited in Percival 2005). It is not known whether this inconsistency in behaviour between species is related to the abundance and proximity of alternative suitable habitat: a species may be more likely to move away from turbines if there is ample suitable habitat nearby.

The pied oystercatcher (*Haematopus ostralegus*) is the only shorebird species that occurs in New Zealand that was listed by Kingsley & Whittam (2005) as having been found fatally injured after colliding with wind turbines. Other genera that are represented in the mortality lists and have representatives in New Zealand are *Charadrius* (dotterels) and *Pluvialis* (plovers). Many endemic and native shorebirds occur in New Zealand. Given the threatened status of some endemic species (Hitchmough et al. 2007) and our lack of knowledge about their vulnerability to wind farm developments, a precautionary approach should be taken when considering any wind farm developments in shorebird habitats and along their migration routes.

5.1.5 Diurnal raptors

Collision has been the focus of raptor studies at wind farms, due to the high collision rates observed at a small number of sites. One study at Altamont, California, USA, which involved observations and carcass searches over six seasons and covered c. 16% of the 7000 turbines, found 183 dead birds (0.05 birds per turbine per year), 65% of which were raptors (Orloff & Flannery 1992). Of these deaths, 55% were attributed to turbine collisions, 8% to electrocution and 11% to wire collision; for 26%, the cause of death could not be determined (Orloff & Flannery 1992). There has also been significant raptor mortality at Tarifa, Spain (0.34 birds per turbine per year) (Percival 2003). This site is near the Strait of Gibraltar, and forms a bottleneck that concentrates bird migration between Europe and Africa in the Mediterranean basin; at least 30 000 raptors and large numbers of storks pass through the area each autumn (Marti 1995). There are several wind farms in the area, with a total of

268 older-style turbines (lattice tower, with a relatively fast rotor speed) in operation (Marti 1995). Many bird collisions with the turbines have been recorded, including an estimated 106 deaths in a single year, most of which occurred on days with high visibility (Marti & Barrios 1995, cited in Kingsley & Whittam 2005). However, a subsequent study at a different wind farm at Tarifa resulted in only two carcasses being found over 14 months, suggesting that death rates can vary with year and wind farm (Janss 2000).

Very few raptor fatalities have been reported at other sites. In parts of the USA outside California, raptors comprised only 2.7% of turbine-related deaths (Erickson et al. 2001; Kerlinger 2001). However, even though this percentage seems small, an increase in mortality of greater than 0.5% could have a serious impact on a population of long-lived raptors with low productivity (Dierschke et al. 2003, cited in Drewitt & Langston 2008).

The most important factor that influences raptor collision rate appears to be topography, in particular elevation and the presence of ridges and slopes (Anderson et al. 2000; Morrison et al. 2007). The low numbers of raptor fatalities observed at the majority of wind farms is most likely due to improved siting of turbines, away from problem topography and high raptor concentrations. It has been speculated that the construction of tubular (as opposed to the lattice type) towers and slower rotor speeds may also have helped to lower raptor fatalities, but no studies to date have shown a significant relationship between mortality levels and turbine type (Anderson et al. 2000). Percival (2003) considered that the high mortality at Altamont and Tarifa resulted from a combination of sensitive species (soaring raptors) flying through the area in large numbers (important feeding areas and migration route, respectively), and turbine layout (hundreds in densely packed formation) and design (lattice towers attractive to raptors as perches).

There is no information available on how raptors react behaviourally to turbines (Kingsley & Whittam 2005).

Although no raptor species that occur in New Zealand are represented in the mortality list of Kingsley & Whittam (2005), the genera *Circus* and *Falco* are present in the list, both of which have representatives in New Zealand (Australasian harrier *C. approximans* and New Zealand falcon *F. novaeseelandiae*). Species of nocturnal raptors (owls) are also represented in the list of birds reported to have collided with wind turbines (Kingsley & Whittam 2005).

5.1.6 Landbirds

Amongst the landbirds, passerines are the group most commonly affected by wind farms in parts of North America outside California. Protected passerines comprise 78% of all fatalities documented at wind farms in the USA (Erickson et al. 2001). This proportion would be even greater if it included unprotected species, such as the starling (*Sturnus vulgaris*) and house sparrow (*Passer domesticus*). Grassland bird species with aerial courtship displays, such as the horned lark (*Eremophila alpestris*), appear to be particularly prone to collisions with turbines, as they fly high enough when displaying to collide with turbines (Kerlinger & Dowdell 2003). However, during migration most passerines fly at night and at an altitude in good weather (1000–1500 m; Alerstam 1990) that takes them well above turbine height.

The greatest threat from wind farms to migrant passerines in North America was found to be habitat loss (Kingsley & Whittam 2005). In contrast, the impact of turbines on forest-nesting passerines was found to be low, with several nesting in the forest within 20–30 m of the turbines, although a few species were found to avoid clearings where turbines were located, and some appeared to move further into the forest (Kerlinger 2003). However, since there has only been one study to date into the effect of wind turbines on forest-nesting birds, more studies are needed to understand these effects.

Turbines may displace some grassland species of landbirds. Leddy et al. (1999) found that there were fewer nesting grassland birds within 100–200 m of turbines than beyond, and densities decreased by more than 50% within c. 50 m of turbines. In contrast, Devereux et al. (2008) found that the distribution of four functional groups of wintering farmland birds (granivores, corvids, gamebirds and the skylark *Alauda arvensis*) was unaffected by turbines in East Anglia, England (in 150-m-wide blocks), at distances ranging from 0 m to 750 m. They also measured occurrence in areas 0–75 m and 75–150 m from the turbines, and found no evidence that the four functional groups of farmland birds avoided areas close to turbines.

Gamebirds (pheasants and quail in New Zealand), which are a subset of the landbirds group, are vulnerable to habitat destruction and fragmentation, and disturbance of local breeding populations as a result of human-induced changes in the landscape, such as wind farm developments (see Kingsley & Whittam 2005). In North America, much of the remaining suitable habitat for gamebird species is located in remote areas or where topography makes agriculture difficult. Some of these sites may be suitable for wind farms, and so turbines and associated structures could adversely affect sensitive and vulnerable gamebird species (Kingsley & Whittam 2005). In agreement with this conclusion is the finding of Devereux et al. (2008) that the distribution of the pheasant (*Phasianus colchicus*) was negatively effected by turbines. S.M. Percival (Ecology Consulting, pers. comm., 5 March 2008) considered that there is a low risk of gamebirds colliding with turbine towers.

The feral pigeon (*Columba livia*), rook (*Corvus frugilegus*), skylark (*Alauda arvensis*), blackbird (*Turdus merula*), song thrush (*Turdus philomelos*), starling, chaffinch (*Fringilla coelebs*), greenfinch (*Carduelis chloris*) and house sparrow are landbird species that occur in New Zealand and were listed by Kingsley & Whittam (2005) as having been found fatally injured after colliding with wind turbines. In addition, the genera *Hirundo* and *Anthus* are represented in their mortality list, both of which have representative species in New Zealand (welcome swallow *H. tahitica* and New Zealand pipit *A. novaeseelandiae*). Most species mentioned above are introduced and none are threatened.

The California quail (*Callipepla californica*), chukor (*Alectoris chukar*) and pheasant (*Phasianus colchicus*) are gamebird species that occur in New Zealand and were listed by Kingsley & Whittam (2005) as having been found fatally injured after collision with wind turbines. All of these gamebirds were introduced to New Zealand, and all except the chukor are widely distributed (Heather & Robertson 2005).

5.2 SEASONAL GROUPS

5.2.1 Breeding birds

In general, birds breeding near wind turbines have been reported to have lower collision rates than non-residents (Kingsley & Whittam 2005). In part, this is probably because local birds become familiar with turbines, whereas individuals passing through the area would not have that familiarity and may be unable to detect turbines before a collision occurs if weather conditions are poor, e.g. during fog. However, wind farms are likely to have a greater impact on breeding birds as a result of habitat loss, obstruction of regular flight paths, disturbance by people servicing turbines and obstruction to important feeding areas (particularly important in coastal areas).

Bird productivity (breeding success) does not appear to be negatively affected at many wind farms. For example, in one study, mean productivity at a 66-turbine site, was the same as in surrounding areas (Guyonne & Clave 2000, cited in Kingsley & Whittam 2005). However, few such studies have been carried out (Kingsley & Whittam 2005).

Reduced breeding bird populations were noted at a few wind farms where breeding habitat was destroyed during installation of turbines, and where people and vehicles were continuously present in the area (Percival et al. 1999, cited in Percival 2000). It has also been found that many grassland birds avoid nesting within 100–200 m of turbines (Leddy et al. 1999). Ketzenberg et al. (2002) investigated the breeding densities and spatial distribution of the common skylark (*Alauda arvensis*) and some species of breeding waders (Eurasian oystercatcher *Haematopus ostralegus*, northern lapwing *Vanellus vanellus*, common redshank *Tringa totanus* and black-tailed godwit *Limosa limosa*) before and after installation of wind farms in four coastal areas in Lower Saxony, Germany. They found no consistent pattern in the change in number of breeding pairs following construction, with some decreases but also some increases: for some species of waders, the numbers increased near wind turbines because of the change in farming practice post-construction, emphasising the need to consider other changes contemporary with wind farm development. Similarly, there was no significant difference in numbers of breeding pairs of ducks (Anatinae), waders (Charadriiformes), Arctic skua (*Stercorarius parasiticus*), gulls (Laridae) and small passerines between the year of installation of a 3-turbine cluster and the subsequent 8 years at Burgar Hill, Orkney Islands (Meek et al. 1993).

Many seabirds, including coastal species such as gulls and terns, are readily disturbed by the activities of people near their breeding colonies, so that the presence of turbines may cause the abandonment of a site. Although I am not aware of studies that support this suggestion, it is of note that English Nature (the UK government agency that promoted the conservation of wildlife until 2006, when it was integrated into Natural England) recommended that turbines should not be located within 20 km of sensitive or important colonies of seabirds (e.g. albatrosses, petrels, shearwaters), and should not be within 1 km of sensitive or important gull or tern colonies (Percival 2001).

5.2.2 Wintering birds

The numbers and movements of sedentary species remain much the same year round, particularly for most forest-dwelling and open-country species. However, physical or biological factors, such as localised habitat and/or food supplies, may act to concentrate birds such as waterfowl and shorebirds. Thus, depending on the site of a wind farm, bird densities in the vicinity may remain much the same, increase or decrease during winter. For example, studies at Urk, The Netherlands, found reductions in density within a wind farm area in winter for four duck species (mallard *Anas platyrhynchos*, tufted duck *Aythya fuligula*, common pochard *A. farina* and common goldeneye *Bucephala clangula*), which extended to 300 m away from the farm (Winkelman 1989, cited in Percival 2003). In contrast, there was little or no effect on great-crested grebe (*Podiceps cristatus*), Eurasian coot (*Fulica atra*) or common gull (*Larus canus*), and increased numbers of black-headed gulls (*Larus ridibundus*) and greater scaup (*Aythya marila*). At Blyth Harbour wind farm, UK, great cormorants (*Phalacrocorax carbo*) were temporarily displaced from their roost during construction, but returned once the farm was operational. Numbers of great cormorants, common eiders (*Somateria mollissima*), purple sandpipers and gulls were comparable before and after construction (Still et al. 1995, cited in Langston & Pullan 2003). This wind farm is sited in a commercial harbour and comprises nine turbines built at 200-m intervals along the estuary's breakwater. The harbour is a Site of Special Scientific Interest because it hosts a large winter roost of the purple sandpiper, and the estuary it protects adjoins a Ramsar site.

Wind farm layout can also affect avoidance behaviour. For example, for pink-footed geese, the avoidance distance was c. 100 m for lines of turbines, compared with c. 200 m for clusters of turbines, and geese did not enter the area between turbines arranged in a cluster (Larsen & Madsen 2000).

5.2.3 Migrating birds

Although long-distance movements of birds can occur in any month, the periods of peak migration in New Zealand occur in spring, summer and autumn (Dowding & Moore 2006; Williams et al. 2006). Different species, and possibly different age and sex categories of the same species, migrate through the same area during different periods. Migration can also occur in winter, e.g. northward movements following unusually severe southerly storms that bring snow to sea level. In summer, there can also be movements of subadult birds or failed breeders from nesting areas to staging areas (coastal sites), or to wintering sites further north. Thus, the pattern and timing of migration can be highly unpredictable (Kingsley & Whittam 2005). The broader the spatial and temporal scale, the more predictable migration movements appear, but with regard to a particular local area on a given day, it is very difficult to predict whether migrants will be present (Mabey 2004).

Meteorological conditions can have a large influence on the numbers of birds involved in migration. In Canada, numbers of birds migrating have been shown to vary 10-fold or even 100-fold from one day or night to the next, depending largely on weather (Richardson 2000). A bird may migrate several hundred kilometres in a day or night when the weather is favourable, and then may not migrate for several days when the weather is poor (Richardson 2000). Migrant numbers appear to be greater at times with (or following) light tail winds than when winds are strongly opposing. Such winds allow birds to travel a given distance more quickly and with less energy expenditure than would be required while flying into a headwind (Richardson 2000). There is also a close interaction between migration and other weather variables such as temperature, humidity and pressure, and it is not well established which specific variables cue birds to migrate rather than remain on the ground (Richardson 2000).

In the case of migrants, flights once underway tend to be at high altitude, well above turbine height, to maximise flight and energy efficiency. Birds wait for suitable conditions before embarking on migration, but may be forced to lower their flight altitude if they encounter bad weather during migration (Newton 2007). Therefore, migrants are at risk of collision with wind farms mainly during takeoff and descent, when their flight paths take them through the height range of the rotor-sweep zone (Drewitt & Langston 2008).

Many collisions reported at wind farms in North America involve migrating birds. For example, Johnson et al. (2002) noted that 71% of carcasses were migrants. Sites in different regions differ in the magnitude of bird migration and the influences on this migration. For example, in western North America, there is little evidence that tall human-made structures kill large numbers of night-migrating birds (Evans 2003), whereas this is a well-documented phenomenon in eastern North America. The reason for this regional difference is unclear, although it may be due to lower densities of nocturnal migrants in the west, or differing meteorological conditions leading to different avian behaviour. Whatever the reason, this is an important point that must be considered when comparing mortality studies from sites outside the general area of a proposed wind farm.

Inclement weather can increase the risk of migrant collision with wind farm structures. For example, a cloud ceiling that drops to near or below the height of turbines will affect high-altitude migration, inducing migrants to move at or below treetop level, and therefore increasing the probability of collisions with tall obstacles (Robbins 2002; Langston & Pullan 2003; Kingsley & Whittam 2005). Drizzle and fog impair visibility, and cause birds to fly at lower altitudes and follow topographical cues. The combination of such weather with lighting at wind farms may attract migrating birds, and so increase the collision rate. Thus, if there is a high proportion of foggy days during a period of migration at a proposed wind farm site that is on a migration route, there is likely to be an increased risk of collision.

Wind farms situated on prominent landforms can also represent greater potential risks to migrating birds. Features that rise abruptly in the landscape, such as high ridges and mountains, can influence bird movements, and if wind farms are sited at high elevations, turbines may end up at a height that enters the altitudinal strata typically used by migrants. For example, the turbine rotor sweep zone of 100-m towers located on a ridge 200 m above the surrounding landscape are effectively 300 m in the air and at an altitude where nocturnal migrants may be flying (Kingsley & Whittam 2005).

Diurnal migrants

Some groups of birds, e.g. raptors, are principally diurnal migrants (Kingsley & Whittam 2005). Diurnal migrants that use thermals (rising warm air caused by the sun heating the earth) to reach their preferred altitude do so to facilitate soaring and conserve energy. As a result, the number of such migrants tends to decline in the late morning and through the afternoon. Diurnal migrants can be more constrained by topographical features than nocturnal migrants, and tend to concentrate along linear features, such as coastlines, rivers, ridges and valleys (Richardson 2000). Birds will often divert by as much as 45° from their preferred course in order to fly along such a 'leading line' (Richardson 2000). The greatest concentration of birds often occurs at these features when there is a crosswind relative to that feature. Therefore, the placement of wind farms on such topographical features may result in interactions with diurnal migrants.

Nocturnal migrants

Many bird species migrate at night (e.g. grebes, ducks, rails, waders, cuckoos). There are three main reasons why birds flying at night collide with wind turbines, and these are often inter-related: height of the structure (and the landform it is located on), lighting and weather (Kingsley & Whittam 2005) (see sections 2.3.2 and 3). The flight heights of nocturnal migrants are quite variable and not well understood, even in North America and Europe (Kingsley & Whittam 2005). According to Kerlinger (1995, 2000), the majority of migrants fly between 90 m and 900 m a.g.l. (above ground level), with small numbers flying above 1500 m a.g.l., and few below 150–180 m a.g.l., except during landing and takeoff. Able (1999) stated that most nocturnal migrant songbirds usually flew below 600 m when over land. Cooper (2004) found that 16% of migrants flew at or below turbine height (< 125 m), with most passing at 250–750 m. Similarly, Richardson (2000) believed that most nocturnal migrants flew well above turbine height (50–1000 m a.g.l.). These data suggest that only a small percentage of nocturnal migrants passing over a wind farm with tall turbines (150 m) would fly within the rotor sweep zone. However, migration altitudes are affected by weather, with birds tending to fly lower when heading into opposing winds than when flying with tailwinds. Therefore, numbers of migrating birds flying at turbine height may be as great or even greater when winds are opposing than when they are following, even though total numbers aloft tend to be much reduced with opposing winds (Kingsley & Whittam 2005). Poor weather (cloud and rain) increases the effect of lighting and also lowers the flight altitude of migrants, so that greater numbers fly at turbine height.

Many UK and North American nocturnal migrants continue to migrate for at least part of the day, but do so at lower altitudes, tending to stay within 20–30 m of the ground (within or near vegetation) to avoid predation (Kingsley & Whittam 2005). On a typical day during migration, birds move between higher and lower altitudes at dawn and dusk, and it is during these times that birds may be at risk of colliding with wind farm structures (Richardson 2000; Langston & Pullan 2003). At daybreak, or just before it, nocturnal migrants drop rapidly from higher altitudes (> 200 m) and fly at or above treetop level (< 200 m) until they find a suitable location for landing, features of which will depend on the conditions and the requirements of the individual birds (Kerlinger 1995).

There appears to have been only one comprehensive study calculating the collision risk for nocturnal migrant birds (Winkelman 1992a). This was performed in The Netherlands, and collision risk was calculated by means of observed collisions (using thermal image intensifiers). The results showed a high nocturnal collision probability, with 1 in 40 (2.5%) birds passing at rotor height. Daily searches for collision fatalities during the migration periods, together with systematic field observations of passing birds, could lead to a better picture of the behaviour and collision risk of birds (Everaert & Stienen 2007). The use of night vision devices and/or radar, and thermal image intensifiers are regarded as necessities (Everaert & Stienen 2007).

Staging areas

Some types of migrants, such as shorebirds and waterfowl, flock at restricted areas of suitable habitat while resting and feeding between migratory flights. These 'staging areas' are often lakes, marshes, estuaries, mud flats or other areas that can provide food and/or shelter for large numbers of birds (Richardson 2000). Once a migrant decides to stop, it is constrained by the availability of habitat and resources within the local landscape. Stopover sites are not necessarily large expanses of high-quality habitat, such as mudflats where thousands or millions of birds congregate; they can also include marginal habitat when nothing else is available in the immediate area. For example, a flock may be forced to land and stopover at a marginal site during bad weather (Mabey 2004).

At staging areas, flights of migrants are often concentrated into corridors when the birds are either taking off or approaching to land (Richardson 2000). The flight height of these migrants is often at the height of wind turbines. Some birds, like swans, typically climb only very gradually, and may remain low for a considerable distance after takeoff from the stopover area, while other birds climb more rapidly (Richardson 2000). Therefore, the distance from the stopover area within which flight altitudes will be low enough to be at risk of collisions with turbines will depend on the species (Kingsley & Whittam 2005).

Collision with wind farm structures is not the only potential effect on migrating birds. Disturbance can also affect migrants if turbines are located near important staging areas. Additionally, the alteration or destruction of habitat used by birds during migration can also contribute to adverse environmental effects.

6. Mitigation of impacts

The most useful way to ensure minimal negative effects of wind farms on birds is to choose an appropriate site. However, a number of mitigation measures have been suggested to reduce collision fatalities at operational wind farms, although it must be emphasised that most have yet to be tested to determine their effectiveness.

Mitigation may involve on-site and/or off-site measures. Temporary shutdowns of turbines during periods of high bird activity, especially at migration bottlenecks and staging areas, and near breeding or wintering concentrations, have been proposed (Smallwood & Thelander 2004; Everaert & Stienen 2007; Hotker et al. 2006). Since turbine shutdown has yet to be routinely implemented, it is not known to what extent it would reduce collision fatalities, although stationary blades are likely to pose less of a risk to flying birds than rotating blades (Drewitt & Langston 2008). However, because collisions also occur with turbine towers, this does not remove the need to avoid siting wind farms on migration routes or at other sites where concentrations of species vulnerable to collisions occur. In this regard, it is of note that in response to a 2004 lawsuit filed against the Altamont turbine operators (California, USA) over raptor kills, wind-power companies and local county officials agreed to shut down half the turbines during winter months, and permanently remove 100 turbines over 5 years (Nijhuis 2006).

It has been suggested that scaring devices, such as playback of alarm calls, could be used as a deterrent (Drewitt & Langston 2008). However, this is likely to be of short-term effectiveness and unacceptably intrusive close to human habitation. Radar- or audio-activation of possible risk-reduction measures, such as alarm calls or turbine shutdown, has the potential advantage that it could be initiated when a hazardous situation is developing, as birds approach (Evans 2000; Drewitt & Langston 2008). However, given that such scaring devices have not been trialled at wind farms, much development and testing would be required before they could be accepted as an effective method for deterring bird species from wind farms in New Zealand.

It has been proposed that the visibility of rotating blades to birds could be increased by having high contrast patterns on blades (McIsaac 2001; Hodos 2003). This proposal requires field testing, but even if it reduced collision risk, such obvious turbine blades visible from urban areas may not be acceptable to the general populous (Langston & Pullan 2003). The use of ultraviolet paint has also been suggested as potentially helpful in alerting birds to the presence of rotors while not increasing their visibility to people (Drewitt & Langston 2008). However, results from limited trials have been equivocal, perhaps because of different species' sensitivities to different UV wavelengths (Hotker et al. 2006).

Smallwood & Thelander (2004) found that turbines at the ends of lines and edges of clusters killed disproportionately more birds, and so hypothesised that a pair of poles could serve as dummy turbines beyond the end of lines and edges of clusters. These poles would be placed 5–10 m apart, just beyond the rotor plane of the end turbine and upward to the maximum height of the rotor. These 'flight diverters' would be expected to encourage birds to fly around or over the operating turbines (Smallwood & Thelander 2004). Another suggestion to overcome this problem is to relocate turbines that kill disproportionately more birds because of where they are located (Langston & Pullan 2003).

Another suggested mitigation measure could involve adjusting turbine tower height to minimise collision rates (Anderson et al. 1999; Hotker et al. 2006). Taller or shorter towers could expose fewer birds to collision, although little research has been conducted on this factor. It would require detailed knowledge of the variability of flight altitude of species prone to collision mortality at the site to determine whether such an adjustment would be effective.

Reducing collision mortality of resident species could involve making the site unsuitable for use by birds or a specific bird species through changes in habitat (Anderson et al. 1999). This action has been effective in reducing bird abundance on grassed airfields, where mown swards were made unsuitable to foraging and roosting species by being left to grow long (> 230 mm) (Caithness et al. 1967).

Off-site mitigation can involve actions taken to increase the security of at-risk species at sites away from wind farms (Percival 2003; Smallwood & Thelander 2004; Kuvlesky et al. 2007). This might involve creating or improving habitat near a wind farm to encourage birds to use it rather than the wind farm site. An alternative procedure could involve management to improve adult survival or fledgling production, e.g. by carrying out mammalian predator control for New Zealand species (Ashby 2004). Ideally, where an assessment has quantified the level of adverse effect on a bird population, there may be an opportunity to carry out management to mitigate against such effects (Percival 2003).

An essential aspect of any mitigation measure would be to monitor its impact and test its effectiveness in either reducing collision fatalities or increasing numbers of individuals above those lost to collision fatalities.

7. New Zealand wind farms and their impact on birds

During 2007, wind generation capacity in New Zealand almost doubled to 322 MW, representing 2.2% of total electricity generation (New Zealand Wind Energy Association 2008). Installed wind generation capacity is expected to grow to 494 MW by the end of 2009, and to supply up to 20% of New Zealand's energy needs by 2020 (Rodgers 2006). Lists of operational and proposed wind farms are provided in Appendix 1.

As far as I am aware, there has been no report of carcass searches made at New Zealand wind farms using a scientifically robust methodology. Instead, reports only include anecdotal information. For example, in a popular article, Rodgers (2006) noted that the only fatality at the Brooklyn turbine in more than 10 years of operation was a blackbird, and that 'elsewhere the deaths of a few magpies, gulls and blackbirds have been recorded' (Rodgers 2006: 111). Similarly, ten deaths (all magpies *Gymnorhina tibicen*) have been recorded at the Tararua wind farm, while at Te Apiti five magpies and one kingfisher (*Halcyon sancta*) died during 2004–06 (Clutha District Council 2007). Thus, post-construction monitoring at New Zealand wind farms to date has been inadequate with regard to searches for birds killed as a result of collision with turbines. Maintenance workers are requested to document carcasses they encounter during their work (Seaton 2007). However, this is unlikely to turn up many carcasses unless large birds are killed, because carcasses can be lost due to scavenging, carcasses of small birds can be concealed in vegetation, and untrained personnel, lacking a systematic survey effort, find fewer carcasses than trained staff (Morrison et al. 2007). Since even a low impact can have significant implications for a threatened species' population viability, concerted efforts need to be made to improve post-construction monitoring at wind farms in New Zealand.

I am not aware of any reports or published papers detailing the effects of habitat loss or disturbance on bird populations at New Zealand wind farms.

8. Conclusions

A number of key findings have come from this literature review:

- The effects of wind farms on birds are variable, and can be species-, season- and site-specific. Thus, how applicable the information and conclusions provided in this review are to the New Zealand situation is unknown. Although the general conclusions from studies elsewhere may be pertinent to the New Zealand situation, we need to carry out research at New Zealand wind farms to have confidence in their applicability, particularly with regard to species impacts.
- The four main factors that contribute to collision fatalities at a wind farm are high densities of birds or frequency of movements through it, presence of species prone to collision with turbines, landscape features that concentrate bird movement, and poor weather conditions.
- Species groups that are most prone to collision fatalities at wind farms in Europe and North America are herons and allies, swans, geese, ducks, large soaring raptors, gulls, terns, owls, and nocturnal migrant passerines.
- While carcass numbers found at wind farms have been documented, these will underestimate fatalities unless a systematic methodology is used, including taking into account scavenger rate and searcher efficiency.
- Loss of or damage to habitat as a result of wind farm construction (roads, turbines, buildings) tends to be a minor impact, unless sensitive or rare habitats are involved, or habitat management at the site changes as a result of the development.
- Disturbance of birds as a result of wind farm development and operation may arise from increased activity of people and/or the presence, motion or noise of turbines. Disturbance may lead to displacement or exclusion of birds from areas of suitable habitat. The degree of disturbance can be highly variable, depending on the bird species, wind farm layout and availability of alternative habitat nearby.
- The choice of an appropriate site for a wind farm is the most useful way to ensure minimal negative effects on birds.
- The amount and extent of ecological baseline data collected at a proposed wind farm site should be determined on a case-by-case basis. A minimum of 3 years of detailed investigation should be carried out to determine which bird species use the site, and how and when they use the site.
- Any detailed study should ensure that seasonal, annual and weather variables are suitably investigated, particularly if a site is found to be used by a species that is threatened or likely to be at risk of disturbance or collision by an operational wind farm.
- Wind farm layout is probably important in reducing disturbance and collision risk to birds. It has been suggested that wide corridors between clusters of closely spaced turbines is the most appropriate layout to minimise collision fatalities and prevent barrier effects for both resident and migrant birds. However, a line formation parallel to the main flight direction of migrants has also been suggested.

- Wind farm developments should ensure that blade revolutions per minute are as low as possible, to avoid motion smear and thus promote blade visibility during the day.
- Bright white lighting is regarded as the main attractant of nocturnally active birds leading to collision with tall buildings, so its use should be avoided at wind farms. Ideally, the intensity of lighting should be minimal and be white and flashing, with the interval between flashes being as long as possible. In New Zealand, the lighting required on turbines is specified by the Civil Aviation Authority on a case-by-case basis.
- Although a number of on-site mitigation measures have been suggested to reduce collision fatalities at operational wind farms (e.g. temporary shutdown of turbines, bird scaring devices, high contrast patterns or UV paint on blades, flight-diverter poles, and adjustments to tower height), almost all have yet to be tested in the field to determine their effectiveness; therefore, these should be considered with caution. Off-site mitigation measures could involve habitat management to encourage birds to use sites away from wind farms and/or to improve adult survival or fledgling production.
- Post-construction monitoring at New Zealand wind farms has been inadequate to accurately determine bird fatalities as a result of collision with turbines because neither systematic search procedures nor trained staff have been used. Fatalities have been reported to involve magpies, gulls, blackbirds and a kingfisher, but these results are probably not indicative of the full range of species killed.

Although some of the findings from studies in other countries described above are applicable to New Zealand wind farms, some are not (e.g. there are no large soaring raptors in New Zealand). In addition, each wind farm site tends to be a little different from any other because of variation in topography, weather, habitats, land use and bird species present. Furthermore, our ability to draw conclusions from the review information is constrained because of changing technology, such as turbines becoming taller, having tubular steel bases rather than being of a lattice construction, and having a slower rotor speed. All of these factors need to be considered when investigating possible impacts of wind farm proposals on New Zealand birds. Pre-construction assessments with regard to birds should always be carried out, but the complexity of the assessment required will depend on various attributes of the site, such as the bird species present, their threat status, collision risk, and vulnerability to disturbance. Post-construction assessments should always be carried out when threatened or vulnerable species are likely to be using the site, or population impacts are likely to occur.

Due to a paucity of studies, it has not been possible to relate habitat type to likely wind farm impacts on birds in New Zealand. However, it is probable that the ideal habitat for wind farms in New Zealand, from an ecological perspective, is pastureland some distance from native forest, wetland or the coast, where it has been shown that the site is not on a migration route. This is because pastureland is largely inhabited by native bird species that are widespread and common (e.g. Australasian harrier, black-backed gull *Larus dominicanus* and paradise shelduck), and therefore are unlikely to be impacted significantly by disturbance and occasional collision fatalities.

There are major gaps in our knowledge with regard to impacts of New Zealand wind farms on birds. For example, it is not known to what extent each species is prone to wind farm development (collision, disturbance, barrier effect), which species are suffering collision fatalities, which routes are taken by migrants, how fixed these routes are in relation to varying weather conditions and time of travel (northward to wintering sites, southward to breeding sites), and the extent to which each species is able to avoid collision with turbines. Given that much effort and funding will go into establishing wind farms in New Zealand over the next 10–20 years (Parliamentary Commissioner for the Environment 2006), much effort also needs to go into filling gaps in our knowledge to ensure that wind farms are sited appropriately with regard to New Zealand bird species.

9. Recommendations

9.1 BIRD MIGRATION

The published literature on bird migration is considerable; however, much of the information is very general and relates to the Northern Hemisphere. Specific information relating to migration routes, timing and prevalence of nocturnal movements for New Zealand species is lacking (Williams et al. 2006). The following questions, in particular, need answering in relation to New Zealand birds and possible impacts of wind farms on their populations:

- Are there identifiable migration routes that should be avoided when siting wind farms?
- Do migrant birds follow or concentrate their flights along ridges, mountains, coastal margins, waterways and/or through saddles?
- At what heights do diurnal and nocturnal migrants fly during various weather conditions?
- What fatalities of migrant species are occurring at New Zealand wind farms (location of wind farm, species involved, numbers and months of occurrence)?
- How successful are birds in New Zealand at avoiding collisions with wind turbines when involved in nocturnal migration during various weather conditions?
- How will any cumulative detrimental impact (as collision fatalities) at more than one wind farm on a species during migration be monitored and considered when there is a further proposal for a wind farm along the migration route?

The issue of identifying important migration routes in New Zealand is a crucial one. It may be informative to overlay a map of annual median wind speed (which would suggest where most wind farms will be located) with likely migration routes and significant bird habitats (e.g. estuaries, freshwater wetlands) of New Zealand bird species. This information would enable a developer of a wind farm to determine whether the prospective site is on the route taken by any migratory species and whether a species' flight characteristics would make it vulnerable to collision with turbines. The following would be required for this project:

- Mapped routes for each species involved in migration.
- Information about the migration of these species, including timing, altitude of flight in relation to weather conditions, total number of migrants and flock size (mean and range).

While various sources provide information on the timing of migration, and departure and destination locations for some species (volumes 1–4 of the Handbook of Australian, New Zealand and Antarctic birds (Marchant & Higgins 1990, 1993; Higgins & Davies 1996; Higgins 1999); Dowding & Moore 2006; Williams et al. 2006), additional field studies would be required to provide much of this information. For example, information on migration routes would require telemetry studies, and determination of flight statistics (e.g. altitude, flock size) would require the use of marine and/or meteorological radar scans (Kingsley & Whittam 2005; Sun 2007).

With suitable siting (lack of tall structures and complex landforms nearby) and in conjunction with computer-assisted data processing, the latest marine radar units can apparently reliably detect small birds (starling (*Sturnus vulgaris*) size) at a range of 3 nautical miles horizontally (5.6 km) and up to 1500 m vertically, and medium to large birds (gulls, harriers) or flocks of smaller birds out to 6 nautical miles (11.1 km) and up to 3000 m vertically. This equipment would be useful where there are large resident populations or significant seasonal bird movements that require quantification for risk modelling. When used in conjunction with audio recordings and observers, these systems can identify species, range, direction of movement, speed of flight and altitude (if vertical and horizontal radars are combined), and can provide highly accurate records of each bird's or flock's flight path across the landscape. However, the radar is not able to determine the number of individuals in a flock or identify the species when used on its own (Fuller 2008; S. Fuller, Boffa Miskell, pers. comm., 24 October 2008). Meteorological radars can be used on a broader scale to determine the relative size and direction of migrating flocks. Also, the development of PTTs (platform transmitter terminal, satellite transmitter) or GPS (global positioning system) tags may allow barometric pressure or temperature to be measured, which would give an estimate of flight altitude. Before embarking on this migration research, it is important that New Zealand prioritises the order in which New Zealand at-risk species will be investigated.

9.2 COLLISION FATALITIES

Protocols for monitoring collision fatalities and analysing the results have been developed (Anderson et al. 1999), but have not been used at New Zealand wind farms in a systematic way that takes account of searcher efficiency, scavenger activity, habitat type and cause of death. The present information for New Zealand wind farms is inadequate to assess which species have died as a result of collisions with turbines and the number killed per turbine per annum. Therefore, it is important that New Zealand researchers collate information on species impacted and mortality rates at several New Zealand wind farms in various habitat types using the internationally accepted protocols that have been developed to detect collision fatalities.

9.3 AVOIDANCE RATE

Collision risk models have been developed to predict the theoretical numbers of birds that would collide with wind turbines at a proposed wind farm in the absence of any avoidance behaviour (Tucker 1996; Band et al. 2006). In order to make realistic predictions about the number of collisions that may actually occur, the inclusion of various avoidance rates (proportion of flights that might, in theory, result in successful avoidance) has been advocated: 95% by Scottish Natural Heritage (2008) and 97–99% by Percival (2007). Avoidance estimates should include species that continue to fly during conditions of poor visibility, when their ability to detect and avoid operating turbines is likely to be much reduced (Madders & Whitfield 2006). The precise estimation of collision and avoidance rates has proven difficult to determine because the frequency of such events is generally very low. Nevertheless, there is an urgent need for studies to determine avoidance rates of New Zealand birds. New technologies to achieve this are currently being developed, including the use of infra-red video cameras to monitor collisions (Percival 2007). Until avoidance rates have been determined for New Zealand species, a precautionary approach should be adopted, whereby 95% avoidance is assumed when calculating collision risk.

9.4 COLLABORATIVE RESEARCH

A collaborative approach to the research required into the impacts of wind farms on New Zealand's birds should be adopted, including in the development of research programmes, data collection and analyses, and funding. The various parties involved in the research should include wind-power generators, regulatory bodies that are promoting the use of wind energy (central government) and deciding the merits of particular sites (regional government and local authorities), and the Department of Conservation, whose responsibilities include the conservation of New Zealand's indigenous flora and fauna that may be impacted by wind farm developments. Since the membership of the New Zealand Wind Energy Association (NZWEA, www.windenergy.org.nz; viewed 24 October 2008) includes most businesses involved in wind-energy generation, including site development, service industries (law, finance and consulting), construction, engineering and generation, this seems to be the appropriate body to promote such a collaborative research programme among wind-energy businesses.

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Appendix 1

OPERATIONAL AND PROPOSED WIND FARMS IN NEW ZEALAND

A1.1 Operational wind farms

The following operational wind farms are listed in order of construction (Ashby 2004; Rodgers 2006; www.windenergy.org.nz, viewed 7 October 2008):

- Brooklyn, Wellington: a single 225 kW turbine, erected in 1993 by Meridian Energy.
- Hau Nui stage 1 near Martinborough: seven turbines each of 550 kW capacity (3.85 MW), erected in 1996 by Genesis Energy.
- Tararua stage 1 near Palmerston North: 48 turbines each of 660 kW capacity (31.7 MW), erected in 1999 by TrustPower.
- Gebbies Pass near Lyttelton: a single 500 kW turbine, erected in 2003 by Windflow Technology.
- Tararua stage 2 near Palmerston North: a further 55 turbines each of 660 kW capacity (36.6 MW), erected in 2003/04 by TrustPower.
- Te Apiti near Palmerston North: 55 turbines each of 1.65 MW capacity (90.7 MW), erected in 2003/04 by Meridian Energy.
- Hau Nui stage 2 near Martinborough: a further eight turbines each of 600 kW capacity (4.8 MW), erected in 2004 by Genesis Energy.
- Southbridge near Geraldine: one turbine of 100 kW capacity, erected in 2005 by Energy3.
- Te Rere Hau stage 1 near Palmerston North: five turbines each of 500 kW capacity (2.5 MW), erected in 2006 by New Zealand Windfarms Ltd.
- White Hills near Mossburn: 29 turbines each of 2 MW capacity (58 MW), erected in 2006/07 by Meridian Energy.
- Tararua stage 3 near Palmerston North: a further 31 turbines each of 3 MW (93 MW), erected in 2006/07 by TrustPower.
- Te Rere Hau stage 2 near Palmerston North: 14 turbines each of 500 kW capacity (7 MW), erected in 2007/08 by New Zealand Windfarms Ltd.
- Project West Wind near Makara: Meridian Energy has been given approval to erect 62 turbines each of 2.3 MW (142.6 MW). Under construction, and is expected to be fully commissioned by late 2009.

A1.2 Proposed wind farms

Planned farms for which resource consent has been granted or applied for, and for which preliminary investigations are underway are as follows:

- Titiokura near Napier: Unison / Hydro Tasmania has been granted approval for stage 1 (16 turbines, 48 MW), but construction is on hold at present.
- Te Waka near Napier: 111 MW. On being declined by the Environment Court, this application was modified by the developers (three turbines removed) and awaits a hearing by the Environment Court after being called in by the Ministry for the Environment.
- Hawke's Bay near Napier: Wind Farm Developments, Hallblock Resources Ltd & Lowe Family Interests have been granted approval for 75 turbines each of 3 MW, awaiting construction.
- Taumatatotara near Te Anga, King Country: approval granted by council to Ventus for a 20 MW wind farm in June 2006, awaiting construction.
- Awhitu Peninsula near Waiuku: resource consent granted by the Environment Court to Genesis Energy to build 19 turbines each of 1.0 MW turbines, but construction on hold at present.
- Teviot Valley east of Roxburgh, central Otago: resource consent granted in 2007 to Pioneer Generation to construct a 1.5 MW (three 0.5 MW turbines) wind farm at Horseshoe Bend on the Teviot River. Awaiting construction (this apparently depends on availability of second-hand turbines).
- Lake Mahinerangi of inland Otago: following feedback to a resource consent application for a 200 MW wind farm (up to 100 turbines), TrustPower submitted a revised application for a smaller wind farm in December 2006. Awaiting outcome of an appeal to the Environment Court.
- Taharoa C near Kawhia: 42 turbines (100 MW) to be erected by Taharoa C Incorporation and PowerCoast; consent was granted in August 2006, but has been appealed.
- Project Hayes of inland Otago: Meridian Energy has been given approval to erect 176 turbines (1.8–3.6 MW turbines, 630 MW in total) adjacent to the Lammermoor Range, awaiting construction. May be appealed in the Environment Court.
- Motorimu near Shannon: resource consent application lodged by Allco Australia to build 127 turbines of 500 kW each; local council commissioners gave approval to erect 75 (109.7 MW), but has been appealed.
- Te Uku near Raglan: resource consent application lodged by WEL Networks for an 84 MW wind farm.
- Epakauri on the Northland west coast: resource consent application lodged by Meridian Energy for 18 turbines each of 2.74 MW (49.3 MW) on land administered by the Department of Conservation, and surrounding farmland.
- Kaiwera Downs near Gore, Southland: TrustPower applied in November 2007 for resource consent for a 240 MW wind farm (up to 83 turbines).
- Puketiro near Upper Hutt: the Greater Wellington Regional Council applied to dedicate land to a wind farm in June 2005. In 2006, RES NZ Ltd was awarded the tender, and is now monitoring wind at the site. They propose to erect about 50 turbines each of 2–3 MW capacity. Expected to lodge for resource consent in 2009.

- Project Mill Creek in Ohariu Valley near Wellington: Meridian Energy has lodged resource consent applications for the project (31 turbines each of 2.3 MW capacity, 71 MW combined capacity).
- Project Central Wind near Waiouru: preliminary investigation by Meridian Energy for a wind farm of 51 turbines.
- Hauauru ma raki, Waikato Wind Farm, between Port Waikato and Raglan: consent application being prepared by Contact Wind Ltd for a wind farm consisting of up to 220 turbines with a capacity of 540 MW in total (turbines up to 3 MW and up to 150 m high at blade tip).
- Turitea near Palmerston North: feasibility study being carried out by Mighty River Power and Palmerston North City Council for a 120 MW wind farm.
- Rock and Pillar Gorge in Otago: feasibility study being carried out by Windpower for a 25 MW wind farm.
- Waverley near Wanganui: a wind farm of 135 MW is under investigation by Allco Wind.

How do wind farms impact on birds?

Wind generation is poised for rapid expansion in New Zealand, being expected to supply up to 20% of New Zealand's energy needs by 2020. However, nothing is known about the likely impacts of wind farms on our bird populations. This literature review shows that the main impacts of wind farms on birds in other countries include collision fatalities, habitat loss and disturbance. A key finding is that wind farms have variable effects on birds, depending on species, season and site, and no two wind farms are the same, making it difficult to generalise from studies carried out in other countries. Therefore, it is imperative that we gain more information about the New Zealand situation.

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New Zealand Government