Appendix 23

Mt Emerald Wind Farm: Turbine collision risk assessment for Sarus Crane & Wedge-tailed Eagle

Prepared by Biosis

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FINAL REPORT

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Contents

1 Introduction

1.1 Project background

Ratch Australia Corporation Limited is in the process of developing a wind energy facility at Mount Emerald in the Herberton Range approximately 50km west/south-west of Cairns, Queensland. The project has been determined to be a Controlled Action under provisions of *Environment Protection and Biodiversity Conservation Act 1999*. The controlling provisions are listed threatened species and ecological communities and listed migratory species. The assessment process under the Act is an Environmental Impact Statement and *Final Guidelines for an Environmental Impact Statement for the Mt Emerald Wind Farm* were issued in April 2012. Amongst other requirements, the *Guidelines* require:

> *a) A detailed assessment of the nature, extent, likelihood and consequence of the likely short-term and long-term impacts including but not limited to:*
>
> *i. collision risk from turbines*

Biosis has been commissioned by RPS Australia Asia Pacific to undertake the present assessment of the risk of collision with wind turbines for two bird species at Mt Emerald Wind Farm. The first, Sarus Crane *Grus antigone* is a listed migratory species under provisions of the EPBC Act. The second, the mainland Wedge-tailed Eagle *Aquila audax* is not listed under provisions of the EPBC Act nor the *Nature Conservation (Wildlife) Regulation 2006* of the Queensland *Nature Conservation Act 1992*. Nonetheless, Wedge-tailed Eagles are readily observed and have been documented to have collided with turbines at wind farms elsewhere in Australia, albeit at lesser frequency than some other bird species that are also not threatened (Smales in press).

The collision risk assessment has been undertaken using a mathematical modelling process for which the primary inputs are data for flights by the two species collected at the Mt Emerald Wind Farm site. The data were collected by RPS to a rigorous program of point counts designed to quantify bird flights under a protocol provided by Biosis. The fieldwork was undertaken in 2012 and 2013.

The Biosis Deterministic Collision Risk Model was used to provide the risk analysis (Smales et al. 2013). It provides annual projections of potential numbers of collisions by the two species for the number and specific dimensions of the turbines proposed to be used at Mt Emerald Wind Farm.

2 Background to collision risk modelling

Mathematical modelling is simply a method by which available information is used to predict what may occur in the real world. We all use modelling all the time – although we generally don't call it that. Simple examples are when we calculate how long it will take us to travel from one place to another or how much fuel we will use to do so. We are using maths to make predictions based on available evidence.

The fundamental objective of modelling of risk is to provide a rigorous process by which probability can be assessed and to do so in a manner that can be replicated.

When making predictions of risk using a model, the rationale behind the predictions is explicitly stated in the mathematics of the model, which means that the logical consistency of the predictions can be easily evaluated. This is the case regardless of the type of model used.

The only real alternative to the use of a model is the use of subjective judgement to predict risks. Compared to subjective judgement, the explicit nature of inputs and rigour entailed in modelling makes models more open to analysis, review or modification when new information becomes available. Although there may be assumptions used and some arbitrary choices made when deciding on the structure and parameters of a model, these choices are stated explicitly when using a model but this is difficult to do when making subjective judgements. The assumptions underlying a model can be tested. Models can be used to help design data collection strategies. They can also help to resolve and avoid inconsistencies, and the rigorous analysis of data can help to clarify thoughts.

Models are often also valuable for their heuristic capacities, by focussing attention on the important processes and parameters when assessing risks (Brook et al. 2002). All risk assessment must incorporate processes for refinement and improvement as more data come to hand. It is vital that there is a feedback loop allowing this to occur (Burgman 2005). This should be expected of a model and the use of a model explicitly facilitates that process.

All of these benefits are difficult, if not impossible to achieve with subjective judgement. Another drawback of subjective judgement is that it may lead to biased predictions of risk, and such biases vary unpredictably among people (Tversky and Kahneman 1974; Ayton and Wright 1994; Gigerenzer and Hoffrage 1995; Anderson 1998). The predictions of models tend to be less biased (Brook et al. 2000, McCarthy et al. 2004). There are thus considerable benefits to be gained by employing a model when assessing risk.

In the case of modelling for risk of avian collisions with wind turbines, Madders and Whitfield (2006) have drawn attention to the transparency and objectivity of collision risk modelling relative to assessment without quantitative modelling. As those authors do, we also recognise that collision risk modelling is reliant on a combination of empirical data and some assumptions.

With regard to the purpose and capacities of collision risk modelling, we also agree with Madders and Whitfield (2006) that, “care must be taken not to over interpret the model outputs, which are probably best used to evaluate different wind farm configurations”. In that respect, it is worth noting that numerical results of modelling we present here are provided to two or more significant places. This should not be misinterpreted to indicate a particular level of precision in the results. The purpose of providing results in this form is to permit comparative evaluation between species or, potentially, between different turbines in precisely the manner suggested by those authors.

Ideally, collision risk modelling should provide projections which reflect mean annual risk for various species over the expected life of the wind farm. In order to achieve that, input values for bird activity that pose risk should be values that are as representative as possible of long-term variations in bird utilisation of the site. The model's projections are determined from empirical data as this offers the only valid basis for such analyses, but it must be recognised that there are practical limitations on obtaining longitudinal datasets that may account for all possible environmental variables. In the present case, a substantial body of data has been collected in various seasons and times of the diel cycle, a range of weather conditions and extrinsic factors experienced during data collection such as land management practices and activities on the site. However, the data were collected in just one twelve-month period and it should be recognised that this may not be entirely representative of longer time frames.

It is important to recognise that while a model such as the one used here attempts to quantify risks, it makes no assessment of the 'value' of its subjects. Whether any species has more or less significance than any other taxon, and thus whether predicted risk to any particular taxon is 'acceptable' or not, is a further evaluation that must be made. Use of a model allows a clear distinction to be made between potential risks and subsequent judgements about those risks.

Biodiversity legislation and accompanying guidelines for its application provide the legal mechanisms for the subsequent evaluation of the significance of potential impacts on a threatened species. For instance the *EPBC Act policy Matters of National Environmental Significance Significant Impact Guidelines 1.1 Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth of Australia 2009) provides specific criteria applicable under that legislation to define significant impacts on taxa listed under various categories of threat and for listed migratory species. In the main, those criteria relate to impacts on populations rather than on individuals since populations are the key units of conservation.

3 Methods

The Biosis Deterministic Collision Risk Model was used to provide the risk analysis. A full, published description of the model is provided in Smales et al. (2013), which is reproduced as Appendix 1 of this report. The following provides details of the inputs parameter requirements of the model and the specific values used for Sarus Cranes and Wedge-tailed Eagles for Mt Emerald Wind Farm.

3.1 Input parameters of birds

Bird utilisation data

Numbers of flights made by Sarus Cranes and Wedge-tailed Eagles that may be at risk of collisions with turbines are drawn from empirical data collected during bird utilisation surveys at the Mt Emerald Wind Farm site. Surveys were conducted by RPS during a total of 26 days of fieldwork. These included five days in August 2012; four days in November 2012; four days in January 2013; two days in February 2013; four days in April 2013; and seven days in July 2013.

All surveys took the form of timed, fixed point counts at a number of predetermined locations across the study area. Count sites were selected to provide a representative sample of topography and environments within the overall site.

Observation time of all point counts combined totalled 21760 minutes. During the counts the following flights were documented and are used in the model:

Sarus Cranes: 0 flights below rotor-swept height; 132 flights within rotor-swept height.

Wedge-tailed Eagles: 15 flights below rotor-swept height; 79 flights within rotor-swept height.

(see *Risk relative to flight height and turbine components*, below).

Numbers of birds at risk

Where an estimate of the size of the population at-risk is available, this is factored into the model to provide results in the form of an expected number of individuals at risk of collision per annum. This is an important consideration because an input measured in terms of bird movements cannot provide an output in terms of individual birds. Where a species makes more flights per year than the number of individuals, as is frequently the case, this also provides for the logic that the number of collisions cannot exceed the number of birds that could collide. The population at-risk is the number of individual birds per annum that fly within the wind farm and thus may encounter turbines.

In the present case, the maximum number of Sarus Cranes near the wind farm is a flock estimated to include 600 Sarus Cranes observed approximately two kilometres south east of the wind farm site (RPS data). Experience of RPS on the site suggests there were up to 18 Wedge-tailed Eagles at the site on occasions. For the two species, these two values have been used as the total populations at risk of collisions at Mt Emerald Wind Farm.

Risk relative to flight height and turbine components

Collision risk is considered to differ according to whether a bird in flight may encounter the simple, static structure of a turbine or the rotors in motion. This allocation of differing risk is based on the consideration that birds will avoid collision with the stationary elements of turbines (static components) in all but the most exceptional circumstances and the model uses 99% avoidance rate for these components. The capacity of birds to avoid moving rotor blades (dynamic components) is generally expected to be lower, and the model has the scope to examine multiple scenarios for birds' avoidance capacity of the dynamic elements of operational turbines (see *Collision avoidance capacity*, below).

Thus, for the purposes of the model, a turbine is decomposed into its static and dynamic components. The static components include the entire turbine (nacelle, tower structures and the stationary rotor). The dynamic component incorporates the additional risk associated with the area swept by rotors in the time it takes the particular bird to fly through the depth of the swept disk. This additional risk is relevant only to flights within rotor-swept height. Turbine dimensions used to determine these are taken from specifications of the particular make and model of turbine proposed for the wind farm.

In order to account for the static and dynamic turbine components, data for bird flights are divided into two height zones: those below- and those within-rotor swept height. Siemens SWT 3.0-108 turbines with a hub height of 79.5 metres are proposed to be used at Mt Emerald Wind Farm. Rotor-swept height of this turbine spans the zone from 25.5 to 133.5 metres above the ground and flights below rotor-swept height are those between the ground and 25.5 metres high. Note that flights above the maximum height of the rotor tips are not at risk of collision and for that reason flight records from above that height are not relevant to collision risk modelling.

Flights relative to time & space

The collision risk model generates a measure of site utilisation from flights recorded in a defined amount of airspace and a defined time period. The model assumes no relationship between this constant, average utilisation of the site by birds, and the location of individual flights relative to the geographic locations of turbines. The model thus assumes a flat rate of utilisation across the site to account for the infinite possibilities of individual flight paths relative to turbine placements. Although this uniform utilisation measure means the model is not geographically spatial, it still requires metrics to account correctly for the interactions of bird flights with the volume of space occupied by turbines, including rotor swept volumes.

For this reason flight data has been documented from a specified volume of airspace. A cylinder of space used for this purpose is defined by the top height of the rotor tips for the turbine in question (in this case 133.5 metres) and a horizontal radial distance from observers. The size of this cylinder of space is considered to be large enough to sample the airspace meaningfully with minimal influence of surveys on bird behaviours, yet not so large as to be affected by observer detectability range, and with a view to avoiding double counting of bird flights that might otherwise occur due to overlap of simultaneous counts by more than one observer. The radial distance used can be tailored to the capacity for observers to detect particular species in flight. Large birds including Sarus Cranes and Wedge-tailed Eagles are readily detected over a considerable distance and we have used 2000 metres as this is strongly supported by multiple records in the present data of flights observed at that distance and beyond. The observational cylinder is a device used to calculate the flight density under the assumption that all observational cylinders used are in other respects equivalent to each other.

The numbers of bird flights-at-risk, as recorded during the combined duration of all timed point counts, are extrapolated in the model to determine an estimated number of movements-at-risk per annum. This extrapolation is based on the number of hours per day during which particular species may be in flight and whether they are year-round residents or annual migrants and thus the portion of the year that they may be at risk on the wind farm site. In the present case, Wedge-tailed Eagles are diurnal and were modelled for an average daily period of twelve hours of available flight time and for their being year-round residents. Sarus Cranes appear to fly primarily during daylight hours and were also modelled for an average daily period of twelve hours of available flight time, however, it is acknowledged that they may fly at night although the frequency of any such flights is unknown. Sarus Cranes are annually present in the region between June and late November or early December and we have modelled for their presence and potential risk for six months per annum.

Collision avoidance capacity

As outlined above, the model provides for different capacities of birds to avoid collisions. This capacity may include cognitive behaviours, in which a bird becomes aware of a potential risk and takes evasive action, and involuntary behaviours such as the variations between species in natural flight modes and innate aerial agility. A 90% avoidance rate means that in one of every ten flights a bird would not avoid an obstacle in its path. While many bird species have better avoidance capacity than this and it is well established that most species avoid collisions with wind generators on most occasions, actual turbine avoidance rates are unknown or poorly defined for most taxa (Chamberlain et al. 2006). Avoidance rate of Wedge-tailed Eagles has been investigated at Studland Bay and Bluff Point Wind Farms in north-west Tasmania (Hull and Muir 2013). In respect of risk modelling, an avoidance rate of 95% has been found to equate closely with the actual experience of Wedge-tailed Eagle collisions there (Smales et al. 2013). However, there are some ecological differences between Tasmanian and mainland Wedge-tailed Eagles and specific conditions of particular sites may influence avoidance rates, so we still provide a range of avoidance rates for the species in collision modelling for Mt Emerald Wind Farm.

We consider that birds will avoid collision with the static components of turbines in all but the most exceptional circumstances and the model uses 99% avoidance rate for these components. The capacity for birds to avoid the dynamic components of turbines can be expected to be lower, and the model provides scope to examine avoidance rates for the dynamic elements of operational turbines. Since the avoidance capacity exhibited by particular species requires confirmation based on actual experience, we provide results for a range of avoidance rates for both species. In the current case, predictions for the dynamic components are provided for each of 90%, 95%, 98% and 99% avoidance rates.

3.2 Parameters of turbines

Turbine presented area

Turbines present risk to flying birds both by the static obstacle they present and due to the motion of rotors. The first of these is represented by mean area (m^2 per turbine) of the entire machine, including tower, nacelle and stationary rotor blades. The mean area presented by a turbine to a bird in flight is between the maximum (where the direction of the bird is perpendicular to the plane of the rotor sweep) and the minimum (where the direction of the bird is parallel to the plane of the rotor sweep). The mean presented area is determined from multiple dimensions and rotor speed of the particular make and model of turbine, as supplied by the manufacturer.

The additional area (m^2 per turbine) presented by the movement of rotors during the potential flight of a bird through the disc swept by rotors is determined via a calculation involving species-specific, independent parameters of the bird's body length and flight speed and of rotor geometry and rotation speed, as supplied by the turbine manufacturer.

Body lengths of birds are as provided in standard references, primarily the various volumes of the Handbook of Australian, New Zealand and Antarctic Birds (Birds Australia, various editors). Body length of Sarus Crane used in the model is 1.60 metres and for Wedge-tailed Eagle is 0.95 metres.

Accurate determinations of bird flight speeds are complex and difficult to obtain (Videler 2005; Pennycuick 2008). Pennycuick (2008) makes the point that for reasons of physical dynamics of flight and of optimal energetics, there is generally little difference between average maximum and average minimum flight speed of most species. We are not aware of published empirical data for average flight speed of Sarus Crane or Wedge-tailed Eagle, but mean air-flight speeds for closely related northern hemisphere taxa, Common Crane *Grus grus* and Golden Eagle *Aquila chrysaetos*, are provided in Bruderer & Boldt (2001) and equate to 45 km/h for both species.

The component of risk associated with the rotation of blades is not applicable for time when the rotors are stationary and the static turbine alone presents risk. The percentage of the year when this applies because turbines are not expected to be operational is derived from wind speed data collected from the site and accounts for the average time per annum when wind speed is too low or too high for turbines to operate in addition to time required for turbine maintenance. The projected annual percentage downtime for Mt Emerald Wind Farm site is 7.8%.

Potential number of turbine encounters

The number of turbines that a bird may encounter in a given flight depends on the total number of turbines and their configuration in the wind farm, as well as the flight behaviours of the species.

As it is not realistic to assume that a bird might encounter every turbine in the wind farm in a given flight, we need to ascertain the average number of turbines that might be encountered in a flight. It is assumed for the purposes of the assessment that a bird might fly from any point in the wind farm to any other and that many flights will not follow a straight path. In the case of a scattered turbine array, when multiple flight paths are drawn randomly across a plan view of the wind farm, some paths may be circuitous and have potential to encounter many turbines while others will pass through a small portion of the site and have potential to encounter relatively few turbines. Mathematically, the 'average' path will intersect with $\sqrt{N}$ turbines (where N is the total complement of turbines comprising the wind farm). For scattered turbine configurations this value is used in the model for the number of turbines that might be encountered per flight.

For the case of a linear, single row of turbines the number of turbines that may be encountered in a given flight requires a different calculation. In this array it will be rare, but not implausible, for a bird to fly along the row of turbines encountering all of them. It is much more likely that a given flight will encounter few of the turbines and the closer the flight is to a perpendicular crossing of the row, the more likely it is that the flight will encounter a maximum of one turbine. In modern wind farm designs a whole or part of a wind farm comprised of a single rows of turbines is rare, but it can be seen that the risk rate would generally be low compared to a scattered array, as the majority of bird flights are likely to encounter few turbines.

As required, the model has capacity to scale between the scattered and linear configurations for a wind farm that is either one or the other, or consists of any combination of a clustered and linear array of turbines. This is done by a single parameter which scales linearly between the two extremes.

The turbine layout proposed for Mt Emerald Wind Farm is a scattered configuration and bird encounters with turbines are modelled as such.

3.3 Model output metrics

Data collected during point counts documents the number of flights made by particular species of birds ('flights-at-risk'). It is important to note that the number of flights-at-risk differs from the number of individuals that might collide with turbines ('individuals-at-risk'). Only where an estimate is available for the size of the population at risk, flights-at-risk may be converted into a number of individuals-at-risk by incorporating a population estimate into calculations. One logical outcome of this function in the model is that the projected number of collisions cannot exceed the number of birds at risk.

As outlined above (Section 3.1 *Numbers of birds at risk*), the sizes of populations at risk of both Sarus Cranes and Wedge-tailed Eagles have been determined and have been incorporated into the model. A modelled projection of the mean annual number of individual birds at risk is thus provided here for each species.

[If data for flight-at-risk are available but no population estimate is available, risk is necessarily expressed only in terms of the number of flights-at-risk per annum. Whilst this metric is not the same as the number of collisions that might occur, it is nonetheless of value for purposes such as comparing risk posed by different types or configurations of turbines.]

4 Results

On the basis of input values described above, collision risk modelling has provided projected mean annual number of individuals at risk of turbine collisions for the Sarus Cranes and Wedge-tailed Eagles. The results are presented in the table below for both species at four different avoidance rates for dynamic components of turbines and a standard 99% avoidance rate for static components.

Table 1. Mean projected numbers of collisions per annum for Sarus Crane and Wedge-tailed Eagle at four dynamic avoidance rates.

Static avoidance rate	**99%**	**99%**	**99%**	**99%**
Dynamic avoidance rate	**90%**	**95%**	**98%**	**99%**
Sarus Crane	0.83	0.45	0.22	0.14
Wedge-tailed Eagle	0.76	0.42	0.22	0.15

For both species, the projected estimates equate to an average of a little less than one collision per annum (if dynamic avoidance rate is 90%) to an average of about one every seven years (if dynamic avoidance rate is 99%).

The range of results is slightly wider for Sarus Crane than for Wedge-tailed Eagle. This is because the range of results for any species is influenced by the relative proportion of flights below- and within rotor-swept height and the avoidance rates assigned to those two height zones. In the case of these two species at Mt Emerald, all observed Sarus Crane flights were within rotor-swept height, whereas 84% of observed Wedge-tailed Eagle flights were within rotor-swept height and16% were below that height.

5 Discussion

The results of collision risk modelling provides projected estimates of turbine collision risk encompassing a range for each species depending on the rate at which birds avoid turbines, especially the moving rotors. As discussed above, there is no empirical information available about turbine avoidance behaviours – and thus avoidance rates - for Sarus Cranes. The empirical information for avoidance rates for Wedge-tailed Eagles (Hull and Muir 2013) is from a quite different environment in Tasmania.

It is important to note that the projections represent *annual average numbers* of potential collisions. As a consequence, and also because the projections are for statistically small numbers, prediction of a frequency distribution for any real collisions is beyond the capacity of the model. Behaviours of the birds and numerous other factors may influence the real-life incidence of any collisions. It is thus well within probability and the annual average predictions provided here that no collisions might occur over many years, or that more than one collision could occur in close succession.

Potential limitations of this modelling are that it is based on flight data obtained during one twelve-month period which may or may not be representative of longer-term movements by the two species and these may be affected by a wide range of environmental influences. The data were collected prior to construction of the proposed wind farm and it is possible, that an operational wind farm could influence flight behaviours. Evidence from an operational wind farm in Tasmania suggests that there is little effect on utilisation of sites by Wedge-tailed Eagles but their behaviours were responsive to the presence of turbines (Hull and Muir 2013), As yet there is little empirical experience of cranes interacting with wind farms in Australia and none for Sarus Crane.

Behaviours and collisions have been investigated for Whooping Crane *Grus americana* and Sandhill Crane *Grus canadensis* at some operating wind farm in the USA (Nagy et al. 2012; Derby et al. 2012). Nagy et al (2012) monitored both species intensively during five seasons in which they were present at a wind farm. They documented 11,330 Sandhill Crane flights over, around and through the wind farm during spring and autumn periods. Up to five endangered Whooping Cranes were also observed there. No collisions of either species were detected. Their observations of the cranes indicated they avoided turbines by flying over, around or through spaces between turbines. Derby et al. (2012) monitored both species at five wind farms. They reported that approximately 600,000 Sandhill Cranes and 300 Whooping Cranes migrate twice per year through the area where these wind farms are situated. Their study included approximately 61,700 individual searches for bird carcasses under turbine over multiple years. Both studies detected no crane collision casualties or fatalities and concluded that collision risk for these species was low.

This is not to suggest that collisions by those species do not occur, nor that collisions of Sarus Cranes at Mt Emerald Wind Farm may not occur. This discussion is not intended to present an exhaustive review of crane collisions with wind turbines, but it does represent some of the latest information from relatively large studies of congeneric species to the Sarus Crane. We consider it is probable that Sarus Cranes will have high collision avoidance capacity.

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Appendix

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Wind Energy and Wildlife Conservation

A Description of the Biosis Model to Assess Risk of Bird Collisions With Wind Turbines

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ABSTRACT We describe the model of Biosis Propriety Limited for quantifying potential risk to birds of collisions with wind turbines. The description follows the sequence of the model's processes from input parameters, through modules of the model itself. Aspects of the model that differentiate it from similar models are the primary focus of the description. These include its capacity to evaluate risk for multi-directional flights by its calculation of a mean presented area of a turbine; its use of bird flight data to determine annual flux of movements; a mathematical solution to a typical number of turbines that might be encountered in a given bird flight; capacity to assess wind-farm configurations ranging from turbines scattered in the landscape to linear rows of turbines; and the option of assigning different avoidance rates to structural elements of turbines that pose more or less risk. We also integrate estimates of the population of birds at risk with data for numbers of their flights to predict a number of individual birds that are at risk of collision. Our model has been widely applied in assessments of potential wind-energy developments in Australia. We provide a case history of the model's application to 2 eagle species and its performance relative to empirical experience of collisions by those species. © 2013 The Wildlife Society.

KEY WORDS bird, collision, model, risk, turbine, wind energy.

A number of mathematical models have been developed for the purposes of either describing the interaction of a bird with a wind turbine or to predict the risks of bird collisions with turbines (Tucker 1996*a*, *b*; Podolsky 2003, 2005; Bolker et al. 2006; Band et al. 2007). Tucker (1996*a*, *b*) and Band et al. (2007) detailed their models in the peer-reviewed literature. The collision risk model developed by Biosis Propriety Limited has been widely used to assess wind-energy developments in Australia since 2002, but it has not previously been described in detail. Given high levels of interest in effects of wind turbines on fauna, we believe it is important for the model to be accessible.

Our model provides a predicted number of collisions between turbines and a local or migrating population of birds. It has the potential to be modified to accommodate Monte-Carlo simulation, although at its core it uses a deterministic approach. It is modular by design, and allows various customizations, depending upon the unique configuration of the wind facility and characteristics of the taxa modeled.

The initial calculation involves species-specific parameters for speed and size of birds and specifications of the turbine, including its dimensions and rotational speed of its blades. Using these parameters, we derive the mean area of turbine presented to a bird in flight. This allows the model to accommodate flight approaches from any potential direction. Alternatively, unidirectional flights can be modeled by using the relevant turbine surface area presented to birds approaching from a given direction.

Data for bird flights are collected at the wind-farm site according to a specific and consistent field methodology. These data are used to determine the flux (density) of bird flights. When combined with turbine specifications, this yields the probability of collision during a single flight–turbine interaction. The density flux approach has not been used for this application previously.

The number of movements at risk of collision with one turbine is then scaled according to a typical number of turbines that a bird might encounter in a given flight. This is further refined by a metric for the capacity of the particular species to avoid collisions. Where a population census or estimate is available for the number of birds that may be at risk, a further deduction is used to attribute the number of flights-at-risk to individuals, and hence provide a final model output as the number of individuals at risk of collisions. The ability to transform from flights-at-risk to individuals-at-risk has been uniquely developed and applied as a routine component of our model.

DESCRIPTION OF THE MODEL

The model requires data for input parameters and, using these, functions in a sequence of modules (Fig. 1).

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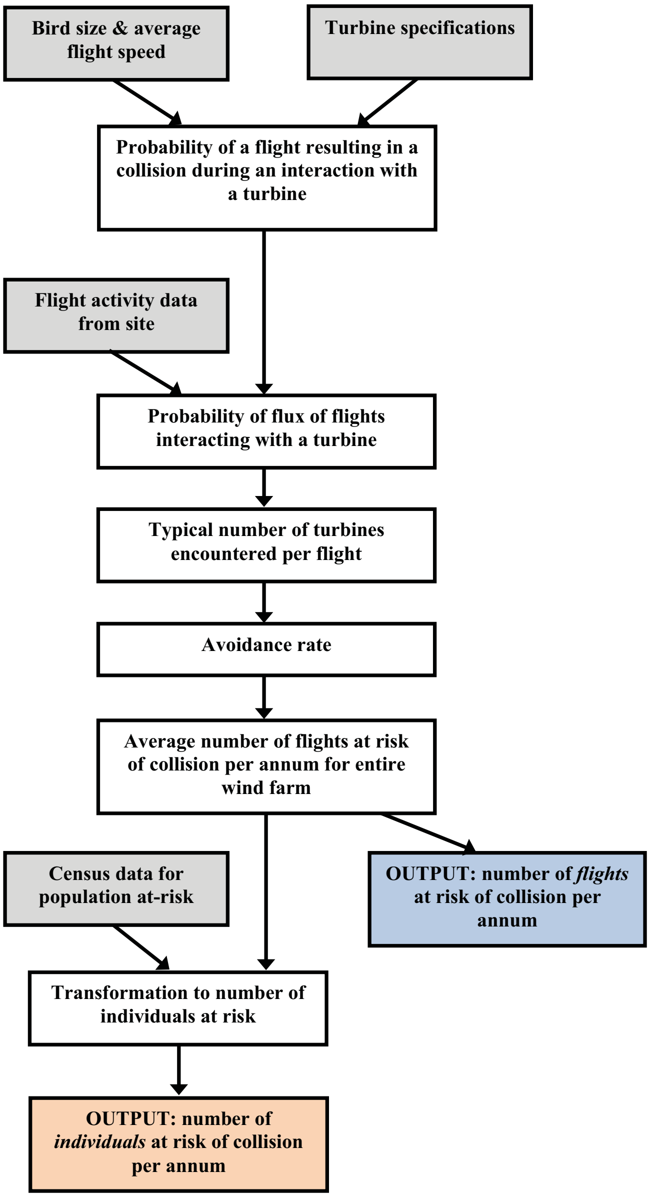

Figure 1. Overview of the collision risk model that quantifies risk to birds of colliding with wind turbines, showing input parameters (gray boxes), modules, and sequence.

Model Inputs

Turbine parameters.—The primary risk faced by a flying bird, whether it may strike or be struck by a turbine, is that the machine presents a potential obstacle in its path. Ultimately this equates to the surface area of the turbine presented to the bird from whatever its angle of approach. Other models, such as probably Band et al. (2007), use individualistic representations of birds. Our model uses a projection of the presented area onto all possible flight angles. For this reason, multiple dimensions of turbine components and rotor speed for the particular type of turbine are used as input values to the risk model. Turbine specifications are as provided by the machine's manufacturer.

The modeled wind turbine consists of 2 fundamental components representing potentially different risks. We refer to these as the static and dynamic components (Fig. 2). The static areas of a turbine include all surfaces of the entire machine comprising a tower, which in current turbines is a simple taper with known base and top diameters; a rectangular nacelle housing the generator; a hemi-spherical hub; and rotor blades that taper in 2 planes. The dynamic component is the area swept by the leading edges of rotor blades during the time that a bird would take to pass through the rotor-swept zone.

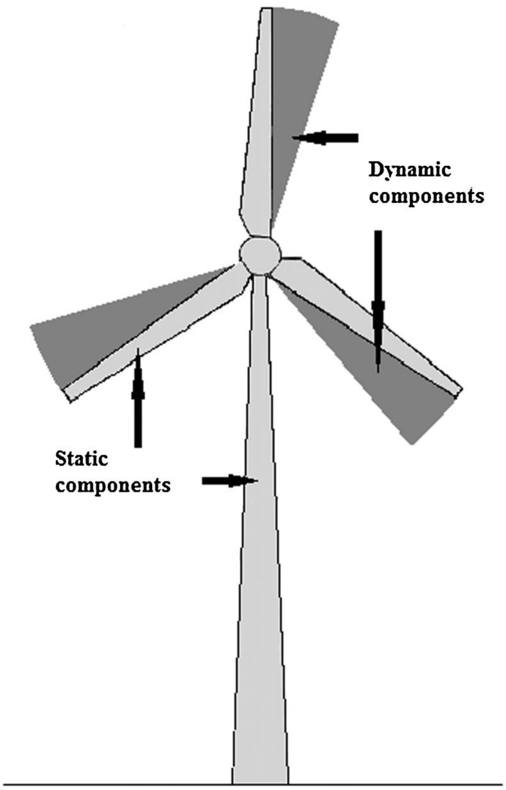

Figure 2. Schematic indication of the static and dynamic components of a wind turbine that may be encountered by a flying bird. The dynamic component is the area swept by rotor blades during the time that a bird of a particular species would take to pass through the rotor-swept zone.

Size and flight speed of birds.—For each taxon, the model requires values for the total length of the bird in flight, from bill tip to tip of the tail or outstretched legs, and the average speed of the species' flights. We obtained bird lengths either from museum specimens or from standard ornithological texts.

Accurate determinations of bird flight speeds can be complex and difficult to obtain (Videler 2005, Pennycuick 2008) and published data are not available for most species. However, published radar studies (e.g., Bruderer 1995, Bruderer and Boldt 2001) provide ranges of flight speeds for a variety of species, including congenerics with similar morphologies and ecological traits to a number of species we have assessed. Use of radar to collect bird flight data at the wind-farm site may provide flight speeds for species of interest. We consider that average ground speed (as opposed to air speed) is appropriate for modeling of multidirectional movements of birds.

Bird flight data.—The model requires data from the wind-farm site for the number of flights made by species of interest within a measured time and volume of airspace. Movement data may be obtained from fixed-time point counts using a methodology adapted from Reynolds et al. (1980), incorporating an effective detection range (Buckland et al. 1993). It may be collected by human observers or by using horizontal and vertical radar combined with call recording or visual species identification (e.g., Gauthreaux and Belser 2003, Desholm et al. 2006). Data represent the number of flights that birds make within a cylinder of airspace that is centered horizontally on the observer and the height of which is the maximum reached by rotor blades of the turbines. The data collection regime is designed with the aim of providing a representative sample of flight activity across the local range of diel, seasonal, and other environmental variables.

Model Modules

Probability of a single flight interacting with a turbine.—In some situations, such as during highly directional migratory passage, the presented area of turbines is determined from the angle of the birds' flight relative to the compass orientation of turbines. However, for the great majority of species (including temporary or permanent residents at an on-shore wind farm) this does not apply, and flights can be expected to approach turbines from any direction. For this situation, all dimensions of the turbine contribute to the area with which a flying bird might collide and the model uses a simple integration to determine a mean presented area. This represents a substantial advance over other collision risk models that depend on the assumption of a specific angle of approach as a bird encounters a turbine (e.g., Tucker 1996*a*, *b*; Bolker et al. 2006; Band et al. 2007).

We calculate the area presented by the static components of a turbine using a conservative assumption that none of them overlap or obscure any others. The area of each component is calculated individually, and these are then summed to determine a total static area for the turbine. Static areas are calculated from the simple length × width dimensions of all components visible by line of sight. These are then projected onto an arbitrary approach direction (effectively scaling by the cosine of the approach angle). For example, viewed directly from one side, only the side panel of the nacelle is visible. However, approached from 45° to the turbine, both the front and side panels are visible, and are thus scaled by $\cos(45)\varrho 1/\sqrt{2}$ to match that particular angle of view.

We calculate the dynamic area, swept during the movement of blades, from the dimensions of the stationary blades and the distance they travel at their average speed during the time taken by a bird to fly through the rotor-swept area. We assume that all flights involve forward movement, so the swept-area is derived from the length and speed of the particular species of bird, in combination with the thickness of the sweeping blade.

Each rotor blade is tapered in 2 planes. Thus the thickness of the blades, used to determine the time taken for a bird to cross through the swept area, is actually a function of the point in the rotor radius at which an individual bird's flight intersects the swept area. This presents a complication that we overcome by defining an effective blade, which is a simple rectangular cross-section that sweeps out precisely the same volume of space as the physical blade. In doing so, we calculate a constant thickness of blade that accounts for the fact that the thinner tips actually sweep far more space than the thicker base of the blade. This ensures also that our flux calculation is not compromised by introduction of a spatial variation at odds with other aspects of the model.

A further input parameter is the percentage of time per annum when rotors are not turning due to inappropriate wind speeds and routine turbine maintenance. Prior to commissioning of a wind farm, wind speed data are usually gathered and the expected percentage of downtime due to inappropriate wind speeds is determined. During downtime periods the rotor simply stops turning; and so risks associated with dynamic components only are reduced by this percentage of time, while all static components of the turbine remain as potential obstacles to flying birds.

Combining all presented areas of the turbine.—Modeling for multidirectional bird movements requires no dependence on approach angles nor on complexities of interactions between flight direction and wind direction. We thus reduce the turbine to its mean presented area. This is solved by the equation

$$\frac{1}{\pi}\int_{0}^{\pi} A(\theta)\,\mathrm{d}\theta$$

where A is the presented area of the turbine as a function of approach angle θ. We solve this numerically using a trapezoidal integrator (Press et al. 1992).

Probability of multiple flights interacting with a turbine.—Because counts of bird flights have been made across the wind-farm site and there is no obligatory relationship between point-count locations and particular sites proposed for turbines, we combine the data collected from all point counts. This provides a measure of flight activity, which is assumed to be constant across the site. Thus the field data reduce to a single ratio value for the subject species, which is the sum of all flights documented during all counts divided by the total time of observations. This equates to a maximum likelihood estimation of the mean of an assumed Poisson distribution.

To calculate a number of flights at risk of collision, we first reduce documented bird movements (M) to a measure of flux (F) using the equation

$$F = \frac{M}{T_{\mathrm{obs}} A_{\mathrm{obs}}}$$

where T_{obs} is the combined total time of all point counts and A_{obs} is the area of the vertical plane dissecting the observation cylinder. This flux is a measure of bird movements per time per square meter of vertical airspace. The third dimension, volume of airspace, is redundant (or tacit) due to the assumption that, unless involved in a collision, flight paths do not end arbitrarily in space.

We next multiply activity measure by the number of minutes in which the species is active during the 24-hour diel period, T, and the total presented area of the turbine, A. For year-round resident species, the "active minutes" are calculated for the entire year, while for seasonal or migratory species, they are calculated for the portion of the year that the species is present at the site. This then gives a measure of risk to the bird movements, $M_{\text{risk}} = \text{FTA}$.

Because the flight data are a measure of movements by the species in question and do not discriminate the number of individuals making the movements, the measure (M_{risk}) quantifies the total movements-at-risk for the species and does not reflect risk to individual birds.

To determine a risk rate from total of recorded movements-at-risk, it is necessary to extrapolate to a total number of expected bird movements per annum, M_{yearly}. We calculate this from the flight data, extrapolating the movements to a yearly total through the equation

$$M_{\text{yearly}} = M \frac{T_{\text{yearly}}}{T_{\text{obs}}}$$

We then deduce a probability of flights at risk of collision as $M_{\text{risk}}/M_{\text{yearly}}$. Note that T_{year} is the total time in a year, and not the diel activity period of the species, which has already been factored into the calculation of movements at risk.

The resultant value is now a probability of flights being at risk of collision with a single turbine. To this point, no account is taken of the bird's own ability to avert a collision. This is modified later through use of an avoidance factor.

Estimating number of turbines encountered per flight.—Every turbine is presumed to represent some risk for birds, so the total number of turbines proposed for the wind farm is an input to the model. Turbine layout of modern wind farms is primarily determined by the wind resource and turbines are micro-sited accordingly. Consequently, the machines are usually scattered on the landscape. Older wind farms had turbines arrayed in rows, and occasional modern facilities may be linear where they follow a single topographic feature.

To account for the number of turbines with which a single flight might interact, it would be necessary either to know precisely the route of every flight or to make informed assumptions about flight paths. The manner in which turbines are arrayed in the landscape is important to ascertain a typical number of turbines that a bird might encounter in a given flight. This number differs according to whether turbines are in a scattered array or a single row, and these require different calculations.

For a row of turbines, the likely number of encounters can be visualized by considering a row of N turbines in plan view and a flight path at angle Φ to the row. A flight directly along the line of turbines (Φ') will interact with all N turbines. As the angle of flight relative to the row increases toward 90°, flight paths have potential to interact with fewer turbines until an angle (Φ'') is reached at which the path has potential to interact with a maximum of one turbine.

For a single row of turbines, we define the piecewise smooth function, which gives the number of turbines for a given angle of crossing with,

$$n_{\text{interaction}} = \begin{cases} N, & \text{if } \theta \leq \phi' \\ \cot(\theta), & \text{if } \phi' < \theta \leq \phi'' \\ 1, & \text{if } \phi'' < \theta \leq \frac{\pi}{2} \end{cases}$$

This gives us an expected number of interactions as

$$\langle n_{\text{interaction}} \rangle = \frac{2}{\pi} \left[N \arctan\left(\frac{1}{N}\right) + \frac{\pi}{4} - \ln\left(\sqrt{2}\sin\left(\arctan\left(\frac{1}{N}\right)\right)\right)\right]$$

For scattered turbine arrays it is not realistic to assume that a bird will encounter all turbines in the wind farm in a given flight. We assume each flight has potential to cross between any 2 points on the outer edges of the farm. Given the size of most on-shore wind farms, this is a reasonable assumption for typical species of concern, such as raptors. When multiple flight paths are drawn randomly across the plan view of a wind farm, some paths may be circuitous and have potential to encounter many turbines, while others will pass through a small portion of the site and have potential to encounter relatively few turbines.

To deduce an average number of turbines likely to be encountered by any flight we use a topological, non-affine mapping technique. This spatial transformation can be illustrated as follows: if we were to throw a lasso around the perimeter of the site and shorten it to its minimum, we would find that all the turbines had collected in a circle. A straight flight path through this "lassoed" site is mathematically equivalent to a random walk across the unconstrained layout. The average of all flight paths crossing the center of this remapped farm will intersect with $\sqrt{N}$ turbines (where N is the total no. of turbines in the wind farm). This value is used in the model for the number of turbines that might be encountered per flight within a scattered turbine array.

For arrays that are neither entirely scattered nor linear, the model employs a simple weighted average of the values for fully scattered and entirely linear arrays.

Application of turbine avoidance capacity.—Birds have substantial ability to avoid obstacles; therefore, it is necessary to incorporate this capacity into the model. In common with other workers (Percival et al. 1999), we use "avoidance" in specific reference to behavior on the part of a bird that averts a potential collision with a turbine. The "avoidance rate" equates to the proportion of flights that might otherwise have involved interaction with a turbine but where the bird alters course and the flight does not result in a collision. For the purposes of the model it is of no consequence whether or not this is a result of a cognitive response by the bird to the presence of the turbine.

Turbine avoidance remains little-studied for any species, and empirical information about actual avoidance can be obtained for a given site only by studying the responses of birds in the presence of operational turbines (Chamberlain et al. 2006). One recent investigation has compared flight behaviors of 2 species of eagles in the presence of turbines at

2 operating wind farms with their behaviors at a site without turbines (Hull and Muir 2013).

Avoidance rate is incorporated into the model by scaling the movements at risk by $(1 - v)$, where v is a measure of the bird's ability to avoid objects. In this scenario, $v = 0$ corresponds to a blind, non-responsive projectile, and $v = 1$ represents a perfectly responsive bird able to avoid any object.

A novel feature of our model is its capacity to apply different avoidance values to the static and dynamic portions of a turbine. As noted by Martin (2011), birds are known to collide with both stationary and moving parts of turbines. This aspect of our model allows for differences in capacity of birds to detect and avoid the large, static components of modern turbines relative to their capacity to detect and avoid the small and fast-moving leading edges of rotor blades.

Size of population at risk.—When information about the size of the population at-risk is available, this can be factored directly into our model to provide results in the form of an expected number of individuals at risk of collision per annum. This is an important consideration because an input measured in terms of bird movements cannot provide an output in terms of individual birds. This aspect appears to have been largely overlooked by other workers, although Chamberlain et al. (2006) alluded to the use of a number of flights only, without incorporation of the number of individuals, as a potential issue in evaluation of collision estimates provided by the Band model (Band et al. 2007).

To deduce a predicted number of individual birds that are at risk of collision, a valid estimate is required of the number of individuals that may interact with turbines at the wind farm in the course of a year. If it is not feasible to obtain this for a species, then the output of the collision risk model will necessarily be the number of flights-at-risk per annum. Although this metric is not predictive of the number of individuals that might collide, it permits risk to be compared for various designs of a wind farm or between one facility and another. In rare cases, such as where there is a single migration passage through the site per annum, the number of movements may equate with the number of individual birds that are at risk. The great majority of risk modeling we have undertaken has been for raptors that are year-round residents. Due to their territoriality and relatively low densities, our studies at wind-farm sites have been able to ascertain the number of individuals using a site per annum, including both resident adults and juveniles, with a high level of confidence. For some other species, such as cranes (Gruidae), we have undertaken home-range studies to determine numbers present during the breeding season, and we have obtained local census data to estimate numbers of individuals that might encounter turbines during non-breeding seasons.

Given a population estimate, the number of flights at risk is attributed equally to the relevant number of individuals through the simple relation $M_{\text{individuals}} = \text{Yearly Movements}/\text{Population}$. We can then attribute individual mortality through

$$\text{mortality} = \text{Population}\left(1 - \frac{\text{Movements At Risk}}{\text{Yearly Movements}}\right)^{M_{\text{individuals}}}$$

MODEL VALIDATION

The model we describe here has been used to assess potential turbine collision risk for numerous species of birds for 23 commercial-scale wind farms proposed in Australia and one in Fiji. Eleven of these facilities have subsequently been built and are now operational. The model's projections have been used by regulatory authorities in determination of approval or modification to wind-farm designs for a range of species of concern. These include taxa as diverse as the orange-bellied parrot (*Neophema chrysogaster*), wedge-tailed eagle (*Aquila audax*), brolga (*Grus rubicunda*), and the large and readily observable Pacific fruit-bat (*Pteropus tonganus*) in Fiji.

The model's performance can be validated only when it can be compared with post-construction mortality data that are sufficient to permit calculation of an actual annual mortality rate and a 95% confidence interval for that rate. Conditions of regulatory approval for most wind farms that have been built to-date in Australia have varied considerably between state jurisdictions and over time. Generally they have not required rigorous investigation or public reporting of avian collisions that occur during operation. We have thus had limited opportunity to validate our model against empirical information for actual collisions. However, where these are available, we can compare the model's predicted average estimates with the measured confidence interval for actual mortalities to assess its predictive capacity. We present one such case study below.

Comparing the Model's Predictions With Empirical Data—A Case History

Substantial investigations have been undertaken at Bluff Point and Studland Bay wind farms in northwestern Tasmania entailing a number of studies of wedge-tailed eagle and white-bellied sea-eagle (*Haliaeetus leucogaster*). These have included utilization surveys designed to measure eagle activity before and after development of the wind farm; collision monitoring; eagle breeding success; eagle behaviors and movements relative to turbines and observers; and investigations and trials aimed at reduction of collisions (Hull et al. 2013). Commissioning of turbines began at Bluff Point Wind Farm in 2002 and at Studland Bay Wind Farm in 2007. Bluff Point Wind Farm consisted of 37 Vestas V66 turbines in a scattered array on an area of 1,524 ha. Studland Bay Wind Farm was situated 3 km south of Bluff Point and comprised 25 Vesta V90 turbines in a scattered array over an area of 1,410 ha. Both wind farms were close to the coast of northwestern Tasmania and resident white-bellied sea-eagles and Tasmanian subspecies of wedge-tailed eagle (*A. a. fleayi*) occurred at both sites.

Monitoring Eagle Flights

Movement data for both species were collected during point counts at Bluff Point Wind Farm site in 3 years prior to construction of turbines and in 4 years after they commenced operating. At Studland Bay, they were collected in 6 years prior to turbine construction and in 3 years after turbines commenced operation. As prescribed by regulatory authorities, point counts were undertaken in the austral autumn and spring. Ten replicate point counts were made in each season at 18 locations per wind farm. There were 545 point counts undertaken at Bluff Point between 1999 and 2007 and 854 point counts at Studland Bay between 1999 and 2009.

Collision Risk Model Results

We used the model to estimate risk based on movement data collected prior to construction for populations of 6 wedge-tailed eagles and 4 white-bellied sea-eagles at-risk per annum at each of the 2 wind farms.

State regulatory authorities have required that the collision risk model be re-run with the accumulated sum of eagle movement data obtained during the entire period of both pre-construction and operation of the 2 wind farms spanning the period from 1999 to 2009 (Table 1). We modeled static avoidance rate at 99% in all cases.

Documented Eagle Collisions

Carcass monitoring surveys were conducted at the Bluff Point and Studland Bay wind farms since they commenced operating. Fences to exclude mammalian scavengers were maintained at 27% of turbines across the 2 sites. All turbines, both fenced and unfenced, were searched routinely within a 100-m radius of the tower base. Search frequency was initially informed by trials to determine rates of loss to scavengers and of observers' capacity to detect carcasses. Since 2007, searches were carried out twice weekly during periods that may have represented higher risk to the species (i.e., eagle display period Jun–Aug, inclusive; and eagle fledging period mid-Dec–Feb, inclusive) and fortnightly outside these periods (Hull et al. 2013). Assessment of the extent of undetected eagle collisions (Hydro Tasmania 2012; Hull et al. 2013) concluded that it is unlikely that significant numbers of eagle carcasses were missed because they are conspicuous; the search zone around turbines was adequate to detect eagle carcasses where they will fall after colliding with turbines (Hull and Muir 2010); personnel on site had capacity to detect carcasses that may have been moved from the formal search zones; eagle carcasses in vegetation were found not to decompose readily and, even when scavenged, remains were identifiable; avian scavengers did not remove all evidence of carcasses and, although mammalian scavengers could remove carcasses, this was controlled at the subset of fenced turbines; survey intensity was informed by predetermined scavenger removal rates; and, although a small number of eagles survived collision with a turbine, in all documented cases such birds were unable to fly and are likely to have been detected because both scavenger exclusion and farm fences prevented them from leaving the site.

Table 1. Modeled mean annual turbine collision estimates for 2 eagle species based on movement data collected over the span of pre-construction and operation of 2 wind farms in northwestern Tasmania, Australia, from 1999 to 2009. Estimates are shown for 4 potential dynamic avoidance rates. Static avoidance rate was modeled at 99% in all cases

	White-bellied sea-eagle		Wedge-tailed eagle	
Dynamic avoidance rate (%)	**Bluff Point**	**Studland Bay**	**Bluff Point**	**Studland Bay**
90	0.9	0.8	2.7	1.9
95	0.5	0.4	1.5	1.1
98	0.2	0.2	0.7	0.5
99	0.1	0.1	0.4	0.3

Comparison of Collision Risk Model Estimates With Actual Mortality Rates

Given constraints of statistically low collision numbers, the model's estimates of annual collisions, based on the combined total of movement data from pre-construction and operation of the 2 wind farms from 1999 until 2009 (Table 1), compare well with actual mortality of the 2 eagle species at both wind farms (Table 2). The model's estimate of the number of wedge-tailed eagle collisions per annum at Bluff Point at a 95% avoidance rate was 1.5, which is the same as the mean number of documented mortalities per annum. Estimates provided for this case by model iterations for 90% and 95% avoidance rates fell within the 95% confidence interval of measured mortality rates. The model's estimates for number of collisions at a 95% avoidance rate for white-bellied sea-eagles at Bluff Point (0.5) and for wedge-tailed eagles at Studland Bay (1.1; Table 1) also closely approximated the mean numbers of documented mortalities per annum for the 2 species (0.4 and 1.0, respectively; Table 2). For those cases, the model's estimates for the range of avoidance rates between 90% and 99% fell within the 95% confidence interval of measured mortality rates. No white-bellied sea-eagle collisions have yet been reported from Studland Bay so, to date, the model's estimates are higher than actual experience for that species there.

MANAGEMENT IMPLICATIONS

We consider that there are 2 different, although not mutually exclusive, applications for modeling of bird collision risks at prospective wind farms. These are to provide projections of long-term effects of a particular wind-energy facility on key bird species; and to determine relative risks for key species that are associated with different wind-farm sites, different portions of large wind farms, and different types of turbines and/or turbine configurations.

In many respects, we consider the latter use of collision risk modeling is the most important contribution it offers. This application provides a tool for planning of wind farms to avoid, reduce, or mitigate potential risks to birds. The model we describe here has now been used in such an iterative manner for a number of prospective sites to evaluate relative risks to key species posed by different types, sizes, numbers, and layouts of turbines.

The integration in our model of data for numbers of bird flights with numbers of birds in the population at-risk is key to the accurate prediction of potential numbers of collisions. This aspect appears not to have been adequately considered previously but has real implications to the appropriate determination of actual risks posed by a wind farm. Our model's use of bird flight data to determine annual flux of movements; a mathematical solution to the typical number of turbines that might be encountered in a bird flight; capacity to assess wind-farm configurations ranging from turbines scattered in the landscape to linear rows of turbines; and the option of assigning different avoidance rates to components

Table 2. Average annual mortality rate and variance for 2 eagle species based on carcasses detected at 2 wind farms in northwestern Tasmania, Australia

	White-bellied sea-eagle		Wedge-tailed eagle	
Wind farm	**Mean annual mortality**	**Annual variance (95% CI)**	**Mean annual mortality**	**Annual variance (95% CI)**
Bluff Point 2002–2012	0.4	0.1–1.0	1.5	0.8–2.6
Studland Bay 2007–2012	0.0	0.0–0.7	1.0	0.3–2.2

of turbines that pose more or less risk, all represent refinements designed to improve the predictive capacity of turbine collision risk modeling.

In the cases outlined here, where long-term mortality data sets have permitted validation of the model's collision estimates at given avoidance rates, the two have closely approximated each other. We will seek further opportunities to compare the results of our model with empirical mortality information from operating wind farms, with a view to wider application of the model.

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The model described here is the property of Biosis Propriety Limited, an environmental consultancy business incorporated in Australia. It is used commercially by Biosis Propriety Limited.

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