Performance of the Biosis wind turbine avian collision risk model evaluated for two species of Australian eagles

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Introduction

A number of avian collision risk models are used internationally to provide forecasts of the potential for various species of birds to collide with wind turbines. Their principal application has been to inform impact assessment as a component of regulatory consent processes for proposed wind energy projects.

While it is difficult to determine the frequency of bird collisions at offshore wind farms because it is not possible to search for bird carcasses as is traditionally done at onshore facilities, validation is feasible at terrestrial wind farms. Nonetheless, few pre-consent projections of avian turbine collision risk models used for onshore wind farms have been validated by comparing them with empirical experience of operational wind farms (Masden and Cook 2016). Since validation of that kind is the real test of the performance of models, it is important that the pre-operational projections of models are compared with subsequent experience at operational wind farms. The nature of mathematical models lends them to refinement based on appropriate validation.

The general lack of model validation seems to result from a regulatory context in many jurisdictions whereby collision risk modelling is undertaken as a prerequisite to a consent decision, but once consent has been granted little further consideration is given to its estimates. However, it is also the case that a variety of factors present significant constraints on the capacity to accurately determine the total numbers of collisions that occur at operational wind farms for almost all species (see *Pre-requisites to validation*, below) and this can make it difficult to validate the forecasts of collision risk modelling.

One evaluation exercise undertaken across 46 small wind farms in Germany (Grünkorn et al. 2017) concluded that the Band model (Scottish Natural Heritage 2010a; b) substantially underestimated real numbers of fatalities for various species. In that study bird activity data was collected during operation of the wind farms rather than prior to construction and it is not apparent whether that may have influenced results.

The Biosis avian collision risk model was developed in the early 2000s when commercial-scale wind energy was in its infancy in Australia. The model has been used to provide quantified assessment of the potential for various species of birds to collide with wind turbines for multiple proposed wind energy facilities since then.

Performance of the model can be evaluated only by comparing its forecasts of bird collision rates (generally prepared prior to wind farm construction) with rates experienced during the operation of wind farms. The latter requires post-construction mortality data of sufficient quality and quantity to permit estimation of annual mortality rate with high precision (see *Pre-requisites to validation*, below).

Background to turbine collision risk modelling

Quantitative modelling to estimate the number of collision mortalities of threatened birds is widely used as part of environmental impact assessments for proposed wind energy facilities (Huppop et al. 2006, Masden & Cook 2016, Smales 2017, Cook & Masden 2019).

Modelling of avian collision risk with wind turbines provides results measured as forecasts of the per annum average number of individual birds that may collide with turbines at a proposed wind energy facility. The forecasts are usually of very low numbers and, by the application of a range of avoidance rates (see below), a range of results is routinely provided. Frequently this range is quite narrow and, as in the examples set out here, is for an impact of within one or two individuals per annum. To the best of our knowledge, no other form of environmental impact assessment for fauna in Australia requires forecasts with this level of precision for the number of individual animals that may be impacted by a proposed action.

A modelling approach to collision risk allows the incorporation of uncertainties. These relate to imperfect knowledge about the behaviours of birds in the presence of a proposed wind farm. All modelling of this type entails the use of assumptions, but the use of a mathematical modelling approach for avian collision risk requires that necessary assumptions are based on available empirical information. Hence, collision risk is best modelled only for species for which empirical data about their flight activity has been obtained from the site of a proposed wind farm, ideally during a period sufficient to encompass a range of seasonal and other environmental conditions.

Mathematical modelling of risk is intended to provide an articulated and replicable evaluation of what may occur in the real world. The rationale behind predictions is explicitly stated in the mathematics of the model, which means that the logical consistency of the predictions can be evaluated. The explicit nature of inputs and rigour entailed in modelling means that the process is replicable, consistent and open to analysis, criticism or modification when new information becomes available. Although it is necessary to include some assumptions and arbitrary choices when deciding on the structure and parameters of a model, these choices are explicit.

Collision risk modelling incorporates multiple variables and uses specifications of the wind farm and of turbines, along with values for size and speed of particular species, and data for flight heights and flight frequency collected during dedicated investigations at the site. The outputs of the model are numerical estimates of the rates of annual mortalities of relevant species of birds due to turbine collisions.

The modelling process uses data specific to particular turbines and relevant species of birds recorded at the wind farm site. Bird flight data represent a sample of the flight activity of particular species measured against time and airspace. In subsequent collision risk modelling, the sample of bird flights obtained from the site are extrapolated to provide per annum rates of flights that might interact with the total number of turbines proposed for the wind farm.

Avoidance rates

Avoidance rate is the capacity for a bird to avoid a collision (Cook et al. 2014), whether that occurs due to a cognitive response on the part of a bird or by chance (Martin 2011).

Birds are generally adept at avoiding obstacles within their flight space but the capacity of a bird to avoid a collision is clearly an important element in consideration of this risk. 'Avoidance' is recognised at different spatial scales. The best definitions of these are provided by Cook et al. (2014) and are summarised as follows: (1) macro-avoidance occurs when a bird responds to the presence of an entire wind farm by flying around or over it; (2) meso-avoidance refers to the response in which birds fly within the overall wind farm but avoid collisions by choosing to fly only in the airspace between turbines, or in the space below rotor-sweep; and (3) micro-avoidance happens when a bird, flying in close proximity to a turbine and that is otherwise on a collision course, does not in fact collide with the turbine. These were illustrated by Smales (2017) and are reproduced here as Figure 1.

Macro-avoidance is a simple measure of displacement of birds from the area occupied by an operational wind farm. Micro-avoidance may include cognitive behaviour in which a bird becomes aware of danger and takes evasive action, or simple chance resulting in inadvertent safe passage between turbine blades. Data for bird flight activity is collected at the site of a proposed wind farm in the absence of any turbines and thus without any avoidance. For this reason, avoidance rates applied in risk modelling must encompass the potential for avoidance at all three spatial scales.

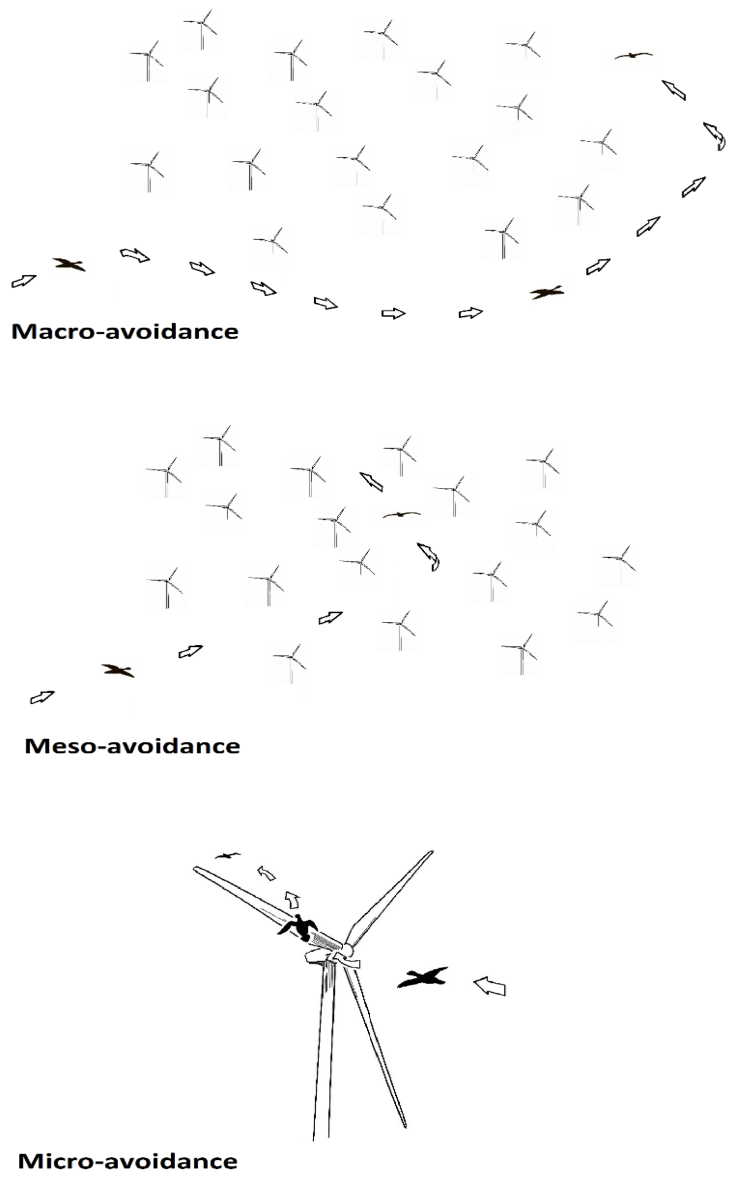

Figure 1 Three spatial scales at which avoidance of collision may occur (Smales 2017).

An avoidance parameter is incorporated into the collision risk model by scaling the number of movements at risk by (1 – v), where perfect avoidance capacity equates to 1.0, and v is a measure of the rate at which birds avoid turbines. Thus, an avoidance rate of 0.90 equates to one flight in 10 in which a bird does not avoid a turbine; an avoidance rate of 0.98 equates to one flight in 50 in which a bird does not avoid a turbine, and an avoidance rate of 0.99 equates to one flight in 100 in which a bird does not avoid a turbine.

Ideally, empirical data from observational investigations of birds flying within an operating wind farm would provide 'real' rates at which birds avoid turbine collisions at the various spatial scales. However, as discussed by various authors (Chamberlain et al. 2006; Madders & Whitfield 2006; Cook et al. 2012, Smales 2017), it has proven difficult to obtain empirical data for actual turbine avoidance rates from observational studies. At least in part, this is because, while human observers very rarely document collisions, they experience difficulty in determining the precise flight path of a bird and whether it is actually on a potential collision course, and hence whether avoidance of any kind was involved when no collision occurs.

Owing to the difficulties associated with observational studies of avoidance, avoidance rates have usually been determined not from direct observations of the behaviour of birds within a wind farm, but by an indirect derivation in which an 'avoidance rate' is calculated from the difference between the collision rate projections of a model and the number of fatalities that actually occur (Whitfield 2009; Band 2012; Cook et al. 2012, 2014; Grünkorn et al. 2017; Smales 2017). That is: avoidance rate = 1 – (actual deaths/predicted deaths assuming no avoidance). This approach has a number of problems. Estimation of the total number of deaths at onshore wind farms is based on the number of collision carcasses detected during a search regime, and accounting for carcasses missed by searchers and lost to scavengers. While methods to account for searcher efficiency and carcass persistence have improved (e.g. Huso et al. 2017), the process most often results in mortality estimates with very large confidence intervals. As a consequence, a derived avoidance rate will be imprecise. In addition, the simple difference between the number of fatalities predicted and those experienced may include multiple factors other than avoidance and will also encompass any error in the model (Whitfield 2009; Hull & Muir 2013; Cook et al. 2014; Grünkorn et al. 2017; Smales 2017).

Some advances have been made recently in efforts to obtain empirical data for actual collisions (e.g. Coppack et al. 2015; Cullinan et al. 2015; Larkin 2015; Perrow et al. 2015; Skov et al. 2018). Such studies describe methods using technologies such as fixed pencil-beam radar in combination with an infrared-sensitive camera system, automated thermal imaging, multidimensional radar and Global Positioning System (GPS) boat-based tracking to detect and record collisions and birds' avoidance of collisions at offshore wind farms. While similar technologies have begun to be applied at a few onshore Australian wind farms to achieve targeted curtailment of turbines when a bird is detected in close proximity to a turbine, they have not been applied to ascertain avoidance rates.

In the Biosis model, the turbine is decomposed into its static and dynamic components. The entire turbine (including the tower, nacelle and the rotor when stationary) represents the static component. The dynamic component is the volume swept by the leading edge of the rotor blades in the time it takes a bird of a given length and flight speed to pass across the depth of the rotor-swept disk. Static components (i.e. the stationary turbine) are considered to pose minimal collision risk as they are very likely to be seen and avoided by birds in flight. The dynamic component of the sweeping rotor blades is considered to represent higher risk due to their speed and the likely difficulty of a bird in flight avoiding them. The model takes the two elements into account by allocating different avoidance rates to them.

Model result metrics

Collision risk results are projections extrapolated from the sampled rates of flight activity of a particular species. With the incorporation of a site population estimate, the model's results are expressed as the average number of potential collisions by individual birds that may occur per annum for the various modelled avoidance rates.

Results are shown to one or more decimal places as per original modelling. This is done for the purposes of indicating differences between results rather than to indicate precision in the results.

The model is necessarily deterministic, but it is important to note that if collisions occur at the operational wind farm their numbers can be expected to vary around a long-term mean for any species.

At present, there are no avoidance rates obtained from empirical studies available for any species of Australian bird. For this reason, results of the Biosis collision risk model are routinely provided for a range of dynamic avoidance rates, often from 0.90 or 0.95 to 0.99.

Model validation

Pre-requisites to validation

Performance of the model can be evaluated only by comparing its forecasts of bird collision rates (generally prepared prior to wind farm construction) with rates experienced during operation of the wind farm. The latter requires post-construction mortality data that is sufficient to permit calculation of a quite precise annual mortality rate. Conditions of regulatory approval for most wind farms that have been built to-date in Australia have varied considerably within and between State jurisdictions and over time. While post-construction monitoring of bird collisions with wind turbines and periodic estimation of total strike rates have been regulatory conditions of approval for many wind energy projects, there has been no standard methodology for these (Moloney et al. 2019) and the consequent variation in reported results has hampered capacity to validate forecasts of the model.

Post-construction monitoring of bird mortalities is a sampling exercise and it is always likely that only a portion of the total number of collision victims will be detected even by well-designed and effective regimes of carcass searches. Factors influencing this include the rate at which carcasses disappear due to scavengers or natural decay; the capacity of searchers to find carcasses; the interval between regular searches and, the portion of the turbine array which is searched. Estimates of total mortality, based on the number of carcasses detected, take account of these additional factors but all of them encompass uncertainty. Worldwide evidence indicates that bird collisions with wind turbines are relatively rare events and for any given species, the number of carcasses detected is most often very low. For each of 56 species of birds, Moloney et al. (2019) document a mode of just 1 fatality detected during monitoring of a combined total 15 wind farms, each of which was monitored for between 2 and 3.5 years. As a consequence, estimates of total collision mortality for birds most often have confidence intervals that may be orders of magnitude greater than the number of carcasses detected. Another consequence of low numbers of collisions is that annual averages of fatalities are prone to significant influence of inter-annual variability (Huso et al. 2017; Moloney et al. 2019).

For these reasons, the ideal species to use in evaluation of the model’s performance will be one that has the following characteristics:

- is not favoured by scavengers so that carcasses are likely to persist and be found
- is readily detected by searchers
- has a relatively high collision rate

These characteristics provide data allowing for greater confidence when the number of carcasses detected is used as the basis for calculating an estimate of total collision fatalities.

A recent study of bird carcass persistence at Yaloak South wind farm in southern Victoria (Elmoby Ecology Bennett 2019; 2020; 2021) placed multiple bird carcasses over a period spanning four years and used remote cameras to monitor their persistence. The study included a total of 24 Wedge-tailed Eagle *Aquila audax* carcasses that were monitored until no evidence of the carcasses remained. This was the first substantial investigation using eagle carcasses in Australia.

The study found that Wedge-tailed Eagle carcasses had a mean persistence time of 260 days with a 95% confidence interval of between 119 and 567 days, whereas for all small and medium-sized birds (including some small raptors) mean persistence time was 2.8 days with a 95% confidence interval of between 2 and 4 days.

It was found that the Red Foxes *Vulpes vulpes*, the principal scavenger of bird carcasses at the site, ignored Wedge-tailed Eagle carcasses. The one potential scavenger detected was other Wedge-tailed Eagles, however they did not remove carcasses, which substantially remained in place (E. Bennett pers. comm.). The Elmoby Ecology Bennett reports conclude that there was a high level of confidence that all Wedge-tailed Eagles killed by collision with wind turbines were found and thus that the number of eagles detected were highly likely to reflect the total number of collisions by the species. A similar conclusion was previously drawn for Wedge-tailed Eagle collisions at Bluff Point and Studland Bay wind farms in Tasmania (Hydro Tasmania 2013; Hull et al. 2013) (see below), albeit it without the corroborating evidence from carcass persistence trials using eagles. At those two wind farms scavenger-exclusion fences were in place around a radius of a subset of turbines and they prevented removal of collision carcasses by mammals such as Tasmanian Devils *Sarcophilus harrisii*.

The Wedge-tailed Eagle is one of a very small number of species that experience a relatively high turbine collision rate. Moloney et al (2019) document a total of 58 Wedge-tailed Eagles found during carcass searches at 15 wind farms that were each monitored for between 2 and 3.5 years.

Wedge-tailed Eagles maintain large territories and, by comparison with many other bird species, occur at low densities. These factors along with their flight behaviour and the capacity to readily distinguish adults from younger birds, makes it relatively straightforward to estimate with good precision the number of Wedge-tailed Eagles utilising a wind farm site. The ability to make such an estimate is a key requirement allowing the Biosis model to provide an output in terms of the number of individuals at risk per annum.

No displacement of eagles is apparent at any operational wind farm studied in Australia and it thus appears that macro-avoidance does not have an influence on collision risk for eagles here.

All of these aspects serve to make the Wedge-tailed Eagle a good species for use in validation of the Biosis collision risk model. For the reasons set out above, estimates of total mortalities for the species (by others) are considered to closely equate to the numbers of carcasses detected and to have small 95% confidence intervals. This means that comparisons of model projections and actual mortalities described below, allow avoidance rates to be derived with a high degree of confidence.

Comparing the model's predictions with empirical data – case histories

The Biosis model has been used to provide projections of potential collisions by Wedge-tailed Eagles and/or White-bellied Sea-eagles *Haliaeetus leucogaster* as part of environmental impact assessments for the following projects:

- Codrington Wind Farm, Victoria
- Bluff Point Wind Farm, Tasmania
- Studland Bay Wind Farm, Tasmania
- Yaloak Wind Farm, Victoria
- Yaloak South Wind Farm, Victoria
- Musselroe Wind Farm, Tasmania
- Cattle Hill Wind Farm, Tasmania
- Low Head Wind Farm, Tasmania
- Kentbruck Wind Farm, Victoria

Codrington, Bluff Point, Studland Bay, Yaloak South, Musselore and Cattle Hill wind farms have all been operational for a number of years. Codrington was the first commercial scale wind farm built in Australia. Carcass searches were undertaken there under seven turbines for just seven months. No eagle carcasses were found. Yaloak Wind Farm did not proceed as proposed but was replaced by the smaller Yaloak South Wind Farm. Collision risk modelling for Cattle Hill Wind Farm was undertaken for a proposal with more than twice the number of turbines that were subsequently installed. Cattle Hill also operates a successful automated system to detect either species of eagle and curtail turbines whilst an eagle is within a predetermined proximity of a turbine (Goldwind 2022). This system facility was not envisaged at the time of the modelling. As a consequence of the differences between the proposed and actual wind farm, the model results were for a greater number of eagle mortalities than have been reported from the operational wind farm. Low Head Wind Farm is not yet operational and planning processes for Kentbruck are in process at the time of writing.

The Biosis model was used to provide projections of potential collisions by Wedge-tailed Eagles for four of these wind farms where intensive carcass searching was subsequently undertaken and for which results are publicly available. They are Bluff Point, Studland Bay, Musselroe and Yaloak South wind farms. At the first three of these, White-bellied Sea-eagles were also resident and modelling was also provided for that species and mortality results for it are also published. We consider it is likely that the factors that make the

Wedge-tailed Eagle particularly suitable for use in validation of the model apply equally to the White-bellied Sea-eagle and the following case examples provide details for both species.

Eagle flight activity data was collected by Biosis prior to wind farm construction at Bluff Point, Studland Bay and Musselroe wind farms. At Yaloak South Wind Farm, eagle flight activity data was collected by others during 2006. Biosis collected additional data in 2009 and 2010. In all cases Biosis prepared the collision risk modelling. Carcass searches during the operation of the wind farms were undertaken by other parties in all cases.

Data for the results of carcass searches for eagles were provided by wind farm operators and/or consultant reports prepared by those parties.

Bluff Point and Studland Bay wind farms

Substantial investigations of the Tasmanian subspecies of Wedge-tailed Eagle *Aquila audax fleayi* and White-bellied Sea-eagle have been undertaken at Bluff Point and Studland Bay Wind Farms operated by Woolnorth Renewables in north-western Tasmania. These included utilisation surveys designed to measure eagle activity before and after development of the wind farm; collision carcass monitoring; eagle breeding success; and eagle behaviours and movements relative to turbines. Details of design and outcomes of these are provided in annual environmental performance reports prepared by Woolnorth Renewables and its predecessors. Hull et al. (2013) detail a specific study of eagle behaviour during early years of the operation of the two wind farms. Commissioning of turbines began at Bluff Point Wind Farm in 2002 and at Studland Bay Wind Farm in 2007. Bluff Point Wind Farm consists of 37 Vestas V66 turbines in a scattered array on an area of 1,524 ha. Studland Bay Wind Farm is situated 3 km south of Bluff Point and comprises 25 Vesta V90 turbines in a scattered array over an area of 1,410 ha. Both wind farms are close to the coast and both species are resident at both sites.

Monitoring eagle flights

Flight activity data for both species were collected during 20-minute point counts at Bluff Point Wind Farm site during three years prior to construction of turbines and in four years after they commenced operating. At Studland Bay, they were collected in six years prior to turbine construction and in three years after turbines commenced operation. As prescribed by regulatory authorities, point counts were undertaken in autumn and spring. Ten replicate point counts were made in each season at each of 18 locations within each 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

The model was used to estimate risk for populations of six Wedge-tailed Eagles and four White-bellied Sea-eagles at each of the two wind farms.

State regulatory authorities 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 two of the two wind farms spanning the period from 1999 to 2009 (Table 1). As the numbers of eagles using the sites were not apparently affected, it was reasonable to pool the data from both periods. Static avoidance was modelled at a rate of 0.99 in all cases and dynamic avoidance at 0.90; 0.95; 0.98 and 0.99 (Biosis Research 2008, 2010; Smales et al. 2013). The model results are shown in Table 1.

Table 1. Modelled mean annual turbine collision estimates for White-bellied Sea-eagle and Wedge-tailed Eagle at Bluff Point and Studland Bay Wind Farms for four avoidance rates.

	White-bellied Sea-eagle		Wedge-tailed Eagle	
Avoidance rate	Bluff Point	Studland Bay	Bluff Point	Studland Bay
0.90	0.9	0.8	2.7	1.9
0.95	0.5	0.4	1.5	1.1
0.98	0.2	0.2	0.7	0.5
0.99	0.1	0.1	0.4	0.3

Documented eagle collisions

Carcass monitoring surveys were conducted at Bluff Point and Studland Bay wind farms from when they commenced operating. Fences to exclude mammalian scavengers were maintained at 27% of turbines across the two sites. All turbines, both fenced and unfenced, were searched routinely within a 100 m radius of the tower base. Red Fox does not occur in Tasmania but native mammals with capacity to scavenge eagle carcasses include the Tasmanian Devil *Sarcophilus harrisi* and Spot-tailed Quoll *Dasyurus maculatus*. The region of the wind farms is an area where facial tumour disease has had little impact on the Tasmanian Devil population.

The frequency of carcass searches was informed by trials to determine rates of loss to scavengers and of observers' capacity to detect carcasses. From 2007, searches were carried out twice weekly during periods that may have represented higher risk to the species (i.e. eagle courtship display period June – August, inclusive, and eagle fledging period mid December – February, inclusive) and fortnightly outside these periods (Hull et al. 2013). Carcass searches were undertaken by human observers. Searches were carried out at Bluff Point in eleven years (2003 – 2013, inclusive) and at Studland Bay they were carried out in seven years (2007 - 2013, inclusive).

Assessment of the extent of undetected eagle collisions (Woolnorth Wind Farm Holding 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 fell after colliding with turbines (Hull and Muir 2010); personnel on site had capacity to detect carcasses that may have been moved from formal search zones; eagle carcasses in vegetation were found not to decompose readily and, even when scavenged, remains were identifiable; and, while mammalian scavengers could remove carcasses this was controlled at the subset of fenced turbines; survey intensity was informed by predetermined scavenger removal rates; and, while 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 as both scavenger exclusion or farm fences prevented them from leaving the immediate area. The empirical results of eagle carcass persistence trials recently provided by Elmoby Ecology Bennett (2021) corroborate the conclusions of Hydro Tasmania (2013) and Hull et al. (2013).

Table 2 shows the numbers of carcasses of the two species detected at the two sites for each year of monitoring.

Table 2. Numbers of collision mortalities of two species of eagle detected during targeted searches at Bluff Point and Studland Bay Wind Farms.

	Bluff Point		Studland Bay	
Year	White-bellied Sea-eagle	Wedge-tailed Eagle	White-bellied Sea-eagle	Wedge-tailed Eagle
2003	0	1		
2004	0	0		
2005	0	0		
2006	0	6		
2007	0	1	0	3
2008	1	3	0	1
2009	1	1	0	0
2010	0	1	0	1
2011	0	0	0	0
2012	0	0	0	0
2013	0	0	0	0
total	2	13	0	5

Mean annual mortality rates and associated 95% confidence intervals for both species at the two wind farms are shown in Table 3.

Table 3. Mean annual mortality rates and variance for eagle species based on carcasses detected at Bluff Point and Studland Bay wind farms.

	White-bellied Sea-eagle		Wedge-tailed Eagle	
Year	Bluff Point	Studland Bay	Bluff Point	Studland Bay
mean annual mortalities	0.18	0.00	1.18	0.71
annual variance (95% C.I.)	0.01-0.41	-	0.15-2.22	0.00-1.48

Comparison of collision risk model estimates with actual mortality rates

Estimates of annual collisions modelled for avoidance rates between 0.90 and 0.99 correctly encompassed the long-term average of real collisions for both species at the two wind farms. The 95% confidence intervals associated with the average real collision rates were entirely encompassed by the model's estimates.

Comparison of the model's projections (Table 1) with the annual average documented collision rates (Table 3) indicate the following:

- For White-bellied Sea-eagle at Bluff Point the annual average of actual mortalities (0.18) is slightly lower than the model's projections for an avoidance rate of 0.98 (0.2 collisions p.a.)
- No White-bellied Sea-eagle collisions were recorded during five years of monitoring at Studland Bay so the model's estimates are higher than actual experience for that species there.
- For Wedge-tailed Eagle at Bluff Point the annual average of actual mortalities (1.18) is between the model's projections for an avoidance rate of 0.95 and 0.98 (1.5 – 0.7 collisions p.a.) and most closely approximates an avoidance rate of 0.96.
- For Wedge-tailed Eagle at Studland Bay the annual average of actual mortalities (0.71) is between the model's projections for an avoidance rate of 0.95 and 0.98 (1.1 – 0.5 collisions p.a.) and most closely approximates an avoidance rate of 0.97.

Hull and Muir (2013) documented turbine avoidance from observations of eagle activity at these two wind farms. They found that White-bellied Sea-eagles showed empirical avoidance rates of 0.89 and 0.97 at Studland Bay and Bluff Point, respectively, and that Wedge-tailed Eagles had empirical avoidance rates of 0.81 and 0.90, at Studland Bay and Bluff Point, respectively. These values are as expected because they indicate that the principal avoidance they documented was meso-avoidance (the rate at which the birds flew within the wind farm but avoided close proximity to turbines). However, as a small number of collisions occurred at the wind farms, it is evident that some eagles did, in fact fly within the rotor-swept zone of turbines. This indicates that in addition to meso-avoidance, a level of micro-avoidance occurs. This additional level of avoidance serves to increase the overall avoidance rate of eagles at the wind farms. It is therefore reasonable to assume that the overall avoidance rates for the two species would be higher than the meso-avoidance rates documented by Hull and Muir (2013).

Musselroe Wind Farm

Substantial investigations have been undertaken at Musselroe Wind Farm operated by Woolnorth Renewables at Cape Portland in north- eastern Tasmania. These have included utilisation surveys designed to measure eagle activity before and after development of the wind farm; collision carcass monitoring; eagle breeding success; eagle behaviours and movements relative to turbines and investigations and trails aimed at reduction of collisions. Details of design and outcomes of these are provided in annual environmental performance reports prepared by Woolnorth Renewables and its predecessors. Commissioning of turbines began at Musselroe Wind Farm in 2013. The wind farm consists of 56 Vesta V90 turbines in a scattered array. The wind farms is close to the coast and both species are resident at the site.

Monitoring eagle flights

Flight activity data for both species were collected during timed point counts at Musselroe Wind Farm site during three years prior to construction of the wind farm. Data were recorded from nine point count locations during 2002 and then at 19 fixed point count locations, including the original nine sites, during 2005 and 2006.

Collision risk model results

The model was used to estimate risk based on movement data for populations of eight Wedge-tailed Eagles and eight White-bellied Sea-eagles at the wind farm.

Collision risk modelling was undertaken for a number of turbine configurations under consideration in 2011 (Biosis Research 2011). That included the design that was subsequently built and has been operational since 2013. Static avoidance was modelled at a rate of 0.99 in all cases and dynamic avoidance at 0.90; 0.95; 0.98 and 0.99. The model results are shown in Table 4.

Table 4. Modelled mean annual turbine collision estimates for White-bellied Sea-eagle and Wedge-tailed Eagle at Musselroe Wind Farms for four avoidance rates.

Avoidance rate	White-bellied Sea-eagle	Wedge-tailed Eagle
0.90	0.53	2.05
0.95	0.31	1.23
0.98	0.17	0.69
0.99	0.13	0.50

Documented eagle collisions

Carcass monitoring surveys were conducted at Musselroe Wind Farm since it commenced operating. All turbines were searched routinely within a 100 m radius of the tower base. Native mammals with capacity to scavenge eagle carcasses include the Tasmanian Devil and Spot-tailed Quoll. Tasmanian Devils have remained quite prevalent at Musselroe Wind Farm (Driessen et al. 2018).

As required by the State and Commonwealth regulators, the monitoring regime for detecting bird collisions at wind turbines during the period from 2013 to 2017 differed in intensity across the site in line with perceived risk. Six turbines in the north-west of the array were monitored twice weekly during periods that were regarded as high risk for migratory waders (during the portion of the year in which those species are present in Australia and utilised nearby wetlands). Outside these periods and across the rest of the wind farm, each turbine was searched once every eight weeks, using a regime in which a quarter of the turbines were searched every two weeks (Woolnorth Wind Farm Holding 2014). After it became evident that migratory waders were not materially at risk of turbine collisions, from November 2017 a change to the search regime was approved and from then all turbines have been searched once every eight weeks, using a regime in which a quarter of the turbines were searched every two weeks (Woolnorth Wind Farm Holding 2019). Carcass searches were undertaken by human observers. Searches have been carried out at Musselroe in 10 years (2013 – 2022, inclusive (Woolnorth Renewables 2022).

Assessment of the extent of undetected eagle collisions at Musselroe is outlined in Woolnorth Wind Farm Holding (2016). Searcher efficiency trials and carcass persistence trials were undertaken and results for eagles is reported to have been similar to that at Bluff Point and Studland Bay wind farms where searcher efficiency for large birds was 98%. Carcass persistence trials at Musselroe demonstrate there was an average time to complete disappearance of 80 days with a 95% confidence interval of between 74 and 86 days. As each turbine was surveyed every 8 weeks, these trials indicate that the majority of eagle collision fatality carcasses would have been detectable during at least one or more surveys. Results of the trials indicate there is a high probability that the great majority, if not all, eagle carcasses have been detected.

Table 5 shows the numbers of carcasses of the two species detected at the two sites for each year of monitoring.

Table 5. Numbers of collision mortalities of two species of eagle detected during targeted searches at Musselroe Wind Farm.

Year	White-bellied Sea-eagle	Wedge-tailed Eagle
2013	1	2
2014	0	0
2015	0	4
2016	0	1
2017	0	2
2018	0	2
2019	0	8
2020	0	7
2021	1	0
2022	0	3
total	2	29

Mean annual mortality rates and associated 95% confidence intervals for both species at the two wind farms are shown in Table 6.

Table 6. Mean annual mortality rates and variance for eagle species based on carcasses detected at Musselroe Wind Farm.

Year	White-bellied Sea-eagle	Wedge-tailed Eagle
mean annual mortalities	0.20	2.90
annual variance (95% C.I.)	0.00-0.45	1.30-4.50

Comparison of collision risk model estimates with actual mortality rates

Estimates of annual collisions modelled for avoidance rates between 0.90 and 0.99 correctly encompassed the long-term average of real collisions for White-bellied Sea-eagle at the wind farm. The 95% confidence intervals associated with the average real collision rates were entirely encompassed by the model's estimates for that species.

Comparison of the model's projections (Table 4) with the annual average documented collision rates for White-bellied Sea-eagle (Table 6) indicate that:

- For White-bellied Sea-eagle at Musselroe the model's projections for an avoidance rate of slightly less than 0.98 (0.17 collisions p.a.) closely approximates the annual average of actual mortalities (0.20).

The model's estimates of annual collisions for Wedge-tailed Eagle at avoidance rates between 0.90 and 0.99 were a little lower than the mean annual number of collisions that occurred.

Comparison of the model's projections (Table 1) with the annual average documented collision rates for Wedge-tailed Eagle (Table 3) indicate that:

- At Musselroe the model's projections for an avoidance rate of 0.90 (2.05 collisions p.a.) was lower than the annual average of actual mortalities (2.90).

While the model's forecasts are lower than the annual average of actual mortalities known to have occurred, they are still close to that value. As noted above, annual averages of fatalities are prone to significant influence of inter-annual variability. In the case of Wedge-tailed Eagles at Musselroe, there were eight years in which mortalities detected were between 0 and 4 and two years in which there were 7 and 8 known mortalities. It is not known whether this degree of variation may continue over the life of the wind farm, but it remains plausible that the model's projections will encompass the annual average of actual mortalities over that timespan.

Yaloak South Wind Farm

Yaloak South Wind Farm is operated by Pacific Hydro Pty Ltd near Ballan in western Victoria. The wind farm consists of 14 Senvion MM92 turbines in a scattered array. The wind farm property and immediate vicinity have a high degree of topographic variability including a significant escarpment associated with the Parwan

Valley. The wind farm is situated on the plateau above the escarpment. The local area is attractive to Wedge-tailed Eagles as its topography creates thermal uplift for soaring and local land uses provide substantial food resources. Studies of the species there have included utilisation surveys designed to measure eagle activity before and after development of the wind farm; collision carcass monitoring; eagle breeding success; eagle behaviours and the most comprehensive and long-term investigations of eagle carcass persistence and searcher efficiency undertaken in Australia. Details of design and outcomes of these are provided in reports prepared by consultants for Pacific Hydro (Biosis 2019; Elmoby Ecology Bennett 2019, 2020, 2021). The wind farm reached practical completion in 2018 and a three-year post-construction program of monitoring of eagles commenced in July 2018.

Monitoring eagle flights

Flight activity data for Wedge-tailed Eagles were obtained during point counts undertaken during 2006 and between July 2009 and March 2010. Ten point count locations were used for a total of 543 x 20-minute counts.

Collision risk model results

The model was used to estimate risk based on movement data for a Wedge-tailed Eagle population in which an average of six birds using the site for 90% of the year and fifteen birds using the site for 10% of the year. These values were agreed to by State regulators prior to final modelling undertaken as part of environmental assessment of the proposed wind farm.

Static avoidance was modelled at a rate of 0.99 in all cases and dynamic avoidance at 0.90; 0.95; 0.98, 0.99 and 0.998. The model results are shown in Table 7.

Table 7. Modelled mean annual turbine collision estimates for Wedge-tailed Eagle at Yaloak South Wind Farms for five avoidance rates.

Avoidance rate	6 Wedge-tailed Eagles (90% of year)	15 Wedge-tailed Eagles (10% of year)	Combined annual total collisions
0.90	4.4	0.9	5.3
0.95	3.2	0.5	3.7
0.98	2.0	0.3	2.3
0.99	1.5	0.2	1.7
0.998	0.3	0.0	0.3

Documented eagle collisions

Carcass monitoring surveys were conducted at Yaloak South Wind Farm since it commenced operating. All turbines were searched routinely to cover a horizontal radius of 60 metres centered on the base of the turbine tower. On the basis of analyses of Huso and Dalthorp (2014) this search zone was selected to encompass more than 95% of collision carcasses for the dimensions of turbines at the wind farm.

As required by State regulators, the monitoring regime for detecting bird collisions at wind turbines differed in frequency over time in response to the findings of preceding search periods. Carcass surveys were conducted by trained detection dogs and their handlers weekly between July 2018 and June 2019, fortnightly between June 2019 and December 2019 and monthly from January 2019 to June 2021, inclusive, at all 14 turbines. Additional 'pulse' surveys were conducted between November and May in each of the three years of the program for the detection of bats, but also documented all birds found. A total of 1355 surveys were undertaken at the 14 turbines over the three-year period.

Overall, searches were carried out at Yaloak South in three years (from July 2018 – June 2021, inclusive (Elmoby Ecology Bennet 2021).

As discussed previously, investigations at Yaloak South included study of bird carcass persistence and searcher efficiency (Elmoby Ecology Bennett 2019; 2020; 2021), with a specific focus on Wedge-tailed Eagles and was the first substantial investigation using eagle carcasses in Australia. The study found that Wedge-tailed Eagle carcasses had a mean persistence time of 260 days with a 95% confidence interval of between 119 and 567 days, whereas for all small and medium-sized birds (including some small raptors) mean persistence time was 2.8 days with a 95% confidence interval of between 2 and 4 days. The Elmoby Ecology Bennett reports conclude that there was a high level of confidence that all Wedge-tailed Eagles killed by collision with wind turbines were found and thus that the number of eagles detected was highly likely to reflect the total of collisions by the species.

Table 8 shows the numbers of Wedge-tailed Eagle carcasses detected at the site for each year of monitoring.

Table 8. Numbers of collision mortalities of Wedge-tailed Eagles detected during targeted searches at Yaloak South Wind Farm.

Year	Wedge-tailed Eagle
2018/19	4
2019/20	3
2020/21	4
total	11

The mean annual mortality rate and associated 95% confidence intervals for the species at Yaloak South Wind Farm is shown in Table 9.

Table 9. Mean annual mortality rate and variance for Wedge-tailed Eagle based on carcasses detected at Yaloak South Wind Farm.

Year	Wedge-tailed Eagle
mean annual mortalities	3.62
annual variance (95% C.I.)	0.04-7.29

Comparison of collision risk model estimates with actual mortality rates

Estimates of annual collisions modelled for avoidance rates between 0.90 and 0.998 correctly encompassed the long-term average of real collisions for Wedge-tailed Eagle at the wind farm. The 95% confidence intervals associated with the average real collision rates were largely encompassed by the model's estimates for the species.

Comparison of the model's projections (Table 7) with the annual average documented collision rates for Wedge-tailed Eagle (Table 9) indicate that:

- The model's projections for an avoidance rate of 0.95 (3.7 collisions p.a.) closely approximates the annual average of actual mortalities (3.62).

Conclusion

The Biosis collision risk model has provided forecasts of the annual average numbers of turbine collisions by Wedge-tailed Eagle and White-bellied Sea-eagle. Comparison of the forecasts with data for known and estimated total collisions from targeted carcass searches at four operational wind farms indicate that results of the model for the range of avoidance rates reported were accurate and in every case the forecasts were precise to within less than one Wedge-tailed Eagle collision per annum and were more accurate for White-bellied Sea-eagles.

It is not feasible to make similar comparisons for the great majority of bird species that may interact with wind turbines in Australia due to a high degree of uncertainty about the true numbers of collisions that occur. The factors influencing uncertainty are outlined in *Pre-requisites to validation*, above. Careful and refined design of carcass search regimes, such as standard use of pulse searches, and the application of appropriate, specific mathematical methods to the estimation of total collisions (e.g. Huso et al. 2017) should be used in efforts to reduce such uncertainties.

In 2006 the then Australian Government Department of the Environment and Heritage published reports by Biosis Research (2006) that provided methodologies for assessment of cumulative impacts due to turbine collisions of multiple wind energy facilities. Four species of birds, including the Tasmanian Wedge-tailed Eagle were used as examples of how this could work. That work was not prepared for, and was not used for, environmental impact assessment of any project. The exercise was undertaken for many wind farms, including a significant number that were then mooted but have not since been carried to fruition and are no longer proposed. Some of the wind farms that have since been built differ from the designs that were then proposed. The reports noted the heuristic value of mathematical modelling. At the time of preparation of that work there was almost no empirical information about actual collisions by Wedge-tailed Eagles. The report said that it was likely that avoidance rates for Tasmanian Wedge-tailed Eagle would generally be in the range of 0.95 to 1.00 in most conditions. Then available information for the closely related Golden Eagle *Aquila chrysaetos* was cited that suggested an avoidance rate of greater than 0.99. At the request of the Department of the Environment and Heritage, the report provided modelling for avoidance rates of 0.95, 0.98 and 0.99, but also noted, “we recommend that [avoidance rate] is a key area requiring further soundly based investigation within operational wind farms.” The case studies detailed above have used collision risk modelling that was prepared specifically for wind farms as designed and subsequently approved and now in operation. The comparisons with documented eagle collisions have achieved the recommendation of the 2006 Biosis Research report.

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