Search areas for monitoring bird and bat carcasses at wind farms using a Monte-Carlo model

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A regularly raised concern for wind farms is the number of species and rate of bird and bat collisions with turbines. Australian regulators require, at some operating wind farms, the monitoring of bird and bat collisions. Although monitoring is becoming more commonplace, the area recommended for searching beneath turbines is inconsistent, with many guidelines both in Australia and overseas being based on conjecture rather than empirical evidence. This has the potential to bias survey results, reduce confidence in the data collected, and preclude meaningful comparisons between sites. By having a measure of the range of the fall zone of a bird or bat, a survey can be designed that ensures that an adequate area is being searched and that the cost of searching outside the area where birds and bats can fall is minimised. This article outlines a model that describes the fall zone of bats and birds of various sizes after colliding with different sized turbines, by applying a Monte-Carlo approach to ballistics theory. The modelling results are benchmarked with data from two Australian wind farms and one from the USA, for which data were available. The results indicate the size of the search area required around already constructed turbines, and the search area required to estimate levels of background mortality for control zones for pre-commission mortality surveys.

Keywords: bird and bat monitoring, wind farms

As part of the strategy to minimise the production of greenhouse gases from electricity generation there has been, and is likely to continue to be, an expansion of the wind industry in Australia. Understanding the effect of wind farms on birds and bats is of interest to regulatory authorities and other stakeholders. One of the potential effects is collisions with turbines. Consequently, a requirement of state and the Commonwealth Regulators' approval conditions on a wind farm can be post-commissioning surveys to detect bird and bat collisions.

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Various techniques are used to measure bird and bat fatalities, including remote sensing ones, such as infra-red cameras. Arguably, the most common technique (particularly in Australia) is searches by human observers. There are a number of difficulties with the use of observers to determine the rate of collision of birds and bats with turbines. These difficulties include the need to account for scavenging rates of carcasses and the ability to detect carcasses (see Anderson et al. 1999). There has also been considerable inconsistency in the size of the search area used (Sterner 2002; Kunz et al. 2007), which may have biased surveys (Young et al. 2003), and limits the ability to compare sites and to determine cumulative impacts on relevant species.

The first approach we located for determining the search area around turbines was that proposed by Gauthreaux (1996), who suggested that the search area should be circular, with the minimum radius proportional to the height of the turbines. He cited the work of Winkelman (1989, 1992) and suggested searching an area within 70 m of a turbine. However, Gauthreaux (1996) highlighted that it would be useful if post-commissioning surveys quantified the distribution of dead birds around turbines of different heights.

Although wind turbines are now substantially larger and rotate at different speeds than when Gauthreaux (1996) made his recommendations, the method of basing the search area radius on the height of the turbine has been used at a number of sites (see Kunz et al. 2007). Similarly, the AusWind (2005) standards prescribe that searches for dead birds, remains and feather spots should cover an area with a radial distance equivalent to the height of the wind turbine. The guidelines state that this distance can be altered if carcass locations indicate this to be warranted. An assessment of the literature reporting bird and bat collisions at wind farms indicates that a variety of search distances have been used (Table 1).

More recently, some authors have used the size of the fall zone of birds and bats to determine the search zone (e.g. Erickson et al. 2004; Arnett 2005; Smallwood & Thelander 2005; Hotker et al. 2006). Osborn et al. (2000) estimated the required search area by dropping bird carcasses from the nacelle and upper limits of the swept area of wind turbine blades on days with 'brisk' wind.

Table 1 **Summary of the distances from wind farm turbines used for searches in published studies**

Search area	Reference
From 50 m	Morrison 1998; Nicholson et al. 2003
30-60 m depending on the size of the turbines at the Altamont Pass Wind Farm	Orloff & Flannery 1992
60 m	Kerns & Kerlinger 2004
90% of tower height	Gehring 2007
Equal to the height of the tip of the turbine	Kunz et al. 2007
Height of the turbine, although the search area can be smaller for large birds and raptors	California Energy Commission & California Department of Fish and Game 2007
One half the maximum blade tip height attainable measured out from the base of the tower	Erickson et al. 2003
1.5 times the rotor diameter	New York Department of Environmental Conservation 2007

However, this approach does not take into account the effect of the energy of a moving blade on the trajectory of a carcass.

Other authors have found that 93 per cent of birds and bats were located within 40 m of 116 m high turbines, with only 1.5 per cent more than 50 m away (Kerns 2005). Thelander and Rugge (2000) found that the average distance away from turbines that birds fell was 20.2 m, with 75 per cent of birds falling less than 30 m away from the tower. The search radius used by Thelander and Rugge (2000) was based on Gauthreaux (1996), and determined from the height of the turbine. However, in some of these documents it is not clear whether there were any biases in the estimates due to insufficient search zones that reduced the detection of carcasses. This highlights a concern raised by Smallwood (2007), that an insufficient search radius could bias data. Barclay et al. (2007) attempted to correct various biases in different studies that they assessed, but made no mention of the adequacy of the search radii used in the assessed data.

Smallwood and Thelander (2004) commented that the lack of standardisation in studies substantially impedes the comparison of impacts at various wind farm sites. Other authors have commented that there is a need for rigorous implementation of search protocols that will provide reliable estimates of bird and bat fatalities (Kunz et al. 2007).

A relatively easy protocol to resolve is the search area around turbines, which takes into account the height of the turbine, its operational speed, and the size of the bird or bat. A maximum distance, beyond which no carcass can be feasibly attributed to wind turbine mortality, needs to be determined. Hence, the application of an *a priori* approach enables adequate mortality surveys, including baseline studies, to be designed.

The use of ballistics theory suggests that there will necessarily be an edge (i.e. boundary) to the physical distance that a carcass resulting from bird strike can be thrown. By modelling this distance for a range of bird and bat sizes and a range of turbine types, we can define the necessary search area for a range of turbines and ensure that control sites for the determination of background mortalities are truly independent, yet reflect the same local conditions.

The aims of this article are therefore to:

1. model the fall zone of bird and bat carcasses of various sizes around turbines using three nominal turbine sizes

2. use this complex model to generate a simple approximation that will aid in the design of post-commissioning surveys, namely, the search radius required to detect bird and bat carcasses

3. benchmark these approximations with data from two Australian wind farms (the Bluff Point Wind Farm and Studland Bay Wind Farm, both in north-west Tasmania, owned and operated by Roaring 40s Renewable Energy Pty Ltd) and the Mountaineer Wind Farm in West Virginia, USA, using the data published in Arnett (2005).

Methodology

Modelling of the fall zone of birds and bats

The aerodynamics of unpowered flight is well understood, and therefore determining the maximum radius of a fall zone is a minor matter. However, we also need to determine the likely distribution of the fall zone. This is a complex interaction of many parameters, for which we know the overall bounds and can estimate the potential shape, but are uncertain of particular parameter values.

To accurately quantify the potential range over which bird and bat carcasses can be found (R_d), a Monte-Carlo simulation based on ballistic theory was employed. Four distinct classes of carcass were modelled using this method (Table 2).

The small-, mid- and large-sized birds, and bats, are hereafter referred to collectively as animals.

Equations of motion

We employ basic Newtonian ballistics theory, whereby the animal is modelled as a projectile, albeit with changeable properties. After an initial impulse and deposition of velocity (taken from the contact point of the rotor), our projectile is assumed to be inert. Therefore, the only forces acing upon it are those of wind drag and gravity.

$$\frac{d^2\mathbf{x}}{dt^2} = \frac{-\rho\left|\mathbf{v}^2\right|C_d A}{2m}\hat{\mathbf{v}} - \boldsymbol{g} \qquad (1)$$

Where:

x is the horizontal displacement along the ground parallel to the rotors

t is time

ρ is the air density

v is the velocity vector

C_d is the drag coefficient (see below)

A is the 'presented area'

m is the mass of the object

g is the acceleration due to gravity at the Earth's surface.

We separate Equation (1) into two coupled, ordinary differential equations, with v as a unit vector in the direction of the velocity:

$$\begin{aligned} \frac{d\boldsymbol{x}}{dt} &= \mathbf{v} \\ \frac{d\mathbf{v}}{dt} &= \frac{-\rho\left|\mathbf{v}^2\right|C_d A}{2m}\hat{\mathbf{v}} - \boldsymbol{g} \end{aligned} \qquad (2)$$

This system is numerically integrated forward in time using a Runge-Kutta fourth order (RK4) method (see, for example, Press et al. 1992).

Initial conditions

The initial velocity and displacement data are taken to be that of the rotor at the point of impact (R_0, Θ). This assumes that any initial velocity of the animal is lost on impact with the blade, and the blade serves to supply an impulse to the body. This is the maximum amount of energy transfer that can occur.

Future iterations of the model allow for fine control of these two parameters. For animals with a ceiling flight altitude that is lower than the sum of the tower and the blade length, Θ might be controlled appropriately.

It was assumed that animals can come into contact with the turbine blade at any radial distance from the hub that is not greater than the length of the blade. This value is randomly selected from a profile that is proportional to the amount of area swept by the section of rotor.

Model parameters and assumptions

As outlined previously, we assumed that, after the initial collision, the animal is unable to fly. We do not account for initial pre-collision velocity, nor do we account for structured and coordinated 'flapping'.

It is assumed that:

- the mass of the animal does not change following the collision with the WTG (Wind Turbine Generator) blade
- the carcass remains intact for the duration of the flight following the collision
- the drag coefficient is set to be a value centred on unity, with a standard deviation of 0.125. There is little evidence available to determine the characteristics

Table 2 **Classes of carcass modelled**

Class	Nominate species	Details (mean ± sd, sd is given by one-sixth of the reported range in relevant literature)
1* Large bird	Wedge-tailed eagle *Aquila audax*	Mass: 4.2 ± 0.3 kg Maximum surface area: 0.6 m^2 Minimum surface area: 0.07 m^2 (morphometrics from Marchant & Higgins 1993)
2* Small bird	Silvereye finch *Zosterops lateralis*	Mass: 11.5 ± 0.25 g Maximum surface area: 0.0036 m^2 Minimum surface area: 0.0013 m^2 (morphometrics from Higgins et al. 2006)
3 Mid-sized bird	Forest raven *Corvus tasmanicus*	Mass: 680 ± 25 g Maximum surface area: 0.1 m^2 Minimum surface area: 0.045 m^2 (morphometrics from Higgins et al. 2006)
4 Insectivorous bat	Gould's wattled bat *Chalinobus gouldii***	Mass: 14 ± 2 g Maximum surface area: 0.014 m^2 Minimum surface area: 0.0028 m^2 (source: Parks and Wildlife Service Tasmania 2003)

* These two classes represent the extreme dimensions of birds that have been recorded as colliding with turbines in Australia, based on available data.

** The only insectivorous bat species recorded as colliding with turbines in Australia, based on available data.

of an injured animal in flight. Work such as that by Tucker (1990) indicates that certain raptors, in balanced flight, have drag coefficients as low as 0.24. However, this is not likely to be the case post-collision, where, at the very least, feathers can be assumed to be out of place and ruffled, and at the worst, the carcass could be flung backwards with a resulting sizeable drag parameter. With this in mind, we have chosen to model the carcass as tumbling, with the drag coefficient able to change randomly during the downward flight

- presented area of the animal also has little evidence upon which to base our assumptions. We can assert a greatest area, which will correspond to the wings outstretched in a 'flaring' position. The smallest area will be that of the chest, with the wings folded back behind the body. These are the presented areas outlined previously in the nominate descriptions. As with the drag coefficient (C_d), we allow the presented area to change throughout the course of the flight
- carcasses will attempt to conform to the smallest area whilst tumbling. The distribution used is then a sawtooth pattern, with the largest and least likely area being the 'flared' position, and the most common, smallest area being the tear drop shape of the chest forward and wings behind. The average will be somewhere in the middle, biased to the smaller of the two extremes.

The precise inefficiencies involved in the collision were beyond the scope of this model and would depend on factors such as the attitude (i.e. orientation) of the animal in flight, the nature of the blade strike on the animal, and the animal's contact time with the blade. These factors can be grouped into a Coefficient of Restitution, defined as the ratio between the blade velocity and the initial velocity of the carcass. This resulting factor will affect the distribution of distances only. The maximum throw value, extending from 'perfect' strike conditions and energy transfer, will occur when this value is unity. For maximum fall zone calculations, this parameter is not a variable, and was set to unity. Certain parameters were required to be fixed for each simulation performed (Table 3).

Table 3 Fixed parameters of nominate turbines of different sizes

	Turbine size		
	Small	Medium	Large
R_{max} (m)	33	45	55
ω (rpm)	21.3	16.1	13.0
H_{hub} (m)	65	80	94

The height of the turbine hub (H_{hub}), the turbine rotor radius (R_{max}), and the rotational frequency of the turbine (ω) are all static parameters, as these are inherent to the WTG. Three nominate turbine sizes were used in the model, based on the size of turbines that are currently used at Australian wind farms (small and medium) and the next generation of turbines that is likely to be commercially available in the next four years (large) (Paul Fulton, Wind Engineer with Joule Logic, pers. comm.):

1. Small, with a hub height of 65 m, rotor swept diameter of 66 m
2. Medium, with a hub height of 80 m, rotor swept diameter of 90 m
3. Large, with a hub height of 94 m, rotor swept diameter of 112 m.

Note that in these three models, the tip moves at the same velocity regardless of turbine size, as the larger the turbine, the slower the rotational speed of the blades.

The air density was set at 1.21 kg per cubic metre, which corresponds to one atmosphere at 20°C (Tipler 1991). The density of air increases with decreased temperature, which in turn will serve to localise the fall locations closer to the base of the turbine.

A typical simulation run consisted of the trajectories of 160 000 carcass strikes and their resulting flight-paths. The vectors for v and $\frac{d\mathbf{v}}{dt}$ are dependent and require the use of a two-dimensional RK4 numerical integrator for their solution. This generates the velocity and position vectors relative to the base of the WTG tower in Cartesian coordinates for each time-step throughout the flight. Technically, the solution is from the point directly below the rotor, as no account was made for the offset of the blade from the tower.

Carcass search data for benchmarking

The data used for benchmarking were from three sites (Table 4). These sites were selected as they were the only ones for which we could access sufficiently detailed data. To most accurately compare the Mountaineer data to the ballistics model, the model was configured to run with the turbine specifications as found at Mountaineer.

At both the Bluff Point and Studland Bay wind farms, turbines were monitored throughout the year with the sampling frequency informed by a series of scavenger surveys, and by presumed peak bird activity (determined

Table 4 **Sites from which benchmarking data were derived**

Site	Details of the wind farm	Carcass monitoring undertaken
Bluff Point Wind Farm, NW Tasmania Analagous to the '**small**' turbine model	37 Vestas V66 turbines (tower height 65 m, blade length 33 m) Staged development, with Stage 1 comprising 6 turbines, and Stage 2 an additional 31 turbines which were commissioned in May 2004	Upon commissioning of Stage 1 (August 2002), all 6 turbines surveyed; Stage 2: sub-sample of 10 Data used for this validation from August 2002 – 25th May 2009 (monitoring is still continuing on site)
Studland Bay Wind Farm, NW Tasmania (3 km south of the Bluff Point Wind Farm) Analagous to the '**medium**' turbine model	25 Vestas V90 turbines (tower height 80 m, blade length 45 m)	Since commissioning in April 2007, monitoring at 7 turbines. Data used for this validation from April 2007 – 3rd September 2009 (monitoring is still continuing on site)
Mountaineer Wind Farm, USA Analagous to the '**small**' turbine model, with a slightly larger rotor size and marginally higher rotational velocity	44 turbines mounted at 67.5 m, with a rotor swept area of 72 m (hence blade lengths of approximately 35 m) and standard operating speed of 17 rpm	A total of 22 searches were conducted on all turbines. Surveys were conducted between April 4 and November 11 2003. Search area was a rectangle 130 m by 120 m, centred on the WTG, with 10 m separating transects (Arnett 2005)

by the relevant regulators). The mammalian scavenger rates were found to be high at the site (dedicated scavenger surveys have been conducted on two occasions, Roaring 40s, unpubl. data) and, to control this effect, monitored turbines were fenced with predator-proof fencing. Although avian scavenging occurred on site, surveys have revealed that avian scavengers leave sufficient amounts of a carcass to allow detection and identification of the animal at least to Order, and sometimes to species level.

Formal sampling at both sites was conducted twice weekly during the periods 15 December – mid-May and 1 June – 31 August, as these were deemed higher risk periods due to eagle (Wedge-tailed eagle (*Aquila audax*) and White-bellied sea-eagle (*Haliaeetus leucogaster*)) activity and possible movements of Orange-bellied parrots (*Neophema chrysogaster*), and once fortnightly outside these periods. In addition to these formal surveys, all wind farm personnel and visitors were required to report bird or bat collisions, and all turbines at both wind farms were checked fortnightly for eagle collisions. However, for the purposes of this analysis only, the data used in formal searches were analysed, as these were at turbines with predator-proof fences and sampling was based on a rigid protocol.

Surveys were conducted from the base of the tower out to 100 m around each of the monitored turbines, by surveying on foot or using slow moving 4WD bikes moving in concentric circles around the turbine tower, 2-4 m apart. All bird remains (including feather spots, defined as at least ten feathers, or three flight feathers: primary, secondary, tertiary or retrices) and bat carcasses were documented, identified, and removed to avoid double counting. The turbine and location of the carcass in relation to the turbine was recorded.

In the vast majority of cases, animals that collided with turbines were found dead. However, two species, Wedge-tailed eagles and Short-tailed shearwaters (*Puffinus tenuirostris*) occasionally survived a collision with a turbine. These individuals were likely to have moved from the place where they had landed after a collision, but as the surveys recorded when a bird was found alive, this was taken into account in the analysis. In each case in which a bird was found alive, its injuries were deemed to be sufficient that veterinary surgeons and the relevant state regulator determined that they should be euthanised.

Note that the collision data reported here are only assessed in relation to the purposes of this article: the locations in which birds and bats fall after colliding with turbines. Detailed analyses of the species involved, the collision rates, factors involved in collisions, and other issues will be addressed in later publications.

Results and discussion

Modelling of the fall zone of birds and bats

A dominant wind direction, or other relation between rotor direction and likelihood of animal strike, will affect the shape of the fall. If we remove such an assumption, then we expect that the distribution within the fall zone should be radially symmetric (we present these results in a later section). As the predominant wind strength increases, we expect the circular fall zone to contract to an ellipse aligned in the direction of the wind.

The modelled distribution of the fall zone for small and large birds (representing the range of fall zones) and bat nominates at a medium type WTG indicated that larger animals are capable of being thrown a much greater distance (Figure 1), due to their central mass condensation. They also produce more of an asymmetry. This effect is not a function of the initial parameters *per se*, as these were set to have no dependence upon the rotational angle of the strike, but describes the ease at which a carcass can arrive at locations within the fall zone given its wind resistance and body size.

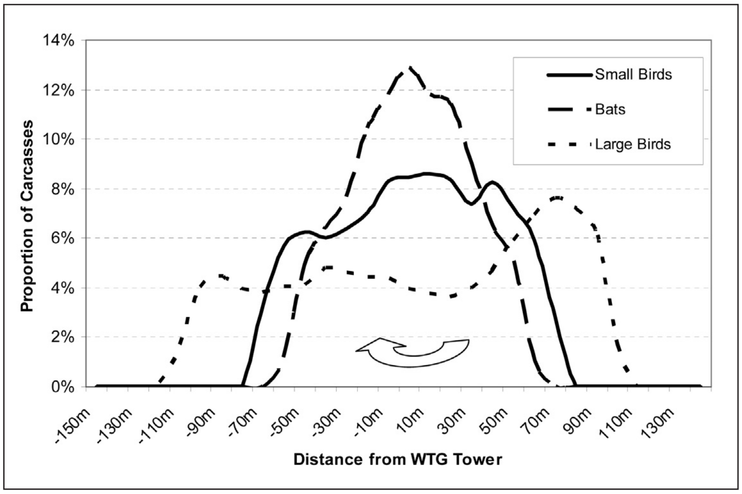

Figure 1 **Modelled fall zones from the base of a medium-sized turbine for animals of different sizes (arrow indicates rotor direction)**

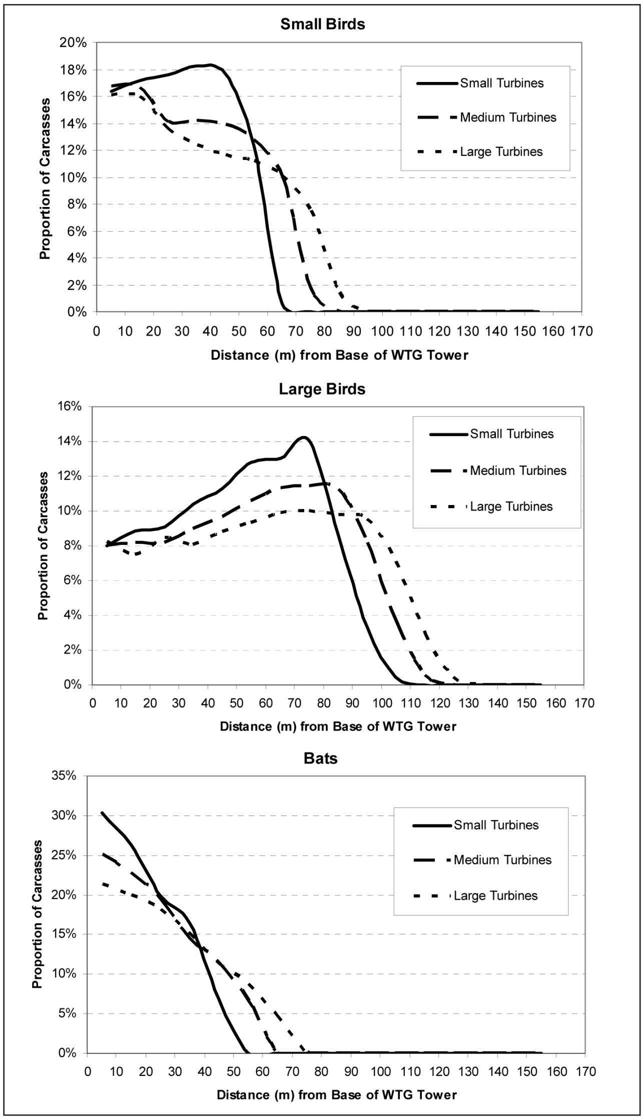

Figure 2 **Full distribution for various sized animals at the three turbine sizes**

Radially symmetric assumptions

We currently do not feel confident that we understand enough about collision risk to animals to include an assumption regarding asymmetry in the fall zones around turbines. Even on sites that have a dominant wind direction, this may not be the direction in which strikes occur (e.g. wind shifts or cold fronts may be more related to risk of strike than are the predominant conditions).

In respect to designing surveys, we were interested in a non-directional radius of the fall zone. Although always a compromise, the study design must take into account the target species. We therefore present each species classification individually (large, small, bat (medium-sized bird will fall between large and small bird)) for each type of WTG.

The important feature is that there did not appear to be a ready rule for predicting the fall zone given the tower and rotor dimensions of Figure 2. It was apparent that the distribution has a sharp edge (approximately 30 m wide) and becomes more uniform as the dimensions of the WTG increased.

Table 5 shows the full distribution for small birds and bats, for each of the turbines. We see from this that, for current generation WTGs, 99 per cent of all small bird carcasses will be found within 71 m of the base of the tower (57 m for bats). Furthermore, half of all carcasses will be found within the first 35 m.

To apply such findings, we benchmarked the model against three operational sites: Bluff Point, Studland Bay and Mountaineer.

Benchmarking the model

Bluff Point Wind Farm

At the Bluff Point Wind Farm, there was a total of 220 carcasses detected, categorised as follows:

- 12 large birds (categorised in the large class)
- 33 small birds (categorised in the small class)
- 59 birds which fitted between small and large (mid-sized birds). These birds did not fit into one of the pre-defined models (being either small, bat or large class birds)
- 55 bats
- the remaining 61 carcasses, being unidentifiable (which were featherspots and could not be identified to species and therefore original size).

Table 5 **Percentile distances (m) of the fall zone of different animals from the base of wind turbine (WTG) of various sizes**

Impactee	WTG	50th	80th	90th	95th	99th
Large	Small	52.01	74.64	82.23	87.92	97.11
	Medium	56.61	83.25	92.43	98.61	108.11
	Large	59.62	89.94	100.49	107.54	116.49
Small	Small	29.43	45.77	51.83	55.43	59.01
	Medium	31.55	53.14	61.35	66.27	70.91
	Large	33.39	59.11	68.93	74.99	80.77
Bats	Small	17.24	31.94	37.99	41.42	45.24
	Medium	20.93	38.62	46.91	51.55	56.98
	Large	24.62	44.26	54.21	59.94	66.46

There were insufficient data to meaningfully compare our model to the large bird class carcasses at Bluff Point; however, the remaining three classes could be compared (Figures 3-5).

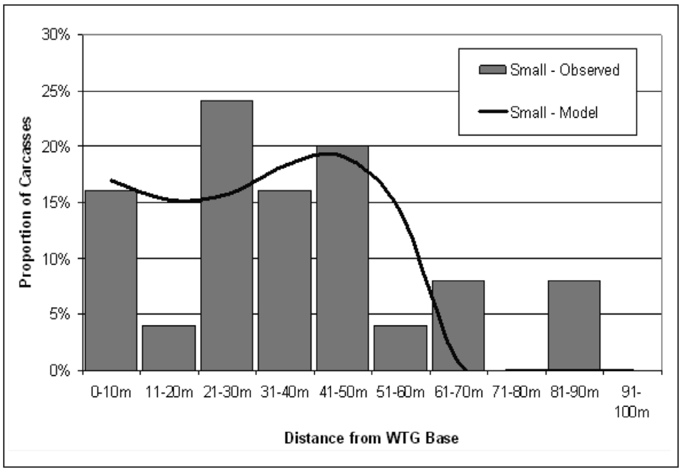

Figure 3 **Comparison between the observed detections at the Bluff Point Wind Farm and those modelled for small birds**

The outlying detections in Figure 3 consisted of two Skylarks (*Alauda arvensis*) at 84 and 85 m. The Skylark is nearly twice the weight of our nominate small bird. Otherwise, the maximum fall zone was correctly placed at less than 70 m. We should not expect that the interior of the curves will align, as this area of the predicted range is dominated by issues such as energy transfer at time of strike (currently assumed to be 100 per cent), and any rotational dependence on the likelihood of birdstrike (currently assumed to be equally likely anywhere on the blade). These factors have less impact farther from the tower base.

We had less success with the mid-sized model, with a number of detections beyond 90 m (Figure 4). Of the 11 records beyond 92 m, nine were Short-tailed shearwaters, with a single Black currawong (*Strepera fuliginosa*) and a single Silver gull (*Larus novaehollandiae*). The Currawong was detected near the perimeter fence at 120 m. One of the Shearwaters (heavily scavenged) was found at 130 m. Of the remaining nine detections, one showed no impact damage whatsoever (hence may not have been a collision mortality), and the rest were alive when found or showed evidence of scavenging. The explanation for the majority of these cases may be that they were moved from the place where they had landed, due to either crawling after landing, or being dragged by scavengers.

The model (Figure 5) shows all the features of the detected counts for bats. The single detection at 77 m was a Gould's wattled bat (*Chalinobus gouldii,* the nominate for the model). This individual may have been scavenged, although it is not clear from the record.

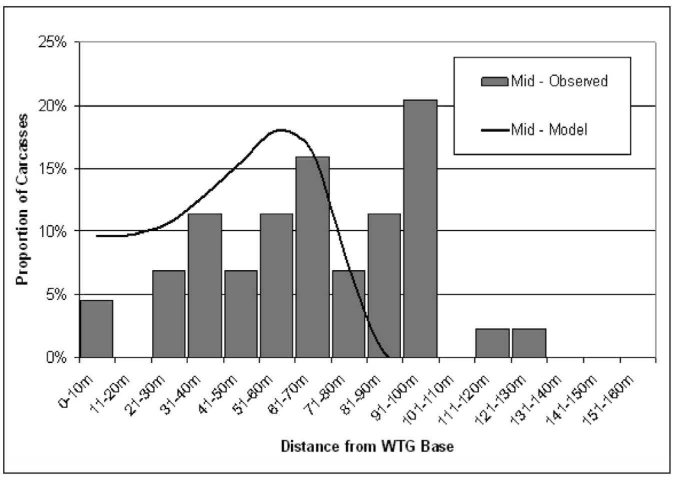

Figure 4 **Comparison between the observed detections at the Bluff Point Wind Farm and those modelled for mid-sized birds**

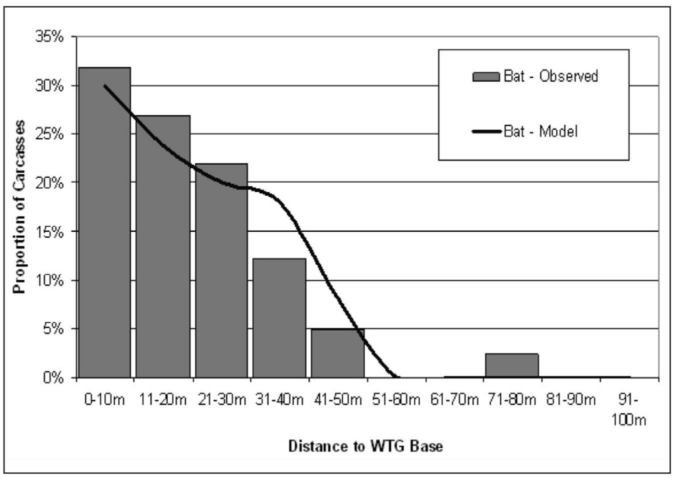

Figure 5 **Comparison between the observed detections at the Bluff Point Wind Farm and those modelled for bats**

Table 6 **Comparison of the fall zone of mid-sized birds from Studland Bay Wind Farm data and the ballistics modelling**

Distance to turbine (m)	Studland Bay (Survey)	Ballistics (mid birds)
0-10	0.00%	10.5%
11-20	15.38%	10.0%
21-30	23.08%	9.9%
31-40	23.08%	10.8%
41-50	15.38%	11.9%
51-60	0.00%	13.3%
61-70	0.00%	13.6%
71-80	0.00%	12.1%
81-90	15.38%	7.3%
91-100	7.69%	0.6%
101-110	0.00%	0.0%
111-120	0.00%	0.0%
121-130	0.00%	0.0%
131-140	0.00%	0.0%
>150	0.00%	0.0%

The Bluff Point data set was the largest available, and showed a strong correlation for small birds and bats. For mid-sized birds, there was a strong peak of detections just outside the predicted fall zone. This peak was predominately due to Short-tailed shearwaters, and records indicated that most showed heavy scavenging, which might explain the peak.

It is important to note that a high number of detections at the limit of the fall zone does not imply that the theory is incorrect, but more that the assumption of equal likelihood of strike anywhere in the swept area could be false. In this case, it would suggest that Shearwaters are more likely to be struck when the rotor is on the upstroke at around 45 degrees below vertical. Alternatively, Shearwaters may be commonly scavenged and moved in the process.

Table 7 **Comparison of the Mountaineer Wind Farm data (Arnett 2005 Table 2.6) to the ballistics modelling**

Distance to turbine (m)	Mountaineer site	Ballistics (bats)
0-10	15%	29.3%
11-20	25.7%	26.2%
21-30	30.3%	19.6%
31-40	22.1%	15.5%
41-50	5.4%	9.3%
>50	1.5%	1.3%

Studland Bay Wind Farm

A total of 25 detected events occurred at this site. Seven consisted of featherspots or otherwise decayed carcasses, and the species could not be determined. Of the remainder, we recorded:

- one large bird
- 13 birds of mixed classification (White-throated needletail (*Hirundapus caudacutus*) through to Australian Shelduck (*Tadorna tadornoides*))
- four bats.

Given the very low count of collisions (13 recorded for birds other than a large bird), a correlation was not apparent. The (Yate's corrected) Chi-squared value was 7.7, which was not large enough to suggest the existence of meaningful difference between the model's predictions and the detections. The model correctly predicted the cliff edge of detections at around 90 m (Table 6).

Mountaineer Wind Farm

Arnett (2005) found that 93 per cent of all (bird and bat) fatalities at the Mountaineer site, USA, were found at 40 m or less from the nearest turbine. As the current article is concerned with setting outer bounds for mortality surveys, we were most concerned with benchmarking the tail of the distribution. When configured with the specifications of the Mountaineer turbines, the model agreed satisfactorily with the outer estimates for ground strike found by Arnett (2005), with less than two per cent of bats occurring at greater than 50 m for both (Table 7).

The apparent difference in the shape of the distribution close to the tower possibly resulted from the present model's assumption that collisions can occur anywhere in the rotor swept area, and presents scope for ongoing improvement of the model. Invoking a coefficient of restitution will increase the detections at lower distances, but have less effect on the outer tails of the distribution. We had a very good fit for bats close to the tower at Bluff Point, yet not at Mountaineer, which appeared to have a decentralised peak.

There were insufficient data available for us to benchmark distributions for larger birds, such as raptors. However, the model functioned well for both bats and small birds, so there is no reason to suggest any failure for heavier carcasses.

Tables 6 and 7 indicate that the model was predicting well what has been seen at both Australian benchmarked sites. It placed the edge of detection at the correct radius, and had a reasonable fit to the internal shape of the

Table 8 **Parameters of the simple model for animals of different sizes**

	a	b	c	r^2
Bats	0.672	0.046	15.9	0.88
Small birds	0.637	0.097	31.6	0.98
Large birds	0.581	0.176	70.6	0.60
Erickson et al. (2003)	0.5	0.5	0	--

Table 9 **Recommended survey zone (m) based on different sized turbines and 95 per cent capture rate (with the maximum survey radii in parentheses), for bird and bat size classes**

	WTG size		
	Small	Medium	Large
Bats	55 (61)	65 (72)	74 (82)
Small birds	68 (76)	78 (87)	87 (97)
Large birds	103 (114)	112 (125)	122 (135)

distribution. This was in spite of its simplistic assumptions about the possible impact areas and energy transfer rates.

Across the three sites, we found good agreement between the model's predictions of the fall zone for all cases, except for the Bluff Point mid-sized birds. This data-set alone raised the issues of scavenging, and their important consideration on any design for mortality surveys.

A Monte-Carlo ballistics model indicated that small birds and bats exhibit very similar ballistic characteristics, while larger birds showed slightly different characteristics; in particular, a tendency to land further from the rotor swept area.

For each of the classes, we also saw a slight asymmetry in the distribution of landing position with it being most marked for large birds. The distributions all showed a higher probability of the carcass landing on the side of the downward blade sweep. This effect was reduced once we removed the assumption of complete energy transfer from the initial conditions, and the effect of a dominant wind direction. This asymmetry is an effect of the dynamics of the situation, and does not reflect upon any behavioural attribute of birds involved in collisions.

All small and large birds and bats showed a strong finite distribution, implying that such a model may be applied with confidence to place an upper bound on distance covered following a strike. This information can thus be used to inform the regions covered by mortality surveys.

A simple model

The previous benchmarking exercise gives us confidence that, without any tuning of the base model, we were reproducing observed effects. We were interested in guiding survey design to ensure that adequate detail was captured, and could produce a simple prediction of the maximum distance that a survey would need to cover to be confident of detecting all relevant data.

To do this, we fitted a model of the form

$$Y_{\mathrm{Max}} = aH_{\mathrm{Tower}} + bR_{\mathrm{Max}} + c \qquad (3)$$

where Y_{Max} is the maximum distance, H_{Tower} is the height of the nacelle, and R_{Max} is the blade length (technically one half of the rotor diameter). The constants *a, b* and *c* were fitted through minimising the sum of the squared deviates.

We allowed all other variables that affect distance to range as before, with the addition of the tower height (70-110 m) and rotor diameter (60-120 m). We supplied the r^2 value (Table 8) that describes the amount of variance explained by the simple model as a fraction of the total variation exhibited by the full scale model.

One can see that 98 per cent of the scatter seen in the maximum throw distances of small birds was explained by just the tower height and blade length. For bats, this simple model captured 88 per cent of the relevant effects. For larger birds, which are susceptible to a larger variation in mass and presented area, the linearised model only accounted for 60 per cent of the total variation. For comparison, we have shown the values of *a* and *b* for the empirical rule of one-half of the maximum blade height advocated by Erickson et al. (2003) (Table 8).

Such a model provides the maximum ranges that these classes of animals will fall. The distances from the base of the WTG, shown in Table 9, are the maximum justifiable, as they include the constant of restitution at unity. Typically, a survey design protocol would run at a 95 per cent or even lower capture rate, which could be around ten per cent less than this value (see Table 9 for the percentile/expected capture rates).

The findings of this simulation assist us in selecting survey designs, which are paramount to the success of any monitoring program. One must balance a number of factors in obtaining adequate results from any survey regime and these should all be considered and accounted for before any data collection is attempted. In the case of concentrated mortality surveys, one needs to balance tiredness of observers (through covering too much ground, which will impact on reliability of observations), detectability (through choice of transect spacing), and the need to capture the information (surveying out to an adequate distance).

These are the simple aspects of a survey design that are easily controlled. Issues such as scavenging rates, detectability and general low counts may yet result in the power of a mortality survey still being too small to achieve anything of merit (these are topics for another paper). The least we can do is account for as many of these factors in the design process as we are able, and ensure the final design has the ability to deliver the management needs.

Specification of a survey protocol is essential to generate a meaningful and transferable insight into the effects of wind farms on avifauna. Basic economics, alongside the need to maintain observer acuity, means that we need to design our survey plots to be as small as is possible, without truncating our detections. This presented model allows us to do this in a robust way without the need to survey for possibly many years with a flawed design to determine the correct survey plot size.

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