Avian collision risk models for wind energy impact assessments

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Abstract:

With the increasing global development of wind energy, collision risk models (CRMs) are routinely used to assess the potential impacts of wind turbines on birds. We reviewed and compared the avian collision risk models currently available in the scientific literature, exploring aspects such as the calculation of a collision probability, inclusion of stationary components e.g. the tower, angle of approach and uncertainty. 10 models were cited in the literature and of these, all included a probability of collision of a single bird colliding with a wind turbine during passage through the rotor swept area, and the majority included a measure of the number of birds at risk. 7 out of the 10 models calculated the probability of birds colliding, whilst the remainder used a constant. We identified four approaches to calculate the probability of collision and these were used by others. 6 of the 10 models were deterministic and included the most frequently used models in the UK, with only 4 including variation or uncertainty in some way, the most recent using Bayesian methods. Despite their appeal, CRMs have their limitations and can be 'data hungry' as well as assuming much about bird movement and behaviour. As data become available, these assumptions should be tested to ensure that CRMs are functioning to adequately answer the questions posed by the wind energy sector.

Keywords: ornithology; EIA; conservation; wind turbines; mortality; renewable energy.

Highlights:

1. We highlighted ten models available to assess avian collision risk
2. Only 4 of the models included variability or uncertainty
3. Collision risk models have limitations and can be 'data hungry'
4. It is vital that the most appropriate model is used for a given task

1. Introduction

As wind energy developments increase globally both onshore and offshore (Lewis & Wiser 2007; Snyder & Kaiser 2009; Bilgili, Yasar & Simsek 2011; Wang, Qin & Lewis 2012), the potential associated environmental impacts are receiving considerable attention, particularly avian impacts. Typically, wind energy developments require an environmental impact assessment to quantify the potential risk to the environment. The potential impacts of wind farms on bird populations can be grouped into three main types: direct mortality due to collision with turbines/infrastructure; physical habitat modification and/or loss; and avoidance responses of birds to turbines (Fox *et al.* 2006; Langston 2013). Avian collision has received much attention as it is considered a very real threat to bird populations (Johnson *et al.* 2002; Krijgsveld *et al.* 2009) and a variety of methods have been developed to aid the assessment of the risk of collision. The methods can be categorized as those that measure and assess collisions empirically including direct and remote observations of bird flights in the development area (pre- and post-construction of the wind turbines) to assess flight behaviour, habitat use and flux of birds (Desholm & Kahlert 2005; Desholm *et al.* 2006; Douglas *et al.* 2012) and corpse searches to document actual collisions (Winkelman 1992; Huso & Dalthorp 2014), and those which are more theoretical such as collision risk models which predict likely collisions (Holmstrom *et al.* 2011; Eichhorn *et al.* 2012; Smales *et al.* 2013). In addition to estimating collisions between birds and wind turbines, collision risk models (CRMs) are used in a range of other situations including marine mammals and marine renewable energy devices i.e. tidal stream turbines (Wilson *et al.* 2006), fish and turbines (Hammar & Ehnberg 2013) and shipping collisions with moving and stationary objects (Montewka *et al.* 2010).

At their core, most avian collision risk models include a calculation of the probability of a collision occurring (assuming no evasive action or behaviour) and a measure of the number of birds within a risk window in order to estimate the likely number of collision events. The probability of collision is generally based on the probability of a turbine blade occupying the same space as the bird during the time that the bird takes to pass through the rotor. This therefore relies upon information on both bird and wind turbine characteristics such as bird morphometrics and flight speed, turbine rotor speed and size, etc. In addition to the probability of collision, an understanding of bird avoidance behaviour is required if realistic estimates of collision events are to be predicted. In the UK, the most frequently used avian collision risk model is commonly known as 'the Band model' (Band, Madders & Whitfield 2007). Since its original development, it has undergone several iterations with the most recent associated with the Strategic Ornithological Support Services (SOSS) (B Band, 2012). However, it is not the only collision risk model available to predict potential collisions of birds with wind turbines, and others are used outside of the UK and vary in their approach to assessing avian collision risk.

The aim of this review therefore is to discuss the range of avian collision risk models in order to raise awareness of those available, their strengths and limitations. In addition we qualitatively compare models, and highlight when it may be appropriate to use different models, as well as discussing the interpretation of results. Finally, we also suggest where future efforts should be focussed to advance collision risk modelling.

2. The collision risk models

The peer-reviewed scientific literature and the grey literature were extensively reviewed for references to avian collision models. Using Web of Science, Google and Google Scholar we searched for relevant peer-reviewed papers, reports, conference proceedings and book chapters relating to wind farms and collision risk models. The search terms used were "collision risk model or CRM or collision model" refined by "bird or avian or ornithology or ornithological" and "wind farm or wind turbine or windmill". We identified 10 distinct collision risk models referring to birds and wind turbines, the earliest dating back to 1996 (Tucker 1996a). We defined the Band model and its various options and iterations as one model, though we will discuss the different versions below. We are aware other models are available, but following our literature review we were unable to find any documentation for these models, and were unable to contact the model developers. In this section we present brief descriptions of the collision risk models available, ordered chronologically in an effort to show the development and history of this field of research. We do not provide the fine mechanistic detail required to reproduce any single model but rather an overview of the methods available. The original intention of the project was to quantitatively compare models, but this was not possible as insufficient details were provided to do so. Although commercial confidentially is often given as the reason for a lack of detail regarding collision risk models, increased transparency would increase confidence in the final model outputs.

2.1 Tucker (1996)

Tucker (1996) was the first to publish a complete analysis of bird-rotor collisions and went on to show how rotors could be designed so fewer birds collide for an equivalent energy generation (Tucker 1996b). "The model analyses the motions and dimensions of both birds and propeller-type rotor blades, and predicts the probability of a collision when the bird flies through the area swept by the blades." (Tucker 1996a) but does not estimate a likely number of collisions as a measure of bird density or flux through the turbine is not included. The probability of collision is calculated as a ratio of the time taken for a bird to move through the rotor swept area compared to the time taken for the turbine blades to complete a single revolution. In the model the theoretical blades are either one, or three dimensional consisting of length, chord and twist but no thickness. Collision with the static turbine tower is not considered in the calculations. The bird moves on fixed wings i.e. gliding not flapping, and is two-dimensional and rectangular with wingspan being greater than body length (Figure 1b). It is therefore the corners of the rectangle which collide with either the leading or trailing edges the blades. The bird always moves perpendicular or parallel to the turbine rotor but flight can be parallel or oblique to the wind direction and the model can accommodate upwind or downwind flight. Avoidance behaviour of the bird is mostly not included in this model though it assumes that there is an inner radius at the turbine hub where birds will always avoid collision with the blades as it is a slow moving object.

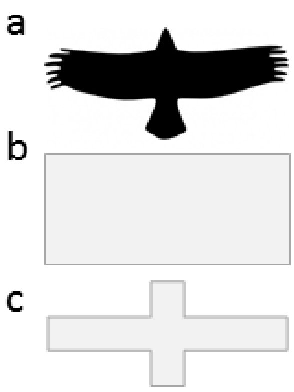

Figure 1. Modelled representation of bird (a) as either rectangular (b) or cruciform (c).

2.2 Band (2012)

The approach was originally developed for onshore wind turbines and promoted as guidance by Scottish Natural Heritage (Scottish Natural Heritage 2000). It has been further developed by Band et al. (2007) and more recently for application in the offshore environment by Band (2012). Similar to Tucker (1996) this model is based on the probability of a turbine blade occupying the same space as a bird during the time it takes the bird to pass through the rotor swept volume of the turbine. The probability of collision relies on information about the bird (wing span, body length, flight speed, flight height, nocturnal flight activity) and the turbine (blade width, blade length, blade pitch, rotor speed, hub height, operational time). The bird is assumed to be cruciform i.e. cross-shaped (Figure 1c), though this simplification may underestimate collision risk and the turbine blade is assumed to have a width (chord) and a pitch angle but no thickness. The model only considers flights that are parallel to the wind i.e. perpendicular to rotation of turbine and assumes that the effects of approaching the turbine at oblique angles will cancel each other out though this may underestimate collision risk (Band 2012b). It also only considers the moving rotor excluding the stationary elements such as the tower.

(a) 'Basic' Band model

The approach of the original model (Band, Madders & Whitfield 2007) had two stages for estimating the number of collisions per annum which included calculating: i) the number of birds flying through the rotor and ii) the probability of collision from a single transit of a rotor. The probability of collision is calculated at fixed intervals along the rotor blade and then averaged over the rotor swept area. The more recent offshore iteration of the model (Band, 2012) includes a method to use boat-based survey data i.e. densities, rather than vantage point data to calculate the number of birds flying through the rotor. This modification is necessary due to the different data collection techniques applied in the onshore and offshore environments. The most recent version also includes a measure of avoidance behaviour, allowing for a proportion of birds to avoid collision.

(b) 'Extended' Band model

The extended model is built on the basic model. The basic model assumes a uniform distribution of birds across the rotor swept area of the turbine. However, it was recognised that the distribution of birds, as well as the width of the turbine, all vary with height within the rotor swept area, thus affecting the collision risk. It is not possible to consider each of these individually due to covariance, however it is possible to use flight height curves (Johnston *et al.* 2014) to calculate the probability of a bird flying at a particular height within the turbine rotor sweep and colliding with a turbine blade. These individual probabilities are then be integrated to gain the collision integral. Although the extended Band model is considered a more realistic model than the basic model, it is potentially more sensitive to uncertainty, particularly in relation to flight height estimates (Cook *et al.* 2014).

2.3 McAdam (2005)

This Monte Carlo model is based on the original Band model (Scottish Natural Heritage 2000) but includes stochastic modifications to account for variation in flight height and the effects of wind. For the height-sensitive variant of the model, it calculates the probability of a bird being struck, given that it passed through the plane of the turbine at a given height h and at a distance less than the rotor length from the centre. The model also considered the effect of variation in wind on collision probability by varying bird speed and direction through the turbine. The model includes oblique angles of approach but does not take into account the variation in bird orientation relative to the turbine.

2.4 Smales et al. (2013)

The collision risk model developed by Biosis Propriety Limited has been widely used to assess wind-energy developments in Australia since 2002 (Smales *et al.* 2013). The model provides a predicted number of collisions between turbines and a local or migrating population of birds. It uses a deterministic approach but has the potential to be modified to accommodate Monte Carlo simulation. Unlike other models, it includes collision with static components of the wind turbine such as the tower. It also does not assume that birds always approach the turbine perpendicular to the blades or from a specific angle but rather flights can approach turbines from any direction meaning all dimensions of the turbine contribute to the area with which a flying bird might collide and the model uses a mean presented area. The model also estimates collision risk as the sum of the average number of turbines encountered per flight within a scattered wind turbine array, rather than for all turbines in an array. The average number of turbines likely to be encountered is calculated using a topological, non-affine mapping technique (Smales *et al.* 2013).

2.5 Bolker et al. (2014)

This collision risk model is based on the geometry of the wind farm and was developed to determine the average number of turbines encountered if birds move through a wind farm, in particular the Cape Wind project in Nantucket Sound of the coast of Massachusetts. It makes the assumption, similar to other models such as the Band model, that birds fly in straight lines, and that the probability of collision is fixed and known and that it incorporates any avoidance behaviour. It also only includes collisions with the rotors and does not include any other related infrastructure.

2.6 Desholm (2006)

The author presents a stochastic simulation model developed to estimate the number of bird fatalities at a wind farm, using the case study of the Nysted offshore wind farm in Denmark. The assessment includes variability in the input parameters of the model. The model includes information on bird migration volume, proportion of birds entering the wind farm, proportion of birds within the horizontal range of the rotor-blades, proportion of birds in the vertical range of the rotor-blades, proportion of birds trying to cross the area swept by the rotor without showing avoidance, the mean number of turbine rows passed, and also the probability of passing safely through the rotor by chance. The probability of passing safely through the rotor by chance was assumed to be fixed and taken from Tucker (1996) rather than calculated directly. Information on wind direction was also included and influenced both the orientation of the blades (and therefore the proportion of birds in horizontal reach of the blades) and the probability of passing safely through the swept area, as it is known that the probability of collision differs upwind and downwind.

2.7 Podolsky (2008)

This model is presented in a patent document (Podolsky 2008) and describes the bird, the turbine and the wind farm. The model follows a similar method to Band et al., (2007) and Tucker (1996) calculating the distance travelled across the rotor disc and thus the time required which is then compared to rotor speed and the time required for a single revolution of the blades. The bird is represented as a cross with length and wingspan and uses the largest linear dimension of the bird so that the most conservative results are produced. The model considers oblique angles of approach, not only those parallel to the wind and includes a proportion of birds which avoid collision. The probability of collision is calculated for a bird colliding with a single rotor and subsequently the model calculates the probability of collision for a given row of wind turbines and for multiple rows.

2.8 Holmstrom et al. (2011)

The Hamer model presented by Holmstrom et al. (2011) is based on that of Tucker (1996). This model however includes oblique angles of approach flight to the wind turbine, which the authors suggests, “provides important improvements over existing models since birds’ flight paths are not always dependent on wind direction” (Holmstrom *et al.* 2011). As with Tucker (1996) the model only considers the calculation of collision probability for a single transit and a single turbine rotor. It only estimates collision risk for a single bird passing through the rotor plane and avoidance behaviour is also not considered within the model (apart from close to the hub) rather it should be incorporated after calculating the mathematical risk of collision.

2.9 Eichhorn et al. (2012)

The purpose of the simulation model produced by Eichhorn et al. (2012) was to determine the annual mortality of a central-place forager, the red kite *Milvus milvus*, as a function of the distance to the bird’s nest and a wind turbine. The model assesses collision risk as a function of distance to turbine, nests and other parameters and combines an agent-based spatial model with a collision risk model. The agent-based model is based on movement processes and two events (collision and prey capture) and movements of individuals are based on decision rules according to habitat quality. “Collisions can occur when an individual occupies a habitat cell where a wind turbine is located, flies at the height of the rotor blades and moves through the part of the cell affect by the rotors” (Eichhorn *et al.* 2012). Should a bird co-occur in space with a wind turbine, the probability of collision is calculated using stage 2 of the Band model (Band, Madders & Whitfield 2007) i.e.

probability of collision from a single rotor transit. This is an example of where a component of another collision risk model has been used rather than developing another method.

2.10 U.S. Fish and Wildlife Service (2013)

The U.S. Fish and Wildlife Service have developed a collision risk model for predicting eagle fatalities that uses a Bayesian estimation framework (U.S. Fish and Wildlife Service 2013; New *et al.* 2015) and is based on eagle exposure to wind turbine hazards. In this model, the total annual eagle fatalities is the product of the rate of eagle exposure to turbines, the probability that eagle exposure will result in a collision with a turbine, and an expansion factor that scales the fatality rate to a predicted number of annual fatalities. The exposure rate is the expected number of exposure events i.e. eagles present (per hour per km^2) in the area of interest. The probability of collision given exposure is based on Whitfield (2009) but any suitable data and studies could theoretically be used. Finally the expansion factor is based on information on the number of turbines and the hazardous area surrounding a turbine. The model does not include detail on the mechanisms of collision but uses the Bayesian method which allows for adaptive management and the updating of information such as actual collision events, over time, as it becomes available. This model is therefore more suitable for onshore wind farm developments where corpse searches are possible, unlike at offshore facilities.

3. Model comparisons

From the model descriptions above it can be seen that there has been a development of collision risk models over time, each with its own purpose, though some clearly influenced by others. Subsequently there is an array of models to choose from that include different components and use different approaches (Table 1). However, of the models included in this review, it is possible to say they comprise two main elements: i) the number of birds exposed to turbines and therefore a risk of collision; and ii) the probability of an individual bird colliding. Many of the differences between models relate to the former rather than the latter. Here we shall compare some of these aspects to highlight similarities and differences which may influence the applicability and suitability of a given model to a given problem.

[INSERT TABLE 1 NEAR HERE]

3.1 Probability of collision

All of the models presented here incorporate a probability of collision for a single transit of a bird through a turbine rotor i.e. an interaction with a wind turbine, however there is variation in how this is estimated or included, and in the complexity of the calculations. Some of the models, for example Tucker (1996), calculate a probability of collision that varies according to bird and turbine parameters i.e. a mechanistic model. Other, more complex, models have been developed based on Tucker (1996a) and Band (Scottish Natural Heritage 2000) but have been adapted for a specific application. For example, Eichhorn *et al.* (2012) used the probability of collision component from the Band model in their individual based model of red kite foraging. In addition and by contrast, several authors (Desholm 2006; Bolker, Hatch & Zara 2014) have chosen to use a constant probability of collision rather than calculate a variable collision probability. The use of a single constant probability removes the theoretical calculation of the probability of collision as presented by Tucker (1996) for example, and the associated uncertainty of factors such as avoidance. As an alternative to this the U.S. Fish and Wildlife Service (2013) have developed a Bayesian method which does not calculate the probability of collision mechanistically and is therefore more similar to those that use a constant but by contrast, their method allows for the estimate of probability of collision to be amended and updated when information becomes available.

3.2 Bird shape

For those models that follow a mechanistic approach to including and calculating a probability of collision, they must include a simplified representation of a flying bird. Tucker (1996) uses a rectangular representation of a bird whereas Band et al., (2007) uses a cruciform representation (Figure 1). It is thought that both slightly underestimate the actual collision risk as a bird is larger than these representation, however the latter gives slightly lower estimates (Holmstrom *et al.* 2011). It is unlikely that the choice of bird shape will dramatically affect the results more than other factors.

3.3 Angle of approach

Models differ in the assumptions made about bird movement and flight, and in particular the angle of approach to the turbine. However, the collision risk is dependent on the angle of approach. Flight paths can be assumed to be perpendicular to the axis of rotation of the turbine or they can be oblique. Birds on oblique angles of approach, rather than perpendicular, are presented with a reduced cross-sectional area of risk. However, should the bird pass through the area of risk, the time required to clear the rotor blades is extended, therefore increasing the risk of collision. Band (2012) assumes all flights to be perpendicular, and that oblique angles of approach will cancel out. This may not always be the case in all situations, for example it is possible that for a turbine placed near a seabird breeding colony, the birds may follow different flight paths in and out of the colony, and they might not be perpendicular to the turbines. Therefore the birds would only be approaching the turbines from a limited number of angles, and thus these would not cancel out. In addition, this does not consider the varying speed of blade approach relative to the bird movement across the rotor. Tucker (1996a) also only considers flights parallel to the wind direction i.e. perpendicular to rotor axis, for the calculations of collision risk in 3 dimensions. However, the Hamer model (Holmstrom *et al.* 2011) explored the importance to oblique angles of approach, building on the original analyses of Tucker (1996a). Using a case study of raptor migration, Holmstrom et al. (2011) demonstrate that the angle of approach has a significant effect on the probability of collision and thus the estimates of mortality, with estimated collision probabilities as much as 31% higher than those estimated for downwind flight. It is therefore important to ascertain which model is more appropriate for the case study and that this may be different for long distance migration than for breeding seabirds foraging from a colony.

3.4 Collisions with stationary components

Another difference the between models is that the majority include only the moving rotor in the collision estimate, because it is assumed that birds will avoid non- or slow-moving parts however Smales et al. (2013) include the stationary turbine tower as well. This therefore means that the collision risk estimated using the method described in Smales et al. (2013) may be greater than estimated using other methods. There is evidence of collisions of birds with fixed structures such as communications towers and fences, as well as power lines (Bevanger 1995; Baines & Andrew 2003; Martin 2012; Loss, Will & Marra 2014). It is possible that some species, when flying and foraging in open airspace e.g. offshore , plains or prairies, and if turning their head to look downwards, will have little visual coverage of what lies ahead so making them particularly vulnerable to collisions with obstacles which are built into these otherwise predictably open airspaces (Martin 2012). Therefore for species known to be at risk of collision with these fixed structures it may be important to include them in the collision estimates as well as moving blades. Subsequently, in some circumstances it may result in species, for example tetraonids such as black grouse in the terrestrial environment or auks in the marine, being included in collision risk assessments which do not fly at heights which would put them at risk with collision with turbine blades (Johnston *et al.* 2014). It should be recognised that estimates are not comparable if they do not consider similar components of the turbines.

3.5 Onshore or offshore

The methods also differ in the setting for which they are developed and the questions that they were developed to address. The U.S. Fish and Wildlife Service model is a good example of this. The

Bayesian method allows for estimates to be updated when information is available. In this case, carcasses provide information on the actual number of collisions. The model was developed for eagles at onshore wind farms where carcass searches are possible, however this method would be less applicable for the offshore environment, although technologies such as Thermal Animal Detection Systems (TADS), as demonstrated offshore by Desholm (2006), may make this possible. The models also vary in perspective, with the majority being turbine-based and focussing on the number of birds encountering and colliding with a turbine (Band, Madders & Whitfield 2007; Smales *et al.* 2013). However, Eichhorn et al. (2012) present an agent-based model which considers collisions from the perspective of the individual and estimates the number of turbines a bird encounters.

3.6 Uncertainty

Uncertainty is a topic addressed to varying degrees within the different collision risk models. The majority of models (Tucker 1996a; Podolsky 2008; Holmstrom *et al.* 2011; Smales *et al.* 2013) are deterministic and do not consider data or parameter uncertainty within the model (Masden *et al.* 2015). The Band model is also deterministic but in the latest iteration of the model, the guidance provides a method to express the uncertainty associated with a collision estimate *post hoc* (Band 2012b). Smales *et al.* (2013) is similarly deterministic however the authors suggest that it would be possible to use Monte Carlo methods to introduce stochasticity into the model. By contrast, McAdam (2005) used a Monte Carlo model to consider joint distributions of wind speed and direction and distributions of flight height to produce collision risk estimates with associated measures of uncertainty and the U.S. Fish and Wildlife Service model uses Bayesian methods which allows for the consideration of uncertainty. Including a measure of uncertainty in collision estimates moves CRM towards a risk-based framework, providing information not only on the magnitude of an event but also on the probability of occurrence.

Uncertainty may also be considered in terms of information available about the model structure i.e. model uncertainty, not only the data and model output (Masden *et al.* 2015). Within this review we provide a qualitative comparison and have adopted a descriptive approach because details about the model structure were often incomplete. Therefore another difference between the models is the quantity and quality of detail provided and whether the model and a detailed description have been subjected to peer-review. This does not signify or relate to the quality of the model itself, but to the information available. Models such as Tucker (1996), Holmstrom et al. (2011) and Eichhorn et al. (2012) have been presented and published in the scientific peer-reviewed literature and Band et al. (2007) has been subjected to scrutiny (Chamberlain *et al.* 2006) but it is not always transparent as to the degree of scrutiny and peer-review that the models may have been exposed to. Economically important decisions are being made on the basis of the outputs from collision risk modelling, so it is important that tools used to reach these conclusions are subject to scrutiny. Transparency is vital as wind farm applications may be rejected on the basis of the predicted collision rate, for example Docking Shoal was turned down due to the collision risk estimate for Sandwich tern (Department of Energy and Climate Change 2012). The method of estimation should therefore be clear and available to be scrutinised.

4. Limitations and assumptions

Although CRMs are a useful tool to estimate likely collisions of birds with wind turbines, and provide information on the potential environmental impacts of wind farm developments, they also have limitations and it is important that these are recognised to ensure that the data outputs are used appropriately.

Potentially the greatest limitation of CRMs is that they generally assume much about bird behaviour. For example, the majority of models assume a linear relationship between bird abundance and collision risk which may not be true for all situations (de Lucas *et al.* 2008); there may be interactions between topography, species-specific behaviour, turbine layout, and wind (Barrios & Rodriguez 2004; Smallwood, Rugge & Morrison 2009; Schaub 2012; de Lucas, Ferrer & Janss 2012). In addition many of the models include avoidance behaviour in the form of an avoidance rate which assumes that a certain proportion of those birds on a collision path, will take avoiding action before a collision occurs. Most models assume that avoidance behaviour is constant across all individuals within a species and this is unlikely. However, there is very limited data available on avoidance rates and estimating variability between species is difficult, least of all within a species (Cook *et al.* 2014).

Also some models such as B Band (2012) assume a constant flux of birds through a wind farm. Such models assume that there are X birds within the wind farm at any given time, each of which takes Y seconds to fly through the rotor. From these data it is possible to estimate the total number of birds passing through a wind farm in a day or year based on the speed of the birds (typically mean flight speed). However, if the birds are not flying at the reported speed, or not commuting through the wind farm but instead moving tortuously within the area (Patrick *et al.* 2014), it is possible to over-estimate the number of birds flying through the wind farm in a given time period, and consequently elevate the total number of collisions; inflated estimates of collision rates can be of serious consequence and cost for a wind farm developer. This is likely the case also for models that use data from vantage point surveys, for example the model developed by the U.S. Fish and Wildlife Service

(2013) uses data on the number of expected exposure events. It may be difficult to distinguish whether two observations of a bird are the same individual or different. This distinction is important because each bird can only collide once (if we assume collision equates to mortality) and if the number of birds using the area is overestimated, it is possible to overestimate the total number of collisions. Eichhorn et al. (2012) circumvent this limitation using an agent-based model to describe movements of individual birds through a landscape and applying a collision risk to each interaction of an individual with a wind turbine, though such a method can be computationally intensive.

Another limitation of collision risk models is that they are frequently 'data hungry' in situations where data availability is often limited. For example, mechanistic models such as B Band (2012) have many input parameters relating both to the birds (flight speed, morphometrics, etc.) and the turbines (rotor speed, blade width, etc.). In relation to birds, there is still much to be learned about behaviour and therefore our knowledge of aspects required within the models, such as flight speed, is limited. This is improving with the development of biologging technologies such as miniaturised GPS tags but often data are limited to the breeding season. In addition for offshore wind, many of the turbines suggested for offshore projects are still under development and therefore only design envelopes can be provided, i.e. a range of values for any given parameter. The approach developed by U.S. Fish and Wildlife Service (2013) removes some of these data requirements by using a Bayesian framework, however it relies on the ability to collect data on actual collisions to validate the model, and thus currently limits the approach to onshore sites. Therefore a Bayesian method is unlikely to be suitable for offshore sites without development of methods to collate data on collisions and therefore a mechanistic theoretical modelling approach will be required, else a constant collision risk be applied.

Not only a lack of data on model inputs but also the opportunities for model validation or lack thereof, is a limitation of collision risk models. Collision risk models are rarely validated, but where they have been, predictions from EIA often show only a weak relationship with observed effects and predictor variables. Ferrer *et al.* (2012) found no relationship between variables predicting risk from EIAs and actual mortality, and only a weak relationship between mortality and the numbers of the study species crossing the area. Similarly, De Lucas et al. (2008) found a weak relationship between abundance and recorded collisions and in addition Everaert (2014) found larger gulls were more likely to collide than smaller birds. More specifically, opportunities for model validation are particularly limited for offshore wind farms because bird mortality events are more difficult to document in the offshore environment as corpses do not remain in the area. In the terrestrial environment i.e. onshore, the U.S. Fish and Wildlife Service (2013) model uses a Bayesian framework within which information can be updated. Although this is not validation, the input of empirical mortality data from corpse searches, allows for the collision estimate to be refined. However, until the collection of mortality data from offshore developments becomes standard practice, Bayesian collision risk models are unlikely to be a feasible option.

Collision risk models are a tool, but only a tool, to aid in the assessment of impacts and management of wind farm developments, and it is important to remember that "Essentially, all models are wrong, but some are useful" (Box & Draper 1987). Due to the limitations of collision risk models discussed above and the assumptions made within each, at present the model estimates provide a means of comparison between different development or management options but the estimates should only be considered indicative and never absolute.

5. Future model developments

Since the first avian collision risk models were created (Tucker 1996a; Scottish Natural Heritage 2000) there have been significant developments in the wind energy industry. Wind turbines have increased in size and energy rating, wind turbine arrays or wind farms have increased in area and number, and wind energy projects have moved offshore, and may move further with the development of floating wind turbines. Collision risk modelling tools must also accommodate these developments to ensure they are fit for purpose, as well as incorporating new methods that become available. From here on in we discuss the areas where we consider that advances in collision risk modelling will likely make the greatest contribution to impact assessments.

Despite the acknowledgement that the environment is variable, the majority of collision risk models to date have been deterministic, excluding variability and/or uncertainty from calculations. Some model input parameters will have associated variability, for example bird body length, others may be expected to be point estimates with associated uncertainty, such as turbine rotor radius, and some parameters may have both variability and uncertainty. The incorporation of uncertainty in future models would reduce the possibility that a collision estimate was driven by the choice of a single input parameter value.

Marques et al. (2014) suggest that collision risk is related to individual bird behaviour, as well as phenology, landscape type, and weather. Collision may also depend on the spatial distribution and configuration of turbines in arrays (de Lucas *et al.* 2008; Ferrer *et al.* 2012). If such factors were incorporated into collision risk models it may be possible to move away from situations where bird survey data collected during the environmental impact assessments of developments and bird abundance are only weakly related to mortality events at wind farm sites (de Lucas *et al.* 2008;

Ferrer *et al.* 2012). Systematic research into the factors affecting mortality events is much needed and with ever increasing amounts of post-construction data, this should be plausible, assuming suitable experimental and/or survey design. Improving our understanding of bird behaviour including avoidance behaviour, would also greatly improve collision risk estimates. With telemetry data becoming available from bird tracking projects it may also be possible to improve our knowledge of bird flight speeds, and potentially in relation to wind conditions. Information from tracking projects could also be used to better understand how birds use wind farms. The data would allow for the assessment of bird movements in and around wind farms and it would be possible to determine the suitability of the oft-used assumption of constant flux.

An alternative approach to the increasingly complex mechanistic or kinematic models for collision risk estimation which are known to lack validation, is to use more simpler models but within a Bayesian framework (U.S. Fish and Wildlife Service 2013). Such models can accommodate increasing complexity, however in the absence of knowledge, these models remain simple, using empirical data on actual collision events to determine parameter values. The Bayesian framework may be progressively used more if these increasingly mechanistic models fail to deliver improvements to the collision risk estimates, and the relationships between predicted and observed mortalities remain weak.

6. Conclusions

Avian collision risk models are a valuable tool used in the impact assessment of windfarms, both on- and offshore. Although the Band model (Band, Madders & Whitfield 2007) is the most frequently used within the UK, a variety of models have been developed and are available to use. These models vary in their suitability for different situations and circumstances, due to the specific case or development they were designed for. Therefore it is important that the most appropriate model or method is used or adapted for the question at hand, and in some situations this may not always be the most frequently used model. This is particularly important as all wind energy stakeholders (developers, consultants, regulators, advisers and conservation organisations) must have confidence in the methods used. Failure to ensure this can lead to disputes and lengthy discussions over project details, potentially causing mistrust and costly delays in the consenting process, to no benefit.

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Model name and reference	Base model	Includes avoidance behaviour	No. of turbines	Tower included	Wind speed/direction included	Oblique angles of approach	Individual or population	Onshore or offshore example	Stochastic	Model output
Band (Band 2012)	-	Y	Multiple	N	N	N	Population	Offshore	N	Number of birds colliding
Tucker (Tucker 1996)	-	N	Single	N	N	N	Individual	-	N	Probability of collision
Biosis (Smales *et al.* 2013)	-	Y	Multiple	Y	N	Y	Population	Onshore	N	Number of birds colliding
Podolsky (Podolsky 2008)	-	Y	Multiple	Y	N	Y	Individual	Onshore	N	Probability of collision
McAdam (McAdam 2005)	Band	N	Single	N	Speed & direction	Y	Individual	Offshore	Y	Probability of collision
Desholm (Desholm 2006)	-	Y	Multiple	N	Direction	N	Population	Offshore	Y	Number of birds colliding
Eichhorn (Eichhorn *et al.* 2012)	Band	Y	Single	N	N	N	Individual	Onshore	Y	Mortality rate
Hamer (Holmstrom *et al.* 2011)	Tucker	N	Single	N	Speed & direction	Y	Individual	-	N	Probability of collision
Bolker (Bolker, Hatch & Zara 2014)	-	N	Multiple	N	N	Y	Individual	Onshore	N	Probability of collision
USFWS (U.S. Fish and Wildlife Service 2013)	-	Y	Multiple	Not specified	N	N	Population	Onshore	Y	Number of birds colliding

Table 1: Summary of avian collision risk models.