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1 **Title: Avian collision risk models for wind energy impact assessments**

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7 **Abstract:**

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

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

24 **Highlights:**

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

29

30 1. Introduction

31 As wind energy developments increase globally both onshore and offshore (Lewis & Wiser 2007;
32 Snyder & Kaiser 2009; Bilgili, Yasar & Simsek 2011; Wang, Qin & Lewis 2012), the potential
33 associated environmental impacts are receiving considerable attention, particularly avian impacts.
34 Typically, wind energy developments require an environmental impact assessment to quantify the
35 potential risk to the environment. The potential impacts of wind farms on bird populations can be
36 grouped into three main types: direct mortality due to collision with turbines/infrastructure; physical
37 habitat modification and/or loss; and avoidance responses of birds to turbines (Fox *et al.* 2006;
38 Langston 2013). Avian collision has received much attention as it is considered a very real threat to
39 bird populations (Johnson *et al.* 2002; Krijgsveld *et al.* 2009) and a variety of methods have been
40 developed to aid the assessment of the risk of collision. The methods can be categorized as those
41 that measure and assess collisions empirically including direct and remote observations of bird
42 flights in the development area (pre- and post-construction of the wind turbines) to assess flight
43 behaviour, habitat use and flux of birds (Desholm & Kahlert 2005; Desholm *et al.* 2006; Douglas *et al.*
44 2012) and corpse searches to document actual collisions (Winkelman 1992; Huso & Dalthorp 2014),
45 and those which are more theoretical such as collision risk models which predict likely collisions
46 (Holmstrom *et al.* 2011; Eichhorn *et al.* 2012; Smales *et al.* 2013). In addition to estimating collisions
47 between birds and wind turbines, collision risk models (CRMs) are used in a range of other situations
48 including marine mammals and marine renewable energy devices i.e. tidal stream turbines (Wilson
49 *et al.* 2006), fish and turbines (Hammar & Ehnberg 2013) and shipping collisions with moving and
50 stationary objects (Montewka *et al.* 2010).

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

63 of birds with wind turbines, and others are used outside of the UK and vary in their approach to
64 assessing avian collision risk.

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

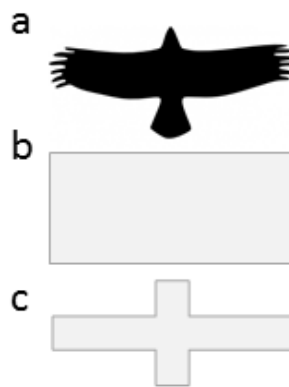
70 2. The collision risk models

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

88 2.1 Tucker (1996)

89 Tucker (1996) was the first to publish a complete analysis of bird-rotor collisions and went on to
90 show how rotors could be designed so fewer birds collide for an equivalent energy generation
91 (Tucker 1996b). “The model analyses the motions and dimensions of both birds and propeller-type
92 rotor blades, and predicts the probability of a collision when the bird flies through the area swept by
93 the blades.” (Tucker 1996a) but does not estimate a likely number of collisions as a measure of bird
94 density or flux through the turbine is not included. The probability of collision is calculated as a ratio

95 of the time taken for a bird to move through the rotor swept area compared to the time taken for
96 the turbine blades to complete a single revolution. In the model the theoretical blades are either
97 one, or three dimensional consisting of length, chord and twist but no thickness. Collision with the
98 static turbine tower is not considered in the calculations. The bird moves on fixed wings i.e. gliding
99 not flapping, and is two-dimensional and rectangular with wingspan being greater than body length
100 (Figure 1b). It is therefore the corners of the rectangle which collide with either the leading or
101 trailing edges the blades. The bird always moves perpendicular or parallel to the turbine rotor but
102 flight can be parallel or oblique to the wind direction and the model can accommodate upwind or
103 downwind flight. Avoidance behaviour of the bird is mostly not included in this model though it
104 assumes that there is an inner radius at the turbine hub where birds will always avoid collision with
105 the blades as it is a slow moving object.



106

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

108 2.2 Band (2012)

109 The approach was originally developed for onshore wind turbines and promoted as guidance by
110 Scottish Natural Heritage (Scottish Natural Heritage 2000). It has been further developed by Band et
111 al. (2007) and more recently for application in the offshore environment by Band (2012). Similar to
112 Tucker (1996) this model is based on the probability of a turbine blade occupying the same space as
113 a bird during the time it takes the bird to pass through the rotor swept volume of the turbine. The
114 probability of collision relies on information about the bird (wing span, body length, flight speed,
115 flight height, nocturnal flight activity) and the turbine (blade width, blade length, blade pitch, rotor
116 speed, hub height, operational time). The bird is assumed to be cruciform i.e. cross-shaped (Figure
117 1c), though this simplification may underestimate collision risk and the turbine blade is assumed to
118 have a width (chord) and a pitch angle but no thickness. The model only considers flights that are
119 parallel to the wind i.e. perpendicular to rotation of turbine and assumes that the effects of

120 approaching the turbine at oblique angles will cancel each other out though this may underestimate
121 collision risk (Band 2012b). It also only considers the moving rotor excluding the stationary elements
122 such as the tower.

123 (a) 'Basic' Band model

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

133 (b) 'Extended' Band model

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

143 2.3 McAdam (2005)

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

152 2.4 Smales et al. (2013)

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

165 2.5 Bolker et al. (2014)

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

172 2.6 Desholm (2006)

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

183 the proportion of birds in horizontal reach of the blades) and the probability of passing safely
184 through the swept area, as it is known that the probability of collision differs upwind and downwind.

185 2.7 Podolsky (2008)

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

195 2.8 Holmstrom et al. (2011)

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

204 2.9 Eichhorn et al. (2012)

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

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

217 2.10 U.S. Fish and Wildlife Service (2013)

218 The U.S. Fish and Wildlife Service have developed a collision risk model for predicting eagle fatalities
219 that uses a Bayesian estimation framework (U.S. Fish and Wildlife Service 2013; New *et al.* 2015) and
220 is based on eagle exposure to wind turbine hazards. In this model, the total annual eagle fatalities is
221 the product of the rate of eagle exposure to turbines, the probability that eagle exposure will result
222 in a collision with a turbine, and an expansion factor that scales the fatality rate to a predicted
223 number of annual fatalities. The exposure rate is the expected number of exposure events i.e. eagles
224 present (per hour per km²) in the area of interest. The probability of collision given exposure is based
225 on Whitfield (2009) but any suitable data and studies could theoretically be used. Finally the
226 expansion factor is based on information on the number of turbines and the hazardous area
227 surrounding a turbine. The model does not include detail on the mechanisms of collision but uses
228 the Bayesian method which allows for adaptive management and the updating of information such
229 as actual collision events, over time, as it becomes available. This model is therefore more suitable
230 for onshore wind farm developments where corpse searches are possible, unlike at offshore
231 facilities.

232 3. Model comparisons

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

242 [INSERT TABLE 1 NEAR HERE]

243 3.1 Probability of collision

244 All of the models presented here incorporate a probability of collision for a single transit of a bird
245 through a turbine rotor i.e. an interaction with a wind turbine, however there is variation in how this

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

260 3.2 Bird shape

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

267 3.3 Angle of approach

268 Models differ in the assumptions made about bird movement and flight, and in particular the angle
269 of approach to the turbine. However, the collision risk is dependent on the angle of approach. Flight
270 paths can be assumed to be perpendicular to the axis of rotation of the turbine or they can be
271 oblique. Birds on oblique angles of approach, rather than perpendicular, are presented with a
272 reduced cross-sectional area of risk. However, should the bird pass through the area of risk, the time
273 required to clear the rotor blades is extended, therefore increasing the risk of collision. Band (2012)
274 assumes all flights to be perpendicular, and that oblique angles of approach will cancel out. This may
275 not always be the case in all situations, for example it is possible that for a turbine placed near a
276 seabird breeding colony, the birds may follow different flight paths in and out of the colony, and
277 they might not be perpendicular to the turbines. Therefore the birds would only be approaching the

278 turbines from a limited number of angles, and thus these would not cancel out. In addition, this
279 does not consider the varying speed of blade approach relative to the bird movement across the
280 rotor. Tucker (1996a) also only considers flights parallel to the wind direction i.e. perpendicular to
281 rotor axis, for the calculations of collision risk in 3 dimensions. However, the Hamer model
282 (Holmstrom *et al.* 2011) explored the importance to oblique angles of approach, building on the
283 original analyses of Tucker (1996a). Using a case study of raptor migration, Holmstrom *et al.* (2011)
284 demonstrate that the angle of approach has a significant effect on the probability of collision and
285 thus the estimates of mortality, with estimated collision probabilities as much as 31% higher than
286 those estimated for downwind flight. It is therefore important to ascertain which model is more
287 appropriate for the case study and that this may be different for long distance migration than for
288 breeding seabirds foraging from a colony.

289 3.4 Collisions with stationary components

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

307 3.5 Onshore or offshore

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

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

320 3.6 Uncertainty

321 Uncertainty is a topic addressed to varying degrees within the different collision risk models. The
322 majority of models (Tucker 1996a; Podolsky 2008; Holmstrom *et al.* 2011; Smales *et al.* 2013) are
323 deterministic and do not consider data or parameter uncertainty within the model (Masden *et al.*
324 2015). The Band model is also deterministic but in the latest iteration of the model, the guidance
325 provides a method to express the uncertainty associated with a collision estimate *post hoc* (Band
326 2012b). Smales *et al.* (2013) is similarly deterministic however the authors suggest that it would be
327 possible to use Monte Carlo methods to introduce stochasticity into the model. By contrast,
328 McAdam (2005) used a Monte Carlo model to consider joint distributions of wind speed and
329 direction and distributions of flight height to produce collision risk estimates with associated
330 measures of uncertainty and the U.S. Fish and Wildlife Service model uses Bayesian methods which
331 allows for the consideration of uncertainty. Including a measure of uncertainty in collision estimates
332 moves CRM towards a risk-based framework, providing information not only on the magnitude of an
333 event but also on the probability of occurrence.

334 Uncertainty may also be considered in terms of information available about the model structure i.e.
335 model uncertainty, not only the data and model output (Masden *et al.* 2015). Within this review we
336 provide a qualitative comparison and have adopted a descriptive approach because details about
337 the model structure were often incomplete. Therefore another difference between the models is the
338 quantity and quality of detail provided and whether the model and a detailed description have been
339 subjected to peer-review. This does not signify or relate to the quality of the model itself, but to the
340 information available. Models such as Tucker (1996), Holmstrom *et al.* (2011) and Eichhorn *et al.*
341 (2012) have been presented and published in the scientific peer-reviewed literature and Band *et al.*
342 (2007) has been subjected to scrutiny (Chamberlain *et al.* 2006) but it is not always transparent as to

343 the degree of scrutiny and peer-review that the models may have been exposed to. Economically
344 important decisions are being made on the basis of the outputs from collision risk modelling, so it is
345 important that tools used to reach these conclusions are subject to scrutiny. Transparency is vital as
346 wind farm applications may be rejected on the basis of the predicted collision rate, for example
347 Docking Shoal was turned down due to the collision risk estimate for Sandwich tern (Department of
348 Energy and Climate Change 2012). The method of estimation should therefore be clear and available
349 to be scrutinised.

350 4. Limitations and assumptions

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

355 Potentially the greatest limitation of CRMs is that they generally assume much about bird behaviour.
356 For example, the majority of models assume a linear relationship between bird abundance and
357 collision risk which may not be true for all situations (de Lucas *et al.* 2008); there may be interactions
358 between topography, species-specific behaviour, turbine layout, and wind (Barrios & Rodriguez
359 2004; Smallwood, Ruge & Morrison 2009; Schaub 2012; de Lucas, Ferrer & Janss 2012). In addition
360 many of the models include avoidance behaviour in the form of an avoidance rate which assumes
361 that a certain proportion of those birds on a collision path, will take avoiding action before a collision
362 occurs. Most models assume that avoidance behaviour is constant across all individuals within a
363 species and this is unlikely. However, there is very limited data available on avoidance rates and
364 estimating variability between species is difficult, least of all within a species (Cook *et al.* 2014).

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

375 (2013) uses data on the number of expected exposure events. It may be difficult to distinguish
376 whether two observations of a bird are the same individual or different. This distinction is important
377 because each bird can only collide once (if we assume collision equates to mortality) and if the
378 number of birds using the area is overestimated, it is possible to overestimate the total number of
379 collisions. Eichhorn et al. (2012) circumvent this limitation using an agent-based model to describe
380 movements of individual birds through a landscape and applying a collision risk to each interaction
381 of an individual with a wind turbine, though such a method can be computationally intensive.

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

397 Not only a lack of data on model inputs but also the opportunities for model validation or lack
398 thereof, is a limitation of collision risk models. Collision risk models are rarely validated, but where
399 they have been, predictions from EIA often show only a weak relationship with observed effects and
400 predictor variables. Ferrer *et al.* (2012) found no relationship between variables predicting risk from
401 EIAs and actual mortality, and only a weak relationship between mortality and the numbers of the
402 study species crossing the area. Similarly, De Lucas et al. (2008) found a weak relationship between
403 abundance and recorded collisions and in addition Everaert (2014) found larger gulls were more
404 likely to collide than smaller birds. More specifically, opportunities for model validation are
405 particularly limited for offshore wind farms because bird mortality events are more difficult to
406 document in the offshore environment as corpses do not remain in the area. In the terrestrial
407 environment i.e. onshore, the U.S. Fish and Wildlife Service (2013) model uses a Bayesian framework

408 within which information can be updated. Although this is not validation, the input of empirical
409 mortality data from corpse searches, allows for the collision estimate to be refined. However, until
410 the collection of mortality data from offshore developments becomes standard practice, Bayesian
411 collision risk models are unlikely to be a feasible option.

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

418 5. Future model developments

419 Since the first avian collision risk models were created (Tucker 1996a; Scottish Natural Heritage
420 2000) there have been significant developments in the wind energy industry. Wind turbines have
421 increased in size and energy rating, wind turbine arrays or wind farms have increased in area and
422 number, and wind energy projects have moved offshore, and may move further with the
423 development of floating wind turbines. Collision risk modelling tools must also accommodate these
424 developments to ensure they are fit for purpose, as well as incorporating new methods that become
425 available. From here on in we discuss the areas where we consider that advances in collision risk
426 modelling will likely make the greatest contribution to impact assessments.

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

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

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

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

457 6. Conclusions

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

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475 References

476 Baines, D. & Andrew, M. (2003) Marking of deer fences to reduce frequency of collisions by
477 woodland grouse. *Biological Conservation*, **110**, 169–176.

478 Band, B. (2012a) *Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Windfarms -*
479 *with Extended Method: Worked Example.*

480 Band, B. (2012b) Using a collision risk model to assess bird collision risks for offshore windfarms.
481 *SOSS report, The Crown Estate.*

482 Band, W., Madders, M. & Whitfield, D.P. (2007) Developing field and analytical methods to assess
483 avian collision risk at wind farms. (eds M. De Lucas, G.F.E. Janss & M. Ferrer), Quercus, Madrid.

484 Barrios, L. & Rodriguez, A. (2004) Behavioural and environmental correlates of soaring-bird mortality
485 at on-shore wind turbines. *Journal of Applied Ecology*, **41**, 72–81.

486 Bevanger, K. (1995) Estimates and population consequences of tetraonid mortality caused by
487 collisions with high tension power lines in Norway. *Journal of Applied Ecology*, **32**, 745–753.

488 Bilgili, M., Yasar, A. & Simsek, E. (2011) Offshore wind power development in Europe and its
489 comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, **15**, 905–
490 915.

491 Bolker, E.D., Hatch, J.J. & Zara, C. (2014) Modeling how windfarm geometry affects bird mortality.

492 Box, G.E.P. & Draper, N.R. (1987) *Empirical Model-Building and Response Surfaces*. Wiley, New York.

493 Chamberlain, D.E., Rehfisch, M.R., Fox, A.D., Desholm, M. & Anthony, S.J. (2006) The effect of
494 avoidance rates on bird mortality predictions made by wind turbine collision risk models. *Ibis*,
495 **148**, 198–202.

496 Cook, A.S.C.P., Humphreys, E.M., Masden, E.A. & Burton, N.H.K. (2014) *The Avoidance Rates of*
497 *Collision between Birds and Offshore Turbines. Scottish Marine and Freshwater Science Volume*
498 *5 Number 16, Report Published by Marine Scotland Science.*

499 Department of Energy and Climate Change. (2012) Amended application for consent to construct and
500 operate an offshore wind farm known as Docking Shoal off the coast of north Norfolk,
501 <https://www.og.decc.gov.uk/EIP/pages/projects/DockingDecision.pdf>

502 Desholm, M. (2006) Wind farm related mortality among avian migrants - a remote sensing study and
503 model analysis. , **PhD.**

- 504 Desholm, M., Fox, A.D., Beasley, P.D.L. & Kahlert, J. (2006) Remote techniques for counting and
505 estimating the number of bird-wind turbine collisions at sea: a review. *Ibis*, **148**, 76–89.
- 506 Desholm, M. & Kahlert, J. (2005) Avian collision risk at an offshore wind farm. *Biology Letters*, **1**,
507 296–298.
- 508 Douglas, D.J.T., Follestad, A., Langston, R.H.W. & Pearce-Higgins, J.W. (2012) Modelled sensitivity of
509 avian collision rate at wind turbines varies with number of hours of flight activity input data (ed
510 A Lehtikainen). *Ibis*, **154**, 858–861.
- 511 Eichhorn, M., Johst, K., Seppelt, R. & Drechsler, M. (2012) Model-Based Estimation of Collision Risks
512 of Predatory Birds with Wind Turbines. *Ecology and Society*, **17**.
- 513 Everaert, J. (2014) Collision risk and micro-avoidance rates of birds with wind turbines in Flanders.
514 *Bird Study*, **61**, 220–230.
- 515 Ferrer, M., de Lucas, M., Janss, G.F.E., Casado, E., Muñoz, A.R., Bechard, M.J. & Calabuig, C.P. (2012)
516 Weak relationship between risk assessment studies and recorded mortality in wind farms.
517 *Journal of Applied Ecology*, **49**, 38–46.
- 518 Fox, A.D., Desholm, M., Kahlert, J., Christensen, T.K. & Petersen, I.K. (2006) Information needs to
519 support environmental impact assessment of the effects of European offshore wind farms on
520 birds. *Ibis*, **148**, 129–144.
- 521 Hammar, L. & Ehnberg, J. (2013) Who Should be Afraid of a Tidal Turbine - The Good the Bad or the
522 Ugly. *10th European Wave and Tidal Energy Conference Aalborg*, Denmark.
- 523 Holmstrom, L., Hamer, T., Colclazier, E., Denis, N., Verschuyf, J.P. & Ruche, D. (2011) Assessing avian-
524 wind turbine collision risk: An approach angle dependent model. *Wind Engineering*, **35**, 289–
525 312.
- 526 Huso, M.M.P. & Dalthorp, D. (2014) Accounting for unsearched areas in estimating wind turbine-
527 caused fatality. *The Journal of Wildlife Management*, **78**, 347–358.
- 528 Johnson, G.D., Erickson, W.P., Strickland, M.D., Shepherd, M.F., Shepherd, D.A. & Sarappo, S.A.
529 (2002) Collision Mortality of Local and Migrant Birds at a Large-Scale Wind-Power Development
530 on Buffalo Ridge, Minnesota. *Wildlife Society Bulletin*, **30**, 879–887.
- 531 Johnston, A., Cook, A.S.C.P., Wright, L.J., Humphreys, E.M. & Burton, N.H.K. (2014) Modelling flight
532 heights of marine birds to more accurately assess collision risk with offshore wind turbines.
533 *Journal of Applied Ecology*, **51**, 31–41.
- 534 Krijgsveld, K.L., Akershoek, K., Schenk, F., Dijk, F. & Dirksen, S. (2009) Collision Risk of Birds with
535 Modern Large Wind Turbines. *Ardea*, **97**, 357–366.
- 536 Langston, R.H.W. (2013) Birds and wind projects across the pond: A UK perspective. *Wildlife Society
537 Bulletin*, **37**, 5–18.
- 538 Lewis, J.I. & Wiser, R.H. (2007) Fostering a renewable energy technology industry: An international
539 comparison of wind industry policy support mechanisms. *Energy Policy*, **35**, 1844–1857.

- 540 Loss, S.R., Will, T. & Marra, P.P. (2014) Refining estimates of bird collision and electrocution
541 mortality at power lines in the United States. *PloS one*, **9**, e101565.
- 542 De Lucas, M., Ferrer, M. & Janss, G.F.E. (2012) Using Wind Tunnels to Predict Bird Mortality in Wind
543 Farms: The Case of Griffon Vultures (ed V Magar). *PLoS ONE*, **7**, e48092.
- 544 De Lucas, M., Janss, G.F.E., Whitfield, D.P. & Ferrer, M. (2008) Collision fatality of raptors in wind
545 farms does not depend on raptor abundance. *Journal of Applied Ecology*, **45**, 1695–1703.
- 546 Martin, G.R. (2012) Through birds' eyes: Insights into avian sensory ecology. *Journal of Ornithology*,
547 **153**, 23–48.
- 548 Masden, E.A., McCluskie, A., Owen, E. & Langston, R.H.W. (2015) Renewable energy developments
549 in an uncertain world: The case of offshore wind and birds in the UK. *Marine Policy*, **51**, 169–
550 172.
- 551 McAdam, B.J. (2005) *A Monte-Carlo Model for Bird / Wind Turbine Collisions*. MSc Ecology. University
552 of Aberdeen.
- 553 Montewka, J., Hinz, T., Kujala, P. & Matusiak, J. (2010) Probability modelling of vessel collisions.
554 *Reliability Engineering & System Safety*, **95**, 573–589.
- 555 New, L., Bjerre, E., Millsap, B., Otto, M.C. & Runge, M.C. (2015) A Collision Risk Model to Predict
556 Avian Fatalities at Wind Facilities: An Example Using Golden Eagles, *Aquila chrysaetos*. *Plos*
557 *One*, **10**, 1–12.
- 558 Patrick, S.C., Bearhop, S., Grémillet, D., Lescroël, A., Grecian, W.J., Bodey, T.W., Hamer, K.C.,
559 Wakefield, E., Le Nuz, M. & Votier, S.C. (2014) Individual differences in searching behaviour and
560 spatial foraging consistency in a central place marine predator. *Oikos*, **123**, 33–40.
- 561 Podolsky, R. (2008) Method of and article of manufacture for determining probability of avian
562 collision. *US Patent 7,315,799*, **1**.
- 563 Schaub, M. (2012) Spatial distribution of wind turbines is crucial for the survival of red kite
564 populations. *Biological Conservation*, **155**, 111–118.
- 565 Scottish Natural Heritage. (2000) *Windfarms and Birds: Calculating a Theoretical Collision Risk*
566 *Assuming No Avoiding Action*. *Guidance Note Series*.
- 567 Smales, I., Muir, S., Meredith, C. & Baird, R. (2013) A Description of the Biosis Model to Assess Risk of
568 Bird Collisions with Wind Turbines. *Wildlife Society Bulletin*, **37**, 59–65.
- 569 Smallwood, K.S., Rugge, L. & Morrison, M.L. (2009) Influence of Behavior on Bird Mortality in Wind
570 Energy Developments. *The Journal of Wildlife Management*, **73**, 1082–1098.
- 571 Snyder, B. & Kaiser, M.J. (2009) A comparison of offshore wind power development in europe and
572 the U.S.: Patterns and drivers of development. *Applied Energy*, **86**, 1845–1856.
- 573 Tucker, V.A. (1996a) A mathematical model of bird collisions with wind turbine rotors. *Journal of*
574 *Solar Energy Engineering*, 253–262.

- 575 Tucker, V.A. (1996b) Using a collision model to design safer wind turbine rotors for birds. *Journal of*
576 *Solar Energy Engineering*, **118**, 263–269.
- 577 U.S. Fish and Wildlife Service. (2013) *Eagle Conservation Plan Guidance Module 1 – Land-Based Wind*
578 *Energy*.
- 579 Wang, Z., Qin, H. & Lewis, J.I. (2012) China’s wind power industry: Policy support, technological
580 achievements, and emerging challenges. *Energy Policy*, **51**, 80–88.
- 581 Whitfield, D.P. (2009) *Collision Avoidance of Golden Eagles at Wind Farms under the ‘Band’ Collision*
582 *Risk Model. Report from Natural Research to Scottish Natural Heritage, Banchory, UK*.
- 583 Wilson, B., Batty, R.S., Daunt, F. & Carter, C. (2006) *Collision Risks between Marine Renewable*
584 *Energy Devices and Mammals, Fish and Diving Birds. Report to the Scottish Executive. Scottish*
585 *Association for Marine Science, Oban, Scotland, PA37 1QA*.
- 586 Winkelman, J.E. (1992) *De Invloed van de Sep-Proefwindcentrale Te Oosterbierum (Fr.) Op Vogels, 1:*
587 *Aanvaringslachtoffers. RIN-Report 92/2. Arnhem, Netherlands*.
- 588

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 <i>et al.</i> 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 <i>et al.</i> 2012)	Band	Y	Single	N	N	N	Individual	Onshore	Y	Mortality rate
Hamer (Holmstrom <i>et al.</i> 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.