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SHORT COMMUNICATION

A refinement of the Band spreadsheet for wind turbine collision risk allowing for oblique entry

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A new spreadsheet is presented, to be used as part of the Band model for estimating potential avian mortality due to wind turbine strike. The spreadsheet extends the Band collision risk spreadsheet by allowing for oblique approach angles and wind speed. The differences in the results between this new spreadsheet and the standard Band spreadsheet are given for two species, the white-tailed eagle *Haliaeetus albicilla* and the South Island pied oystercatcher *Haematopus finschi*, chosen for their contrasting sizes and flight characteristics. Under more representative conditions, the true risk for large birds is shown to be substantially greater than that calculated by the Band spreadsheet. Examples of how to use the new spreadsheet with bird survey and wind data are given.

Keywords: avian mortality; Band model; collision risk; oblique entry; wind turbine

Introduction

Concern over climate change has led to an increase in the contribution of renewable energy technologies to energy generation. Wind power is a rapidly growing renewable energy source across the globe because of its minimal carbon emissions and increasing efficiency. Wind energy capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand. That contribution could grow to in excess of 20% by 2050 (Wiser et al. 2011). As governments pledge to combat climate change, a large number of new wind farm developments, both onshore and offshore, are therefore anticipated.

Wind power is not, however, without environmental impact. The potential impact on bird populations is one such concern, especially following high mortality rates of raptors (Barrios & Rodriguez 2004; Lekuona & Ursúa 2007; Sterner et al. 2007; Bevanger et al. 2009) and seabirds (Everaert & Stienen 2007). However, these are apparently exceptional cases and several other studies suggest that deaths due to collisions with turbines are relatively rare events (Langston & Pullan 2003; Percival 2005), although the number of such studies is relatively low compared with the number of wind farms. Nevertheless, wind turbine collisions can have an impact on individual bird mortality and, under some conditions, a significant impact on species populations.

Due to the potential impact on endangered and/or protected bird species, it is becoming increasingly important to assess the effect of proposed wind farms on important bird populations before planning consent being granted. Although other factors such as species and habitat displacement may also result from wind farm construction (Douglas et al. 2011) and wind turbine operation (Pearce-Higgins et al. 2009), a key component of the impact assessment is an estimation of the annual bird mortality rate resulting directly from wind turbine collisions.

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It may be possible to estimate the probability of collision and therefore mortality rate given some key parameters on the placement, dimensions, structure and operation of wind turbines and the movements, abundance and behaviour of birds. This has led to the development of collision risk models (e.g. Tucker 1996a; Band et al. 2007; Holmstrom et al. 2011; Smales et al. 2013). An advantage of such models is the ability to predict potential impacts of wind farm construction on bird mortality rates through pre-construction field surveys.

An essential element of such models is an estimated probability of collision for a specific flight path based upon the structure and operation of the turbines: number of blades; maximum chord width and pitch angle of blades; rotor diameter and rotation speed; and of bird size and flight: body length; wingspan; flight speed; and flapping or gliding flight (Tucker 1996a; Band 2000; Holmstrom et al. 2011).

Holmstrom et al. (2011) investigated the dependence of collision risk on angle of approach, using a bird modelled as a flat rectangle, building on the original analysis by Tucker (1996a,b). They demonstrate that for large raptors flying downwind through a rotor, the probability of collision increases with an increasingly oblique angle of approach, then tails off as the effect of the reduced cross-sectional area presented by the rotor begins to dominate.

The Band Model, at times known as the Scottish Natural Heritage (SNH) Collision Risk Model, provides a means of estimating collision risk and hence the potential bird mortality that may be caused by a wind farm. The model first estimates the proportion of birds that would fly through the area swept out by the turbine blades, assuming that they did not actively avoid the turbines. The next essential step in the model (Stage 2 in Band et al. 2007), is calculating the probability that a bird which enters the rotor swept area will be struck by one of the blades before it can pass through safely.

Band (2000) constructed a spreadsheet to calculate this single transit probability of collision and he continues to update SNH guidance on estimating avian mortality (see Band 2012). Band's spreadsheet, which is available from the SNH website (http://www.snh.gov.uk/docs/C234672.xls), has been a major tool for practitioners assessing the possible ecological impact of planned wind farms. Inputs to Band's spreadsheet include information about the dimensions and rotation speed of the turbine blades, and the size and flight characteristics of the bird species of interest. The spreadsheet calculates the probability of collision for a bird entering the rotor swept area from both the upwind and downwind sides of the turbine and the average risk is used as one of the inputs to the full Collision Risk Model.

The spreadsheet presented here extends the original model of Band (2000) and Band et al. (2007) in two ways. It allows a bird to enter a turbine at an angle, and it takes into account the wind speed through the turbine. This new spreadsheet was first developed by Christie (2010) and its output was subsequently confirmed by Urquhart using a different, independent approach (Urquhart pers. comm.).

The spreadsheet first uses the wind speed and the bird's air speed and entry angle to calculate the speed at which the bird is approaching the turbine, and its orientation. The bird then enters the turbine at a particular spot. The true speed and direction of both the bird and the turbine blade at the entry point can be expressed as three-dimensional vectors. We now 'freeze' the turbine blade in a way familiar to physicists, by adding the opposite of the turbine blade velocity vector to both blade and bird. This stops the blade and gives us the speed and direction (the velocity vector) of the bird relative to the blade.

The bird with its new relative velocity is effectively heading towards a stationary blade which it may or may not hit. Even if the bird is not heading directly towards the blade, it may still clip it with part of its body or wing. This problem is solved by reducing the size of the bird to a point and extending the blade by half the size of the bird on each side. We now have a wider, stationary blade and a point bird moving towards it. The probability of collision at that point can now be found by comparing the area of the frozen extended blade as seen by the bird with the area of free air between the blades. The total probability of collision with the turbine blade is then found by summing the risk over the entire face of the rotor swept area using numerical integration. A full derivation of the formulas involved is available from the authors and the coding is accessible in the spreadsheet itself.

This article looks at two of the basic assumptions of Band's spreadsheet and suggests refinements that add to the accuracy and the usefulness of the Band Model.

First, the Band spreadsheet assumes that birds enter the rotor swept area perpendicular to the plane of the blades; that is, the birds enter directly upwind or downwind from the turbine. From a bird's perspective, if it approaches the turbine at an angle, then much of what was the circular risk area swept out by the rotor blades, is now clear air. On the other hand any entry into the turbine itself is more dangerous because the bird travels further and for longer inside the volume of air swept by the rotors. The Band spreadsheet assumes that these two effects cancel to a large extent and so assumes that all flights are directly upwind or downwind.

Second, the Band spreadsheet assumes that the bird flies through the turbine at the same speed whether it is moving upwind or downwind. In practice, a bird will fly more slowly upwind relative to the turbine than it will downwind. Band recognises this and suggests that, where possible, actual observed upwind and downwind speeds should be used separately and an average risk found by weighting the two risks according to the relative proportion of upwind and downwind flights (Band 2012). In any event, the slower upwind speed will tend to increase the probability of collision while the faster downwind speed will reduce that risk. Using the Band spreadsheet as it stands assumes that the upwind increase in risk and the downwind decrease are of similar size and the average risk is not changed to any important extent by local wind speed. However, both entry angle and wind speed can alter the probability of collision noticeably.

The refined Band model spreadsheet

Figure 1 shows a section exported from the new sheet, Band Oblique Collision Risk.xls (full spreadsheet available at http://kessels-ecology.co.nz and www.natural-research.org; or see Spreadsheet S1). Columns A to E hold the major parts of the coding. Column B holds the various inputs. In addition to the turbine blade and bird data common to the Band spreadsheet, we have two more inputs. Cell B14 holds the local wind speed and cell B15 holds the angle at which the bird enters the turbine relative to head wind. An angle of 0° is directly upwind, 180° is directly downwind. Columns C and D hold the profile of the blade in terms of the fraction of the blade's length and maximum chord. This particular blade reaches its maximum width one-quarter of the way along its radius from the centre to the tip. Column E calculates the contribution of each section of the rotor swept area using an Excel user defined function. The output, the risk of collision at that particular angle and wind speed, appears in cell B17. This calculated risk takes into account both the actual risk to the bird if it happens to enter the rotor swept area (which increases as the angle becomes more oblique), and the reduced likelihood of it actually entering the rotor swept area as the circle of air swept by the rotors is seen at an angle. When the calculated risk is used in the Band model, the full area swept out by the turbine blades is used.

A major strength of the spreadsheet is that we can use it to estimate overall risk from any available sample flight and wind data. Appendix 1 outlines some of many possibilities. Each combination of wind and flight data demands its own solution and none of them could be considered 'standard'.

If no survey data are available, then the simple example in columns G to J (which comes with the spreadsheet) shows how average risk can be calculated if we assume that flights can come from any direction. In this case, a macro successively inserts the numbers 0 to 180 into cell B15 (angle to head wind), calculates the risk, and copies the risk from cell B17 over to make a table in column J. For situations using wind and flight data already collected, the practitioner will need to write a VBA macro after the style of the example to automate the calculation of average risk.

Results

We investigated the effects of using the new version of the spreadsheet by comparing the calculated probability of collision for two contrasting species

	A	B	C	D	E	F	G	H	I	J
1	**Turbine**		Radius	Chord	Risk				Angle	Risk
2	Radius (m)	**50**	0.05	**0.73**	0.0034		Start	0	0	9.6%
3	Blades	**3**	0.10	**0.79**	0.0039		Finish	180	5	9.6%
4	Pitch (degrees)	**15**	0.15	**0.88**	0.0045		In steps of	5	10	9.6%
5	Maximum chord width (m)	**3.5**	0.20	**0.96**	0.0051				15	9.4%
6	Period (s)	**5**	0.25	**1.00**	0.0056		Table		20	9.3%
7			0.30	**0.98**	0.0059				25	9.1%
8	**Pied Oystercatcher**		0.35	**0.92**	0.0059				30	8.9%
9	Length (m)	**0.46**	0.40	**0.85**	0.0059				35	8.6%
10	Wingspan (m)	**0.83**	0.45	**0.80**	0.0060		Average	6.2%	40	8.4%
11	Speed relative to air (m/s)	**16**	0.50	**0.75**	0.0060				45	8.2%
12	Flapping (0) or Gliding (1)	**0**	0.55	**0.70**	0.0061				50	7.9%
13			0.60	**0.64**	0.0060				55	7.7%
14	Wind speed (m/s)	**5**	0.65	**0.58**	0.0059				60	7.4%
15	Angle to head wind (deg)	**35**	0.70	**0.52**	0.0057				65	7.2%
16			0.75	**0.47**	0.0056				70	6.9%
17	Collison risk at 35 degrees	*8.6%*	0.80	**0.41**	0.0054				75	6.7%
18			0.85	**0.37**	0.0053				80	6.5%
19			0.90	**0.30**	0.0050				85	6.3%
20			0.95	**0.24**	0.0047				90	1.8%
21			1.00	**0.00**	0.0027				95	5.7%
22									100	5.0%

Figure 1 An exported section of the revised spreadsheet showing the probability of collision for a South Island pied oystercatcher entering the turbine at an angle of 35° when the wind speed is 5 m/s is 8.6%. Columns G to J hold a simple application.

across three wind speeds and through all angles of approach. In the examples below we assumed a typical modern 100 m diameter turbine with a rotation period of 5 seconds. We used the white-tailed eagle *Haliaeetus albicilla* as an example of a large, comparatively slow, gliding species and used the South Island pied oystercatcher *Haematopus finschi* as an example of a smaller, faster, flapping species. We calculated the probability of collision for both species for turbine entry through various angles from directly upwind to directly downwind with wind speeds of 0, 5 and 10 m/s.

Table 1 summarises the average risk for each species and for each wind speed with both the standard Band spreadsheet and the modified spreadsheet. Row (a) gives the average risk for each species calculated using the Band spreadsheet the standard way, ignoring wind speed and approach angle only accounting for completely upwind and downwind flights. Row (b) gives the same average risks calculated with the new spreadsheet taking wind speed into account. Row (c) averages the risk from every entry direction.

Figures 2 and 3 show full graphs of the risk under the conditions chosen for the examples. The exact figures will change with different turbines and species but several conclusions are still clear. At low wind velocities, the Band spreadsheet may tend to overestimate the risk for some species and underestimate for others, but it is generally true that

Table 1 Calculated collision risks for the South Island pied oystercatcher and white-tailed eagle.

		South Island pied oystercatcher			White-tailed eagle		
Wind speed (m/s)		0	5	10	0	5	10
(a)	Standard Band sheet average risk (%)	6.3	6.3	6.3	8.5	8.5	8.5
(b)	Average of true upwind and downwind risks (%)	6.3	7.1	9.3	8.5	10.1	18.1
(c)	Average risk over 360° using the new sheet (%)	5.8	6.2	7.5	10.9	11.6	16.1

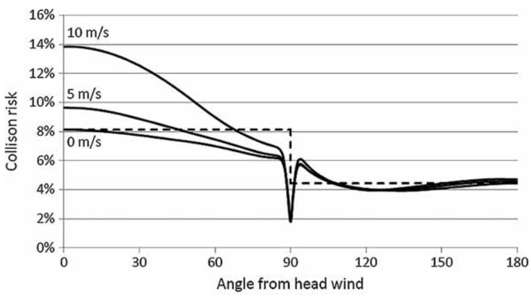

Figure 2 Probability of collision for the South Island pied oystercatcher at wind speeds of 0, 5 and 10 m/s calculated using the new spreadsheet. The dotted line shows the risk assumed by simple application of the Band spreadsheet ignoring wind speed.

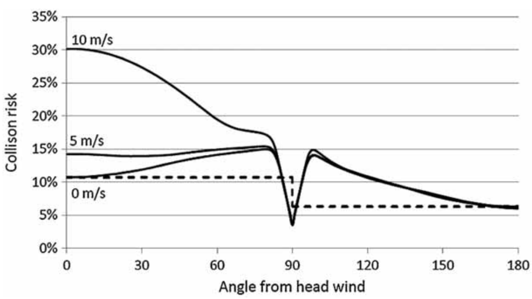

Figure 3 Probability of collision for the white-tailed eagle at wind speeds of 0, 5 and 10 m/s calculated using the new spreadsheet. The dotted line shows the risk assumed by simple application of the Band spreadsheet ignoring wind speed.

increasing wind speed results in increased probability of collision overall and practically all the increased risk occurs on the upwind approach. The downwind risk remains comparatively constant. It is also worth noting that the increased risk with extra wind speed is not linear. This means that using average wind speed to calculate risk will tend to underestimate the probability of collision.

Conclusion

The fundamental objective of modelling collision risk is to provide a rigorous procedure by which probability can be assessed in a manner that can be replicated. Improvements to the modelling process can help to resolve and avoid inconsistencies, and also help design better data collection strategies.

These results indicate a substantial improvement in the capacity to estimate collision rates, allowing for a more representative approach to bird flight behaviour and the effects of wind speed. This enables proponents to better understand the range of factors that may influence collision mortality and allow for changes to a wind farm's layout or turbine numbers to reduce collision rates once wind speed and bird orientation have been considered, the demonstration of which is a question often asked by government decision-makers.

There are substantial differences between species in the sensitivity of their collision risk assessments to wind speed and angle of approach, and it will always be important to calculate the collision risks for the species which are the subject of concern and using turbine parameters appropriate to the wind farm in question.

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Supplementary data

Spreadsheet S1. Band oblique collision risk.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1

Applications

The new spreadsheet calculates the collision risk for a particular entry angle and a particular wind speed, given data about the turbine and the species. One application of this is to construct a table of collision risk for a given wind speed over any required range of angles. This application has been described in the main text and comes with the spreadsheet.

More importantly, virtually any combination of matched or unmatched bird flight and wind data can be used to refine mortality estimates. The more data that are available, the more accurate and realistic the estimate of the collision risk. Here are some examples of possible applications that could be programmed into the sheet to take advantage of wind and bird survey data. Each needs a simple VBA macro.

Scenario 1

The general heading of a migratory species over a proposed wind farm is known. The wind speed and direction near the site have been monitored over the migration period. We have access to wind data arranged as matched hourly average wind speed and direction in two columns.

The application macro would:

1. take each wind speed and direction pair in turn
2. calculate the angle between the heading of the migrating birds and the wind
3. put the wind speed in cell B14
4. put the angle between the bird and the wind in cell B15
5. transfer the calculated risk in B17 back beside the wind speed direction pair
6. repeat for all the wind data and average the risk.

Scenario 2

As part of a survey, birds are tracked by radar over a proposed site. The bearing of each trail is available along with the time it was seen. Also available is the hourly wind speed and direction at the site over the survey period. Arrange the data into three columns holding the bird's bearing and the wind strength and direction at the time the bird was seen.

The application macro would:

1. take each data triplet in turn
2. calculate the angle between the bird's trail and the wind
3. calculate and record the risk for each trail as in scenario 1
4. repeat for each triplet and average the risk.

Scenario 3

Typical hourly wind speed data are known for a proposed site. The target species flies at random across the site. A suitable approach to this would be a Monte Carlo simulation. Only the wind speeds are needed. Arrange them in a column.

The application macro would:

1. pick a wind speed at random
2. generate a bird-to-wind angle at random from 0 to 180°
3. calculate and record the risk as in scenario 1
4. repeat a sufficiently large number of times (e.g. 2000 times) and average the risk.

It is worth noting that because risk is a non-linear function of wind speed, this will give a higher and more realistic estimate of risk than using the average speed over each angle from 0 to 180°.

Scenario 4

Survey data give the bearings of flights of a target species over a proposed site. It seems likely that the flight directions are not random and reflect feeding or roosting areas. Historic wind data are available but cannot be exactly matched with individual flights recorded in the survey. Very probably the patterns of wind speed and direction and bird flights will continue into the future. Start with three columns, matched wind speed and direction, and an independent column of flight bearings. The third column will probably not be the same length as the first two. A Monte Carlo approach is appropriate.

The application macro would:

1. pick a wind speed-direction pair at random from the list
2. pick a bearing at random from the flight bearing list
3. calculate the angle between the bird's trail and the wind
4. calculate the risk as in scenario 1
5. record the calculated risk
6. repeat some sufficiently large number of times and average the risk.

Other factors can be easily included in the spreadsheet where the details are known.

1. Turbine pitch and speed as functions of wind speed.
2. Turbine cut-in and cut-out wind speeds.

3. The adjustment of wind speeds recorded at monitoring stations to those at rotor height. This involves a wind profile function that takes into account the ground surface round the turbine.
4. The possible tendency for birds to work harder against the wind. This sheet assumes that a bird flies at a constant speed relative to the air and its ground speed and direction are influenced by the wind speed and direction. If a bird's airspeed is a known function of the angle it is flying to the wind this can be incorporated into the sheet.