DEVELOPING FIELD AND ANALYTICAL METHODS TO ASSESS AVIAN COLLISION RISK AT WIND FARMS

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ABSTRACT

Most studies of wind farm – bird interactions examine the effects of disturbance on bird use of a wind farm site, and mortality through collision of birds with turbine blades. Here we describe an approach of field study and modelling that can be used to predict collision mortality risk, illustrated by two examples of studies at proposed wind farm sites in Scotland involving greylag goose and hen harrier. We use the modelling method developed by W. Band to estimate the number of bird collisions over a period of time. The calculation is in two stages: number of birds colliding per annum = number flying through rotor (Stage 1) x probability of bird flying through rotor being hit (Stage 2). Vantage point observational studies at a proposed wind farm site are used to gather information on bird use of the site and the frequency of bird flights in the area swept by turbine blades (Stage 1). For Stage 2 the probability of collision depends on the size of the bird (both length and wingspan), the breadth and pitch of the turbine blades, the rotation speed of the turbine, and the flight speed of the bird. Combining Stage 1 with Stage 2 gives a predicted collision mortality rate that assumes birds take no action to avoid collision. In practice, birds probably show a very high degree of collision avoidance, which dramatically lowers predicted mortality. For the collision risk model to predict accurate measures of collision mortality it is essential that more information is collected on avoidance.

INTRODUCTION

Wind farms can potentially have three main adverse effects on birds. Direct habitat loss can occur through construction of the wind farm and take of land associated with infrastructure (e.g. turbine bases, access tracks) and impacts on physical processes underlying habitat function, and disturbance during construction and post-construction operations can potentially occur if birds ‘avoid’ the wind farm area: essentially, this represents indirect habitat loss. Finally, if birds don’t avoid the wind farm area then birds may be vulnerable to death through collision with turbine blades. Collision with power lines and electrocution at power poles, are secondary impacts if connection of the wind farm to the local power grid is over ground, and are potential problems of electricity distribution common to many forms of electricity generation (Erickson et al. 2001).

Direct habitat loss through wind farm construction is generally considered inconsequential, as construction usually only involves loss associated with turbine bases and maintenance tracks (e.g. Percival, 2000). Exceptions to this could include wind farms built on peatland habitats where construction may interfere with the hydrological processes that maintain the peatland and damage an area even wider than the wind farm area itself (Parkyn et al. 1997). A further example may include sand dune systems where turbines may affect the movements of wind and substrate that underlie sand dune formation. Disturbance during construction is short-term and can be readily mitigated against by timing construction outwith sensitive periods for birds. Hence, most potential problems for birds posed by wind farms involve the risks of post-construction disturbance and collision mortality, and most studies of wind farm - bird interactions concentrate on these issues.

Post-construction disturbance and collision with turbine blades are antagonistic processes and spatially are mutually exclusive (if a bird stays away from a wind farm area it is not at risk of colliding with turbine blades). The relationship between the two processes may not be stable temporally, however. Birds may initially avoid a wind farm area but then habituate to it, or conversely, for example, for site faithful birds the original occupants may continue to use the area but the wind farm may reduce the attractiveness of the area to potential replacements when the original occupants die.

Orloff & Flannery (1992, 1996) calculated that several hundred raptors were killed annually through collision with turbine blades in the wind farm at the Altamont Wind Resource Area (AWRA) in California; figures confirmed by similar findings of later studies at the AWRA (Hunt et al. 1999; Thelander & Rugge, 2000). It is not known if post-construction disturbance has reduced use by raptors, since no pre-construction study appears to have been carried out (Orloff & Flannery, 1992, 1996).

Most studies that have been conducted since research at AWRA began have seldom found comparable numbers of casualties (Erickson et al. 2001). However, perhaps because of experiences at AWRA, many studies in North America have tended to emphasise the risk of collision (e.g. NWCC, 2000; although see Leddy et al., 1999), whereas the earliest European studies suggested that post-construction disturbance was a more influential effect of wind farms (Winkelman, 1995). Many of the earliest European studies involved coastal locations, holding concentrations of birds, but later UK studies of upland wind farms with low densities of birds suggested post-construction disturbance was not a serious problem (Percival, 2000), although many of these studies are flawed (Lowther, 2000).

The majority of studies of wind farm - bird interactions are instigated in response to a legal requirement to assess the effects of a proposed wind farm on environmental features; in the present context - birds. Essentially this requires a predictive approach. Predicting post-construction disturbance requires an approach akin to predicting habitat loss, which has received considerable research attention (e.g. Goss-Custard et al. 1995). Predicting collision mortality has received comparatively little attention by researchers (Tucker, 1996), and so here we describe an approach of field study and modelling that can be used to predict collision mortality risk, illustrated by two examples of studies at proposed wind farm sites in Scotland.

METHODS

A MODEL FOR CALCULATING COLLISION RISK

We used the approach developed by W. Band to estimate the number of bird collisions over a period of time. The calculation is in two stages:

Number of birds colliding per annum = number flying through rotor (Stage 1) x probability of bird flying through rotor being hit (Stage 2).

QUANTIFYING FLIGHT ACTIVITY

Under Stage 1 of the Band model it is first necessary to quantify the amount of flight activity within the proposed wind farm site. For some species it may be possible to estimate flight activity reliably using predictive models derived from studies elsewhere. For example, McGrady et al. (1997) developed a simple model to predict the ranging behaviour of breeding golden eagles based on radio-telemetry studies in west Scotland. This model has been advanced through incorporation of additional parameters by McLeod et al. (2002a, b). A similar model is currently being developed for hen harriers *Circus cyaneus* (Madders, 2003). These generic models are probably a good starting point on which to base impact assessments but their accuracy is likely to be improved considerably by the inclusion of site-specific information on bird activity patterns. Moreover, there is insufficient knowledge for most species to develop predictive models, and therefore site-specific observations are essential.

The choice of species selected for study will depend on the objectives of the study. In most cases, the target species will likely be those of highest conservation importance or those perceived to be most vulnerable to collision. At some sites preliminary survey work may be required in order to determine the species, whilst at others there may be adequate existing data. This equates to a basic Level 1 survey of Anderson et al. (1999) who describe the methods that can be employed.

The aims of subsequent, more detailed studies should be to collect data that will enable reliable estimates to be made of:

1. The time each target species spends flying over a defined survey area.
2. The relative use of different parts of the survey area by each target species.
3. The proportion of flying time each target species spend at turbine rotor height.

FIELD METHODS

Methodological frameworks and philosophies for studies of wind farm - bird interactions have been thoroughly described by others (e.g. Gauthreaux, 1996; Anderson et al. 1999; Erickson et al. 2000). Hence, here we concentrate more on describing practical aspects of field methods.

Information on target species' use of a survey area that includes the proposed development is collected during timed observation sessions (watches) from vantage points. The survey area should include an envelope extending at least 500m beyond the outermost proposed turbines to reduce the risk of failing to record birds that use the wind farm area only occasionally. Vantage points should be selected to maximise the visibility of the survey area using the minimum number of points so that all parts of the survey area lie within 2km of a vantage point. Vantage points are best located outside of the survey area to minimise the observer's effect on bird behaviour. It is recommended that individual watches are limited to no more than 3 h duration to maintain observer acuity. Ideally, observations should be made in a range of wind conditions. This is particularly important in the case of soaring birds where wind direction and strength is likely to have a large effect on ranging behaviour. Regular measurement of wind is advised in order to investigate the magnitude of this effect. Owing to the difficulty in estimating flying height with much precision it is better to allocate observations of birds to one of a few height recording bands. Appropriate bands for wind farm developments can be <10m, 10-100m, or >100m above ground.

ESTIMATING THE SIZE OF THE VISIBLE AREA

For some analyses it is necessary to calculate the amount of time birds spend per unit area of ground surveyed (see later under 'Less predictable bird movements'). The use of several vantage points complicates analysis because overlap in visibility means that some parts of the survey area will be observed for longer than others. A measure of cumulative visibility is therefore required in order to calculate the overall observation time per unit area. This is achieved by calculating the size of area visible from each vantage point then summing the results. Visibility can be mapped either in the field, from photographs taken from each vantage point, or using terrain data within a Geographic Information System (GIS). Software used to predict the Zone of Visible Influence (ZVI) of wind farm developments, such as Windfarm 2000', can be useful in this respect.

Mapping in the field or from photographs tends to overestimate visibility because observers are often unaware that some areas are hidden from view. This is particularly true where convex slopes or undulating terrain are being viewed. In general, therefore, use of a GIS is preferable. However, in habitats with much woodland or other tall vegetation it will be necessary to make allowances for the effects on visibility of the vegetation relief. Note that in areas with complex terrain or vegetation relief, visibility can alter considerably in response to small changes in observer position. It is therefore critical that the spatial coordinates of vantage points are measured to the highest level possible, using a Global Positioning System (GPS). Observers should take care to re-use the exact vantage point location in successive watches.

Birds are often visible when the ground they are flying over is not. Thus, birds can sometimes be seen soaring beyond watersheds and over hidden valleys. Since the ultimate purpose of analysis is to estimate the risk of collision with turbines, it is the visibility of the airspace containing the rotors (the “collision risk volume”) that is of prime importance. Therefore, it is recommended that visibility be calculated using the least visible part of this airspace, i.e. an imaginary layer suspended at the lowermost height passed through by the rotor blade tips (typically around 20m above the ground). Predicting visibility at this elevation is a simple matter using a GIS.

RESULTS

We illustrate two types of output. The first is relevant to situations in which the mapped data show that birds mainly cross the proposed wind farm using a restricted number of flight directions, i.e. flight lines are predictable. Examples include regular diurnal movements of geese and divers *Gavia* spp. between specific feeding and roosting / nesting areas, and migratory bird movements in spring and autumn. The second situation is where use of the proposed wind farm by birds is less predictable during, for example, foraging and display activity by raptors and waders.

STAGE 1: PREDICTABLE BIRD MOVEMENTS

This example uses data for Icelandic greylag goose *Anser anser* gathered during timed observations of goose and swan movements across a proposed wind farm site near Dounreay, Caithness, north Scotland. Over 400 hours of observation were made during seven months in which geese were present. Greylag geese mainly used a SW-NE aligned flight path that took them along the length of the proposed wind farm. Geese were observed to fly in other directions, but for the purpose of this example it has been assumed that they did not. The number of geese potentially at risk of collision was calculated as follows:

1. A ‘risk window’ was defined through which geese approaching the wind farm were predicted to pass. The window measured 90m tall (i.e. the height of the 10-100m band used to record flying elevation) and 500m wide (the maximum distance between the turbines being approached plus 100m to allow for the blade length of the rotors). The cross-sectional area (*W*) of the risk window was therefore 90 x 500 = 45,000m^2.

2. The mean number of greylags per hour of observation that flew SW-NE through the risk window was determined (Table 1).

Table 1. *Number of hours observation per month at a proposed wind farm site in north Caithness, north Scotland, and the number of greylag geese recorded flying through the risk window per hour. The dimensions of the turbine blades and the proposed wind farm site (see text for details) defined the risk window.*

	Month							
	J	F	M	A	O	N	D	Mean
Hours of observation	50.7	38.5	103.0	64.3	93.8	41.5	23.8	
Geese hr^{-1}	2.29	0	3.64	0.64	0.60	10.99	4.29	3.21

3. The number of hours geese were potentially active, T, was calculated. It was assumed that greylags were present in the vicinity every day between October and April and were able to fly during 25% of the period between dusk and dawn. The value of T was calculated by summing the monthly totals in Table 2. Therefore T = 2906 hours per year.

Table 2. ***Number of hours for which greylag geese were assumed to be potentially active over the time period when they were present in the vicinity of the proposed wind farm site in north Caithness.***

	Month						
	J	F	M	A	O	N	D
Mean daylight hours	9.0	10.0	12.0	14.0	10.0	9.0	8.0
Mean nocturnal hrs x25%	3.8	3.5	3.0	2.5	3.5	3.8	4.0
Combined daily mean	12.8	13.5	15.0	16.5	13.5	12.8	12.0
No. of days birds present	31	28	31	30	31	30	31
Total hours	396	378	465	495	418	382	372

4. Thus, the number of greylags (n) assumed to fly through the risk window each year was 3.21 x 2906 = 9328.
5. The area (A) presented by the wind farm rotors was calculated as N x πR^2, where N is the number of rotors (in this case ten) and R is the rotor radius (= 33m). Therefore A = 3,421.2 m^2. Note that it is assumed the rotors are aligned in the plane of the risk window. In this model some allowance is made for overlap in the cross-sectional area of separate rotors. This is justified because although collision risk increases in proportion to the number of rotors birds pass through few birds will fly through five successive pairs of rotors. In recognition of this, a 50% overlap is assumed, i.e. A is assumed to be 1,710.6 m^2.
6. The proportion of the risk window occupied by the rotors is A / W = 0.038. Therefore the number of greylags assumed to pass through the rotors each year is n x A / W = 354.

Table 3. *Calculation of collision risk for a greylag goose passing through a rotor area of a V66 wind turbine. Greylag goose length is adapted from Campbell & Lack (1985). Input parameters are shown in the first two columns, and outputs in remaining columns calculate probability of collision at intervals of 0.05 R. See text for details.*

Model input parameters

K: [1D or [3D] (0 or 1)	1
No. Blades	3
Max. Chord	2,8 m
Pitch (degrees)	15
Bird Length	0,9m
Wingspan	1,8 m
F: Flapping (0) or gliding (+1)	0
Bird speed	17 m/sec
Rotor Diameter	66 m
Rotation Period	2,46sec
Bird aspect ratio: b	0,50

Calculation of alpha and p(collision) as a function of radius

			Upwind:			Downwind:		
r/R radius	c/C chord	α alpha	collide length	p(collision)	contribution from radius r	collide length	p(collision)	contribution from radius r
0,025	0,575	8,07	27,48	1,00	0,00125	26,65	1,00	0,00125
0,075	0,575	2,69	9,44	0,68	0,00508	8,61	0,62	0,00463
0,125	0,702	1,61	6,47	0,46	0,00581	5,46	0,39	0,00489
0,175	0,860	1,15	5,38	0,39	0,00675	4,13	0,30	0,00519
0,225	0,994	0,90	4,74	0,34	0,00766	3,30	0,24	0,00533
0,275	0,947	0,73	3,88	0,28	0,00766	2,51	0,18	0,00496
0,325	0,899	0,62	3,28	0,24	0,00764	1,97	0,14	0,00460
0,375	0,851	0,54	2,82	0,20	0,00759	1,59	0,11	0,00428
0,425	0,804	0,47	2,51	0,18	0,00766	1,35	0,10	0,00411
0,475	0,756	0,42	2,32	0,17	0,00789	1,22	0,09	0,00416
0,525	0,708	0,38	2,15	0,15	0,00809	1,12	0,08	0,00423
0,575	0,660	0,35	2,01	0,14	0,00827	1,05	0,08	0,00432
0,625	0,613	0,32	1,88	0,13	0,00842	0,99	0,07	0,00444
0,675	0,565	0,30	1,77	0,13	0,00855	0,95	0,07	0,00459
0,725	0,517	0,28	1,66	0,12	0,00866	0,91	0,07	0,00476
0,775	0,470	0,26	1,57	0,11	0,00873	0,91	0,07	0,00506
0,825	0,422	0,24	1,48	0,11	0,00879	0,93	0,07	0,00548
0,875	0,374	0,23	1,40	0,10	0,00882	0,94	0,07	0,00589
0,925	0,327	0,22	1,33	0,10	0,00882	0,94	0,07	0,00626
0,975	0,279	0,21	1,26	0,09	0,00880	0,95	0,07	0,00662

Overall p(collision) = **Upwind 15,1%** **Downwind 9,5%**

Average 12,3%

STAGE 1: LESS PREDICTABLE BIRD MOVEMENTS

This example uses data for hen harriers gathered during timed observations of raptor movements across a proposed wind farm site in Argyll, west Scotland. The survey area extended 1km beyond the proposed outer turbine bases. A total of 96 hours of observations were made from four vantage points during the breeding period (April to July) in a single year. During this time harriers were observed to fly 10-100m above the ground for a total of 22.3 minutes. Harrier activity was concentrated in the southeast part of the survey area. This might have been because this part provided better foraging conditions or was located closer to locations used for nesting. Because harrier nest locations can vary from year to year it was decided to assume random use of the survey area. The time budget data gathered for the survey area was then used to predict flight activity within the smaller area containing the proposed turbines, as follows:

1. The parts of the survey area visible from each vantage point were determined using Windfarm 2000™. These areas were measured and summed (*Acumulctive* = 1273ha).
2. The proportion of total observation time that harriers were observed flying at 10-100m height was calculated ($t = 0.0039$). Thus, flight activity per hectare of visible area (F) was t / *Acumulctive* = 3.043×10^{-6}.
3. The size of the flight risk area was taken to be the envelope bounded by the proposed outer turbines plus a buffer of 25m representing the rotor blade radius (= 172ha). Therefore the proportion of time that harriers were predicted to spend 10-100m above the ground within the wind farm area was $F \times 172 = 5.23 \times 10^{-4}$.
4. The turbine rotors proposed had a blade diameter of 52m and hub height of 50m. Thus, the rotor tips operate between the heights of 24m and 76m rather than the 10-100m band width used to record harriers. The proportion of time that harriers were predicted to spend flying within the wind farm area was therefore adjusted by multiplying by (76-24)/(100-10) = 0.58 (= 3.03×10^{-4}, i.e. approximately 0.03% of the time).
5. Hen harriers were present at the site mainly during the breeding season (April to July = 122 days). During this period they were active for approximately twelve hours per day. Harrier occupancy (n) of the wind farm area was therefore estimated to be 122 x 12 hours x 0.03%, or 0.439 hours per year.

   This information was then used to estimate the number of passes that harriers made through the rotors per year, assuming that harriers' use of the airspace containing the rotors was random. The maximum depth of the rotor blade from back to front (d) and the length of the harrier (l) were factored into the calculation.
6. The size of the flight risk volume (Vw) was calculated by multiplying the area of the wind farm (172ha) by the diameter of the rotors (52m) = 89 440 000 m^3.
7. The combined volume swept out by the wind farm rotors (Vr) was determined by multiplying the number of wind turbines (in this case 37) by $\pi R^2 \times (d + l)$, where R is the rotor radius (26m), d is 2m, and l is 0.5m (= 196 444 m^3).

8. The bird occupancy of the volume swept by the rotors (b) is then n x (*Vr* / *Vw*) = 3.47 bird-secs.
9. The time taken for a bird to make transit through the rotor and completely clear the rotors (t) is ($d + l$) / v, where v ms^{-1} is the speed of the bird through the rotor (assumed to be 8 ms^{-1}) = 0.31.
10. The number of bird transits through the rotors is therefore b / t = 11.19 per year.

STAGE 2: ESTIMATING COLLISION LIKELIHOOD

Estimating the number of bird transits through the area swept by rotors completes Stage 1 of the Band model. The probability of a bird flying through a rotor being hit is calculated next under Stage 2 of the Band model. The probability depends on the size of the bird (both length and wingspan), the breadth and pitch of the turbine blades, the rotation speed of the turbine, and of course the flight speed of the bird.

To facilitate calculation, many simplifications have to be made. The bird is assumed to be of simple cruciform shape, with the wings at the halfway point between nose and tail. The turbine blade is assumed to have a width and a pitch angle (relative to the plane of the turbine), but to have no thickness.

It is best to visualise this as looking vertically down on the flying bird in a frame which is moving with the bird. In this moving frame, each rotor blade is both moving from right to left (say) and also progressing towards the bird. Each blade cuts a swathe through the air, which depends both on the breadth of the blade and its pitch angle. Successive blades cut parallel swathes, but progressively closer to the bird. The angle of approach of the blade α, in this frame, depends on both bird speed and blade speed. At the rotor extremity, where blade speed is usually high compared to bird speed, the approach angle α is low, i.e. the blades approach the bird from the side. Close to the rotor hub, where the blade speed is low and the bird is therefore flying towards a slow-moving object, the approach angle α is high.

The probability of bird collision, for given bird and blade dimensions and speeds, is the probability, were the bird placed anywhere at random on the line of flight, of it overlapping with a blade swathe (since the bird, in this frame, is stationary). It may therefore be calculated from simple geometric considerations. Where the angle of approach is shallow, it is the length of the bird, compared to the separation distance of successive swathes, which is the controlling factor. Where the angle of approach is high, it is the wingspan of the bird compared to the physical distance between blades, which is the controlling factor.

The calculation derives a probability p(r, j) of collision for a bird at a radius r from the hub, and at a position along a radial line which is an angle j from the vertical. It is then necessary to integrate this probability over the entire rotor disc, assuming that the bird transit may be anywhere at random within the area of the rotor disc:

Total probability

$= (1/\pi R^2)$ ÊÊ $p(r, \varphi)\ r\ dr\ d\varphi$

$= 2$ Ê $p(r)\ (r/R)\ d(r/R)$ ….. **(1)**

where $p(r)$ now allows for the integration over φ.

Probability p of collision for a bird at a radius r from hub

$$p(r) = (\ b\Omega/2\pi v\ )\ [\ K\ |\ \pm\ c\ \sin\gamma + \alpha\ c\ \cos\gamma\ |\ + \begin{matrix} l & \text{for } a < b \\ w\alpha F & \text{for } \alpha > \beta \end{matrix}\ ]$$

…… **(2)**

where β = number of blades in rotor

Ω = angular velocity of rotor (radians/sec)

χ = chord width of blade

γ = pitch angle of blade

R = outer rotor radius

I = length of bird

w = wingspan of bird

β = aspect ratio of bird i.e. l / w

v = velocity of bird through rotor

r = radius of point of passage of bird

$\alpha = v/r\Omega$

F = 1 for a bird with flapping wings (no dependence on φ)

= (2/p) for a gliding bird

K = 0 for one-dimensional model

(rotor with no zero chord width)<<<<<

β = 1 for three-dimensional model (rotor with real chord width)

The chord width of the blade c and the blade pitch γ, i.e. the angle of the blade relative to the rotor plane, vary from rotor hub to rotor tip. The chord width is typically greatest close to the hub and the blade tapers towards the tip. The pitch is shallowest close to the tip where the blade speed is highest. The apparent width of the blade, looked at from the front, is $c \cos\gamma$, and the depth of blade from back to front is $c \sin\gamma$. Although pitch varies along the length of a turbine blade, the model assumes a single value which is probably best determined at $r = 2R/3$ as the outer region of the blade makes the greater contribution to collision risk.

The factor F is included to cover the two extreme cases where the bird has flapping wings ($p(r, \varphi)$ has no dependence on φ) or is gliding ($p(r, \varphi)$ is j dependent, i.e. at maximum above and below hub, at minimum when wings are parallel with rotor blade). F=1 for flapping bird, $F = 2/\pi$ for a gliding bird.

The sign of the c sing term depends on whether the flight is upwind (+) or downwind (-).

The factor K is included to give a simple option of checking the effect of real blade width in the result: K=0 models a one-dimensional blade with no chord width.

As α, c and γ all vary between hub and rotor tip, a numerical integration is easiest when evaluating equation (1).

For ease of use these calculations are laid out on an Excel spreadsheet (available from bill.band@snh.gov.uk or phil.whitfield@snh.gov.uk). The spreadsheet calculates p(r) at intervals of 0.05 R from the rotor centre (i.e. evaluating equation (2)), and then undertakes a numerical integration from r=0 to r=R (i.e. evaluating equation (1)). Using input parameters for the spreadsheet appropriate to the two examples, the risk of collision was calculated for greylag geese (Table 4) and hen harriers (Table 5). The spreadsheet is set out as follows, which should be read in conjunction with Tables 4 and 5 that illustrate the worked examples:

1. The input parameters are in the first two columns. Bird aspect ratio b is calculated.
2. Collision probabilities are then calculated for radii at intervals of 0.05 R from the hub to the tip. Each radius is represented by a row in the table, with the value of the radius r/R in the first column.
3. The second column of the table is the chord width at radius r as a proportion of the maximum chord width. The taper profile used is that of a modern Aerpac turbine blade. The taper will differ for different turbine blades.
4. Factor a is calculated.
5. The ‘collide length’ is the entire factor within square brackets within equation (2) above, using the upwind case.
6. p(collision) is p at radius r, as calculated by equation (2). It is however limited to a maximum value of 1.
7. ‘contribution from radius r’ is the integrand of equation (1) (including the factor 2) prior to integration.
8. The total risk is then the summation of these contributions.
9. The calculation is then repeated for the downwind case.
10. The spreadsheet then shows a simple average of upwind and downwind values. (Note that in a real case it may be important to add in the effect of wind to the bird’s ground speed, and flight patterns may not be such that upwind and downwind flights are equally frequent.)

The result is an average collision risk for a bird passing through a rotor.

In the greylag goose example, assuming equal numbers of upwind and downwind flights, and flapping flight, gives an estimated average of 12.3% of greylag flights resulting in collision with a rotor (Table 4). The turbine rotors are predicted to be inoperative for 25% of the time due to shut downs at very low and very high wind speeds, giving a collision risk of 12.3 x 0.75 = 9.2%. The number of collisions is then given by the combined results of Stage 1 and Stage 2 i.e. number flying through rotor (Stage 1) x probability of bird flying through rotor being hit (Stage 2). Therefore, an estimated 33 greylags per year will die through collision with a rotor, if the birds take no avoiding action.

In the harrier example, assuming equal numbers of upwind and downwind flights, and flapping flight, gives an estimated average of 17.9% of harriers will be hit by a rotor. As in the greylag example, the number of collisions is given by number of birds flying through rotor x probability of bird flying through rotor being hit. Therefore, an estimated 2 harriers per year will die through collision with a rotor, if the birds take no avoiding action.

Table 4. *Calculation of collision risk for a hen harrier passing through a rotor area of a V52 wind turbine. Hen harrier length is taken to be the approximate length of a female, and flying speed is based on "normal" hunting flight speed of 30 km. hr*$^{-1}$ *(Schipper, 1977). Input parameters are shown in the first two columns and outputs in remaining columns calculate probability of collision at intervals of 0.05 R. See text for details.*

Model input parameters

K: [1D or [3D] (0 or 1)	1
No. Blades	3
Max. Chord	2,3 m
Pitch (degrees)	16
r	
Bird Length	0,5m
Wingspan	1,2 m
F: Flapping (0) or gliding (+1)	0
Bird speed	8 m/sec
Rotor Diameter	52m
Rotation Period	1,91 sec
Bird aspect ratio: b	0,42

Calculation of alpha and p(collision) as a function of radius

			Upwind:			Downwind:		
r/R radius	c/C chord	a alpha	collide length	p(collision)	contribution from radius r	collide length	p(collision)	contribution from radius
0,025	0,575	3,74	9,61	1,00	0,00125	8,88	1,00	0,00125
0,075	0,575	1,25	3,45	0,68	0,00508	2,72	0,53	0,00400
0,125	0,702	0,75	2,50	0,49	0,00614	1,61	0,32	0,00396
0,175	0,860	0,53	2,20	0,43	0,00757	1,11	0,22	0,00382
0,225	0,994	0,42	2,04	0,40	0,00903	0,78	0,15	0,00346
0,275	0,947	0,34	1,81	0,36	0,00978	0,61	0,12	0,00330
0,325	0,899	0,29	1,64	0,32	0,01048	0,50	0,10	0,00320
0,375	0,851	0,25	1,51	0,30	0,01111	0,57	0,11	0,00420
0,425	0,804	0,22	1,40	0,27	0,01169	0,62	0,12	0,00516
0,475	0,756	0,20	1,31	0,26	0,01220	0,65	0,13	0,00606
0,525	0,708	0,18	1,23	0,24	0,01266	0,67	0,13	0,00691
0,575	0,660	0,16	1,16	0,23	0,01305	0,68	0,13	0,00769
0,625	0,613	0,15	1,09	0,21	0,01339	0,69	0,13	0,00841
0,675	0,565	0,14	1,03	0,20	0,01367	0,69	0,13	0,00908
0,725	0,517	0,13	0,98	0,19	0,01389	0,68	0,13	0,00969
0,775	0,470	0,12	0,92	0,18	0,01405	0,67	0,13	0,01023
0,825	0,422	0,11	0,87	0,17	0,01414	0,66	0,13	0,01072
0,875	0,374	0,11	0,83	0,16	0,01419	0,65	0,13	0,01115
0,925	0,327	0,10	0,78	0,15	0,01417	0,63	0,12	0,01151
0,975	0,279	0,10	0,74	0,14	0,01409	0,62	0,12	0,01182
	Overall p(collision) =			Upwind	22,2%		Downwind	13,6%
				Average		17,9%		

In both examples, the estimated collision rates take no account of an ‘avoidance factor’, yet in practice a very high proportion of birds are likely to take action to avoid collision (e.g. Erickson et al., 2001). In the absence of any data on avoidance rates for greylags and hen harriers, we assume that no birds will be displaced from the wind farm due to disturbance but on 95% of flights the bird will take action to avoid collision. This gives estimates of mortality due to collision of 1.6 greylags per year, and 0.1 harriers per year.

DISCUSSION

FIELD METHODS

There are many potential biases in detecting flying birds. Birds may be more conspicuous in some habitats than others, or easier to locate when flying at certain elevations. Detection rates may differ between species, leading to underestimation of the risk of collision for birds that are cryptic in appearance or behaviour. Insight into these biases can be tested using data recorded at the point of detection. For example, bias due to distance and height could be analysed using general linear model analyses of variance with species entered as a factor.

Accurately plotting the routes of flying birds is difficult owing to the effects of parallax and tends to be a field skill acquired over many years. Birds such as hen harriers that spend much time flying low over the ground frequently pass in front of landscape features whose distances are known or can be measured. This is not the case with soaring birds such as eagles where the correspondence between a bird and the landscape is harder to judge. In these situations there may be wide variation in estimates of distance, depending on observer experience, knowledge of the terrain and weather. Bias in the way flight routes are plotted can be minimised by ensuring that observers are familiar with the species they are recording and have intimate knowledge of the terrain. The use of a second observer is recommended in order to help triangulate fixes, at least during the initial period of observations. Similar problems are encountered when trying to estimate the height of flying birds. Errors can be minimised by using as few recording bands as possible, set at elevations that are easily envisaged, e.g. 10m and 100m. It is advisable to test the accuracy of distance and height estimates through the use of model airplanes or kites, or more specialised range-finding equipment. Ultimately, however, the quality of the data will be largely determined by the field experience of observers.

COLLISION RISK MODEL

The Band model of collision risk involves many approximations such as assuming that a bird can be modelled by a simple cruciform shape, that a turbine blade has width and pitch but no thickness, and that a bird’s flight will be unaffected by a near miss, despite the slipstream around a turbine blade. Thus the calculated collision risks should be held as an indication of the risk - say to around ±10%, rather than an exact figure. It is also simplistic to assume that bird flight velocity is likely to be the same relative to the ground both upwind and downwind. Ideally, separate calculations should be done for the upwind and downwind case, using typical observed flight speeds. Several additional refinements are possible within the existing model, and include allowance for the respective effects that flight direction and wind speed may have on a bird's flight speed (relative to the ground), and incorporation of changes in pitch along the length of a rotor blade. Some of these influences may be difficult to measure in the field, however, especially as part of a proposed development's assessment, and species-specific published data are extremely rare. In the end, such refinements probably make relatively small differences to the estimated collision mortality. Clearly, however, the extent to which birds avoid colliding with rotors can make very large differences to the estimated collision mortality.

For clarification we prefer to consider a bird's avoidance of an operational wind farm as 'displacement' and it's avoidance of a moving rotor as 'avoidance'. While both factors affect the avoidance rate with respect to collision mortality, they are two distinct processes. Although the evidence, albeit often flawed, appears to suggest that displacement effects are only slight (e.g. Percival, 2000) and could benefit more from the rigorous study designs described by Anderson et al. (1999), limited evidence suggests that avoidance can be substantial (M. Madders & D.P. Whitfield, unpublished data) and may be the main contributor to an overall avoidance rate. It is likely that avoidance rates may typically be even greater than the value (95%) assumed for our examples. Displacement has received and will continue to receive considerable attention, as it is one of the fundamental effects of a wind farm on birds, but avoidance has received relatively little attention. For the collision risk model to predict accurate measures of collision mortality it is essential that more information is collected on avoidance.

Avoidance rates can be observed directly at operational wind farms, but may be difficult to detect, especially if avoidance is manifest by lateral deviations in flight paths. Quantification may be difficult, therefore, as observers may be forced to make judgements rather than measurable observations. Alternatively, where collision mortality and bird utilisation of the 'rotor swept window' have been measured at an operational wind farm, the avoidance rate can be estimated by the difference between the predicted mortality and the observed mortality. This relies on accurate measurement of collision mortality, which is fraught with difficulties. Birds injured by collision may die well away from turbines. Scavengers can remove carcasses before they are discovered (e.g. Strickland et al. 2000). This can be controlled for by putting out marked carcasses and recording the disappearance rate, but extra carcasses may attract extra scavengers and lead to a biased disappearance rate. Marking fresh 'natural' corpses as they are discovered and tracking their visibility on subsequent searches (e.g. Thelander & Rugge, 2000) may be the most effective means of documenting (and accounting for) scavenging and other forms of corpse disappearance. Coupled with a frequent search regime when tracking corpse visibility, this can be used to determine the most effective inter-search interval (see also Strickland et al. 2000). However, observers may not find all carcasses, regardless of scavenging, and smaller corpses are more likely to be missed (e.g. NWCC, 2000; Strickland et al. 2000). Detection rates can vary with the vegetation being searched (Philibert et al. 1993) and in dense vegetation can be markedly improved by the use of dogs (Homan et al. 2001), but this has seldom been used in wind farm studies. Because of the risks associated with attracting scavengers, trials calibrating corpse detection rates by humans or dogs should ideally be carried out in similar vegetation well away from the wind farm site. Finally, expected collision rates may be so low that it is not cost effective to conduct a fixed programme of searches for corpses. If the target species is represented by only a very small number of resident individuals, it may be more efficient to monitor their presence and activity (thereby also gaining information on post-construction utilisation patterns) and only conduct a search when monitoring leads to a suspicion of an individual's disappearance. Given the difficulties in recording collision mortality, automated remote technology for logging collisions is much needed.

If pre-construction information on flight activity is collected in a repeatable way, and also includes similar work on reference sites away from the wind farm, then it can be a baseline against which post-construction survey data can be compared (Anderson et al. 1999). The primary purpose of post-construction surveys is to measure bird displacement due to the wind farm, but they are also invaluable in refining models of collision risk. It is only through studies of this kind that a proper understanding of the effects of wind farms on birds can be developed. This will help streamline the process of selecting potential sites and reduce the uncertainty associated with wind farm development. Concern will inevitably focus on species perceived to have a high nature conservation value; species that by definition are scarce or rare. Clearly, it is important that as much information as possible is gathered on these birds in order to best estimate collision risk. However, in most situations it is possible to gather a much larger sample of observations from commoner species and these data are likely to be more informative when comparing with post-construction studies.

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