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A REVIEW OF THE IMPACTS OF WIND FARMS ON HEN HARRIERS *CIRCUS CYANEUS* AND AN ESTIMATION OF COLLISION AVOIDANCE RATES

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ABSTRACT

Assessment of the impacts of proposed wind farms on hen harriers is often hampered by an apparent paucity of available information from studies of impacts at operational wind farms. To a large degree this is because few studies are readily or obviously accessible, and so the purpose of this review was to utilise those studies which could be accessed (primarily reports posted on websites) to examine the evidence for the susceptibility of hen harriers to the two main impacts of terrestrial wind farms on birds: displacement/disturbance and fatality through collision with rotating turbine blades.

At least eight studies of hen harrier displacement effects have been conducted, using several study designs, in USA and continental Europe. Only one study documented good evidence of displacement and it was reasonable to conclude that although further studies are highly desirable, if displacement of foraging occurs then it will likely be limited to within 100 m of wind turbines if it occurs at all. In keeping with most other studies of raptor displacement, therefore, it appears that foraging hen harriers have a low sensitivity to disturbance at operational wind farms. Persecution of some UK hen harriers may make such populations more susceptible to disturbance, however. Displacement impacts on nest site selection are more poorly studied, and preliminary results from Scotland and Northern Ireland indicate that birds will nest 200 – 300 m from turbines.

At least 10 wind farms where hen harriers occur have been subject to research on collision fatalities. Deaths were recorded at three sites with only a single study, involving searches over 7,500 turbine-years, recording more than one casualty, and no collision victims were recorded at seven sites. Against expectations, documented mortality was not positively related to harrier activity since wind farms with recorded deaths were those with the lowest harrier activity levels. The cause of this apparently counter-intuitive result was not obvious, with the height of rotor blades (since harriers typically fly at low altitudes) and an index of risk exposure not offering satisfactory explanations. It was apparent, nevertheless, that hen harriers do not appear to be susceptible to colliding with turbine blades and that collision mortality should rarely be a serious concern.

Collision risk modelling under the Band Collision Risk Model (CRM) (Band et al. 2006) can be used to estimate predicted mortality rates at proposed wind farms. Avoidance rates under the Band model (the extent to which birds avoid colliding with rotor blades) were estimated from eight wind farms in USA: estimates were 100% (at six sites), c. 99.8% (at one site) and 93.2% (at one site). For the six sites with 100% avoidance, harrier activity levels were relatively high so this could not explain the absence of any fatalities and at two of these sites searches were conducted at 50 to 150 turbines over several years. At the remaining four sites with no fatalities a combined 101 turbines were searched for four years in total. All eight studies accounted for search biases due to observer efficiency and corpse removal. Thus, there was no evidence of any deficiencies in the methods employed at the sites where avoidance was 100%. It is suggested that harrier collisions are relatively rare events and probably subject to stochastic or accidental conditions and hence sampling may produce occasional relatively low avoidance rate estimates while most estimates are substantially higher. Unbiased estimates may therefore require studies at a substantial scale and duration which are probably impractical and difficult to justify cost-effectively. Combining results from several smaller scale studies may thus provide an appropriate solution and for the 'non-Altamont' USA studies a 99% avoidance rate predicted a combined number of harrier fatalities very close to the empirical measure. In conclusion, an assumption of 95% avoidance is likely to be overly cautious and an avoidance rate of 99% appears to be more realistic.

INTRODUCTION

The rapid growth of the wind energy industry has produced an unprecedented single-issue demand on environmental impact assessment in the UK and elsewhere in the world. Birds are a key assessment concern, due to several potential adverse impacts of wind farms (Langston & Pullan 2003). In the UK, assessment of impacts on the hen harrier *Circus cyaneus* is a frequent requirement, especially in Scotland where the majority of the population breeds, since this raptor is listed on Annex 1 of the EC Birds Directive and favours similar habitat to that selected for terrestrial wind farm proposals. As for other terrestrial birds, wind farms pose three main adverse risks to hen harriers: fatality through collision with turbine blades, indirect habitat loss by birds being displaced through disturbance, and direct habitat loss through construction of the windfarm and ancillary development (land take) (Langston & Pullan 2003). A major difficulty in assessing these potential impacts of wind farms on most birds, including the hen harrier, is the apparent paucity of available information from studies of impacts at operational wind farms.

Relatively little material on wind farm impacts has been published in the peer-reviewed literature despite the existence of numerous studies in the 'grey' literature. This is readily apparent by consulting the reference lists of those few studies which have been accepted by scientific journals for publication (e.g. Barrios & Rodríguez 2004, de Lucas et al. 2004). The reasons for this are probably several. For example, many studies are commercially driven, and publication in the peer-reviewed literature increases costs without any obvious commercial benefit to the development company concerned, although there are clear benefits to the wider wind energy industry. On the other hand, it is probably unlikely that several studies would be accepted for publication in journals, not necessarily through a lack of 'quality' but also because of the substantial pressure on space in scientific journals in relation to the large body of wind energy research which could be published, most or all of which would probably be making similar conclusions or simply documenting the presence or absence of effects. Although a greater rate of peer-review publication is clearly highly desirable, the current shortfall should not equate 'unpublished' grey studies with a lack of reliability or low quality research. For instance, the recent studies of collision mortality at Altamont (e.g. Hunt 2002, Smallwood & Thelander 2004) have been transparently conducted to accepted sound standards

(Anderson et al. 1999) and have considerably advanced the research field. The purpose of this review, therefore, is to utilise those studies that may be classed as ‘grey’ literature in an attempt to draw conclusions about wind farm effects on the hen harrier (or northern harrier as the species is known in North America; the northern harrier may be a closely related ‘sister’ species rather than a subspecies of the hen harrier: Wink & Sauer-Gürth 2004). Whenever possible we have utilised literature which is accessible via the internet and have cited appropriate web addresses. Although prey and habitat use may differ between studies (for example, North American breeding harriers appear more reliant on small mammal prey than birds in the UK: Simmons 2000) essentially, when not migrating, all hen harriers typically fly low to the ground (Whitfield & Madders 2006), hunting for prey in ground vegetation, and catching prey on the ground or immediately above it.

Physical land take caused by windfarm construction is generally so small that only rarely will it be influential (when a proposed scheme is especially large or the spatial requirements of a species are especially small or restricted) (e.g. Percival 2000, Langston & Pullan 2003). The two main potential risks to hen harriers, therefore, are displacement/disturbance and collision with turbines, and hence it is on these risks that this review concentrates.

DISPLACEMENT

Displacement effects are best studied with a BACI (Before-After-Control-Impact) design (Green 1979, Anderson et al. 1999), which involves survey of bird numbers or behaviour at the wind farm (impact) site and a similar reference (control) site before and after construction. BACI protocols have been followed by several studies of birds at wind farms, though not all (e.g. Gill et al. 1996, Langston & Pullan 2003) and those which have been unable to adhere to a BACI design are less reliable. As changes in bird numbers or behaviour can be influenced on a wind farm site by a number of factors other than the influence of the wind farm itself, these additional factors should be accounted for; hence the need for a good reference site where the influence of the additional factors should change in tandem with those on the wind farm site. Results will also be most reliable when collected over a number of years because, for example, bird abandonment of a wind farm site through disturbance may be temporary due to habituation.

A full description of the BACI and alternative study methods is given in Anderson et al. (1999). Other approaches include the IR (Impact-Reference) design where the impact indicators measured on the assessment (wind farm) area are compared to measurements from one or more reference sites. In displacement studies the abundance and/or distribution of birds on the operational wind farm area are compared with those on reference site(s) and any difference related to the presence of the wind farm, preferably after controlling in analysis for any confounding environmental factors that may influence abundance. IG (Impact-Gradient) designs lack a formal reference site and look for gradients in impact with distance from the hypothesised impact source – in this case, wind turbines. In displacement studies measures of bird abundance would be expected to increase with distance from turbines if an effect occurs. Again, interpretation is facilitated if potential confounding influences on gradients in abundance, such as vegetation type, are accounted for. Finally, BA (Before-After) designs quantify impact indicators (bird abundance, in this case) on the assessment (wind farm) area before and after the presumed impact (wind farm construction) has occurred. A lack of any reference data or replication sorely limits the ability to interpret such studies objectively, although abrupt changes after construction can give greater confidence in impact detection and reference material on bird abundance away from the wind farm site is often available from sources outwith the study.

Madders & Whitfield (2006) have reviewed several existing studies of displacement in raptors, including hen harriers. There have been no or few indications of hen harrier displacement at most wind farms where it has been studied (Johnson et al. 2000b, Bergen 2001, Kerlinger 2002, Schmidt et al. 2003, Reichenbach 2003, Kerlinger et al. 2005) but Johnson et al. (2000a) found evidence of both small scale (< 100m from turbines) and larger scale (> 100 m) displacement from turbines by harriers in the year following windfarm operation (Table 1), although displacement was clearly only partial since this was one of very few sites where a collision victim was found. Some additional German studies using the IG design may suggest partial displacement from limited (100 m) areas around turbines but others do not (K. Handke, unpubl. data) and in southern Spain foraging also appears to be little affected (M. de Lucas pers. comm.). An interpretational difficulty with all studies in USA and continental Europe is that in the UK the hen harrier suffers unusually high levels of human persecution (Etheridge et al. 1997) and this may make hen harriers in UK more sensitive to a wide range of disturbance, including displacement around turbines. Preliminary results at Argyll and Northern Ireland sites, however, suggest foraging may be little affected but local displacement of nesting attempts may occur in the order of 200 - 300 m around turbines (Natural Research unpubl. data). This tends to support the results from elsewhere. The hen harrier conforms to the results from a number of other raptor species (Madders & Whitfield 2006), which do not appear to be affected markedly by displacement from wind farms, although notable exceptions may occur (resident golden eagles at a site in Scotland: Walker et al. 2005).

In general, although more studies are desirable and some exceptions may occur, foraging activity appears to be little affected by displacement (and if it does, usually only in a very limited area). In the context of the extent of foraging ranges of breeding harriers (Schipper 1977, Picozzi 1978, Martin 1987, Arroyo et al. 2003) and the even larger ranges of non-breeding harriers (e.g. Watson 1977) any such displacement is unlikely to be problematic unless a large number of closely spaced turbines are located close to harrier nests. For example, a 2 km radius home range (crudely approximating a typical breeding range: Picozzi 1978, Martin 1987, Arroyo et al. 2003) is about 1250 ha, and if harriers are displaced from foraging habitat of 100 m around each of 20 hypothetical turbines then effective habitat loss would be about 60 ha, or only about 5% of the range. The main potential impact of most wind farms on harriers when situated away from nest sites, therefore, is likely to be collision with rotating turbines.

COLLISION RISK

Previous studies

At least ten studies have examined collision risk in hen harriers, nine in the USA and one in Navarra, northern Spain (several others are in progress in Spain e.g. Arcos & Salvadores 2001). Mortality was documented in three studies, but no deaths were recorded in six studies (in a seventh, at Ponnequin in Colorado, no harrier mortality was recorded over 4 years at 29 turbines, but activity estimates were not collected on a comparable basis: Kerlinger et al. 2000, and Kerlinger et al. in Schwartz 2004). Against expectations that mortality should rise with increasing harrier activity, there was no evidence that the level of use by harriers *per se* influenced estimates of collision mortality; indeed the indication was that collision risk was lower at higher levels of use (Fig. 1).

This result may seem counter-intuitive, and several factors may explain why higher flight activity did not result in higher estimates of collision mortality:

- Harriers tend to fly at low altitudes (Whitfield & Madders 2006) and so the height of the rotor sweep should strongly influence collision rate. A reliable surrogate of rotor swept height (which was not available from all reports) is the rotor swept area (RSA) of an individual turbine, because a larger RSA indicates a higher rotor swept height due to turbine specifications (larger blades have to be at higher hub heights). The three studies which documented deaths involved turbines with a lower RSA than those where no deaths were recorded (Mann-Whitney $U = 0$, Wilcoxon $W = 6$, $P = 0.024$), as would be expected given the flight altitude of harriers[1]. The reduced mortality in more modern wind farms, despite much higher levels of flight activity, suggested that higher RSA (and other specifications of modern turbines: Tucker 1996a, b) reduces collision risk in harriers due to their typically low flight altitude. Some crude assumptions can be made about the likely flight heights at the sites where this metric was not reported, and this allows a more appropriate 'exposure' risk to be calculated whereby activity is multiplied by the proportion of activity at rotor swept height (e.g. Erickson et al. 2002). Even with this improvement, which better incorporates a reduced risk if flight heights are more likely to be below rotor height, there was no correspondence between exposure to mortality risk and measured mortality, again due to the much higher activity at sites where no mortality was recorded (Fig. 2). This suggests that an absence of recorded mortality at several sites was <u>not</u> entirely due to a higher rotor swept height.

[1] There were far too few recorded deaths, even at Altamont, to allow such potential influences to be examined within a study where different turbine types were evident within a site.

- There was no obvious association with the seasonal occurrence of harriers and whether deaths were recorded. Two of the three sites documenting fatality mainly involved birds on migration, and the third involved both breeding and passage birds. At some of the sites where no fatalities were recorded, similar seasonal patterns were evident and activity was recorded year-round at others.

- Probably largely because of harrier flight behaviour, mortality rates are probably only rarely expected to be relatively high, and may be likely restricted to those sites where turbines are located in the vicinity of several nest sites. Only one of the studies that documented deaths found more than one casualty, and this was at Altamont, California where over five years three victims were found in over 7,500 turbine-years of searches (Smallwood & Thelander 2004). Another study found one corpse in three years of searching 277 turbines (Lekuona & Ursúa 2005). Hence, studies attempting to sample fatalities probably need to be conducted over several years to produce robust estimates of mortality (see also Smallwood & Thelander (2004) for a discussion of this issue): short-duration studies (especially at small wind farms) are liable to be subject to sampling biases. This may explain why studies where harrier activity was highest did not necessarily produce the highest mortality estimates (sampling bias may have inflated mortality estimates as well as underestimating mortality). Hence, we might expect that detecting mortality would be a function of the number of turbines searched, the duration of the search regime and the activity levels of harriers. However, an appropriate index of this function (n turbines searched * n months of study * harrier activity rate) was not related to a study's documentation of mortality (Mann-Whitney U = 5, Wilcoxon W = 26, P = 0.381).

- Biases in corpse detection (e.g. Langston & Pullan 2003) should not have been too influential as all studies corrected for this or, a crude correction could be applied to the results (based on disappearance of corpses only: Lekuona & Ursúa 2005). Even so, if corpses disappear rapidly with respect to the inter-search interval then for a species such as the hen harrier, which appears far less vulnerable to collision than several other raptors, small numbers of carcasses may be more likely to be missed completely, and correction factors are difficult to apply to zero counts.

Several conclusions are apparent from these nine studies:

1. In general, hen harriers appear to be less vulnerable to collision than several other raptors. The cause of this is unknown at present, and a typically low flight altitude of harriers does not appear to explain entirely the low vulnerability, although features of more modern turbines may be involved. Other species of raptorial or scavenging birds also appear to be relatively invulnerable to collision (Smallwood & Thelander 2004).
2. Low expectations of mortality rates may mean that studies of harrier collisions at wind farms have to be conducted over many years to produce reliable estimates of collision rates. Given that very low mortality rates may be expected, this may lessen the desire to undertake such expensive studies, especially as a low vulnerability to collision may mean the studies would not be seen as a priority.
3. Predictions based on extrapolations of mortality rates from existing studies would be widely different, although most would suggest negligible numbers of deaths, if any. Predicting mortality precisely with any confidence from previous studies and on the basis of estimated risk exposure is difficult currently, however, largely because mortality rates appear to be very low. Nevertheless, in the context of likely impacts at future wind farms where hen harriers may occur, precision is relatively unimportant if it is known that mortality will be very low or absent.

Collision risk modelling and avoidance rates

Several collision risk models for predicting bird strikes at wind farms have been developed in recent years (Madders & Whitfield 2006) but most details (and therefore most utility) and frequency of use concern the ‘Band’ Collision Risk Model (CRM) (Band et al. 2006). Modelling collision risk under the Band CRM is a two-stage process (Band et al. 2006). Stage 1 estimates the number of birds that fly through the rotor swept disc. Stage 2 predicts the proportion of these birds that will be hit by a rotor blade. Combining both stages produces an estimate of collision fatality in the absence of any avoiding action by birds. In practice, birds do avoid flying through rotating blades, and avoidance rates appear to be very high (e.g. Gill et al. 1996). Both stages are prone to bias due the inclusion of relatively simplistic assumptions about bird behaviour. An appraisal of the Band model (Chamberlain et al. 2005, 2006) has noted that whilst it appears generally robust there is a strong influence of avoidance rates on estimated collision risk and that information on avoidance rates is scant, confirming Band et al.'s (2006) conclusions. Chamberlain et al. (2005) rightly express great concern about this issue, as relatively little is known about avoidance rates, and suggest that until more is known about avoidance, collision risk modelling has limited value. Chamberlain et al. (2005) offer no suggestions as to alternative approaches to the problem, however, perhaps because alternative methods to assess collision risk provide even less comfort than collision risk modelling but are subject to the same or more potential biases (Madders & Whitfield 2006).

With currently available data at operational wind farms, one method for estimating avoidance rate is the difference between predicted fatality and observed fatality (avoidance rate = 1 – (observed deaths/predicted deaths assuming no avoidance). Chamberlain et al. (2005) highlight that because carcasses may be missed due to several potential biases (under the 'observed deaths' part of the equation), this would result in avoidance rates being overestimated (i.e. actual avoidance should be less than estimated). On the other hand, Madders & Whitfield (2006) illustrate how bird activity levels are probably often underestimated (especially under the circular plot method employed by most USA studies, for example: Reynolds et al. 1980) and this (under the 'predicted deaths' part of the equation) would lead to avoidance rates being underestimated. As most recent studies attempt to account for the biases in carcass searches (e.g. Erickson 2003) the overall tendency may be for avoidance rates to be underestimated (i.e. actual avoidance should be higher than estimated). This will especially be the case when flight activity is nocturnal and estimates of activity rely on visual observations only. For diurnal raptors, this problem does not exist, and so this group offers an excellent opportunity for estimation of avoidance rates, prone mainly to underestimation bias through observational methods, which is fortunate because raptors are considered to be a group especially vulnerable to collision with turbines (e.g. NWCC 2000).

Studies at eight sites in USA presented sufficient data to estimate avoidance rates in harriers (Table 2).[2] Essentially, the method used to estimate avoidance rates involved the same calculations as undertaken to predict fatality levels using the Band CRM, although instead of generating a predicted fatality rate for a given avoidance rate, a given fatality rate was employed to generate a predicted avoidance rate.

The Band CRM requires an estimate of the proportion of time harriers spent flying at rotor swept height (RSH) (Band et al. 2006). This metric is rarely presented in reports of wind farm studies and most reports present the number of birds seen per unit area per time period, the proportion of birds seen at RSH[3] and, less frequently, the proportion of birds seen which were in flight. Hence, it was necessary to approximate the amount of time which each sighting probably entailed. This was done by calculating the average distance flown during each sighting and dividing by the typical flight speed, so for a 800 m radius observation plot the average distance flown will be 1600 * (π/4) = 1257 m, and at a flight speed of 8 m/s the average time per flight will be 157 sec (see also Fernley et al. 2006). In a given observation period (e.g. 40 min), the amount of harrier flying time was given by: (average n sightings *proportion of sightings in flight) * average time per flight. Dividing this by the observation period gave the proportion of time in flight which when divided by the proportion of flights at RSH gave the proportion of time harriers flew at RSH. A summary of values for harrier flight activity at the study sites is shown in Table 3.

The Foote Creek Rim wind farm studies also presented results of ‘instantaneous sampling’ of harrier activity: number of harriers seen every 10 min during a 40 min observation period (Johnson et al. 2000a: Appendix E). This metric allowed a direct

[2] Insufficient information on search bias corrections was presented by Lekuona & Ursúa (2006) for inclusion of the Navarra studies; nevertheless, although highly tentatively, an avoidance rate of c. 95% may be indicated. At Ponnequin, Colorado harrier activity was recorded through transects and so was not compatible with the present analyses (no harrier deaths in four years of searches involving 29 turbines, implying 100% avoidance). Studies at Tehachapi Pass and San Gorgonio Pass in Califormia (Anderson et al. 2004, 2005) were not included, even though a large number of turbines were sampled (>600 across 3 years and >400 across 2 years, respectively) because of low harrier abundance and a 1 month inter-search interval (no harrier deaths recorded).

[3] When studies did not present results on proportion of flights at RSH, the strong similarity of harrier flight heights across many sites (Whitfield & Madders 2006) allowed an estimation of this metric based on the RSH of the turbines drawn from other studies with similar turbines and/or habitat and harrier occurrence.

measure of the proportion of time harriers flew at RSH, without the need to resort to the approximation method described above. Comparison of avoidance rates derived using the two methods thus provided an indicative assessment of the approximation method's robustness.

In all Stage 1 calculations, harriers were assumed to be active for 365 d in a year (weighted seasonal averages were employed to calculate an annual average value when harriers were not present in all seasons) and for 12 hr every day. The effects of turbine operation 'down-time' (proportion of time when turbines were inoperative due to maintenance, for example) was incorporated from published figures for Altamont Pass (45%: Smallwood & Thelander 2004) or, for sites with more modern turbines, by assuming 17% down-time. This was equivalent to assuming harriers were active for 6.6 hr per day (Altamont) or 10 hr per day (other sites). Harrier biometrics and flight speed were taken from Band et al. (2006) and turbine and rotor blade parameters were taken from the relevant site reports or from manufacturer's websites. When more than one turbine type was present, weighted averages were employed. Under Stage 2 calculations (the Band collision probability) flapping flight was assumed.

The Foote Creek Rim research involved the main study (Johnson et al. 2000a, Young et al. 2003a) and a companion subsidiary study of the effects of UV-painted turbine blades on fatalities (Young et al. 2003b) (Table 2). The 'UV study' used results from the 69 turbines employed in the main study and from 36 additional turbines. Avoidance rates were derived both for the two studies separately and combined. For Altamont, it was not clear as to which of two study plot sizes the given raptor flight observation times referred to: 297.5 ha (Thelander et al. 2003: Table 2) or 139 ha (Smallwood & Thelander 2004). Although the 297.5 ha average plot size seemed more likely, avoidance rates were calculated for both potential plot sizes.

A typical example of the calculations is given in Table 4, for Foote Creek Rim, and Table 5 presents the calculations incorporating the 'instantaneous sampling' of harrier flight time, also for Foote Creek Rim. The similarity in the two avoidance rate estimates derived for Foote Creek Rim using reported estimates of flight time and flight time approximation (92.09% and 91.93%, respectively) suggests that the approximation method used to derive a measure of the proportion of harrier flight time at RSH was reasonably robust.

Results for harrier avoidance rate estimates at all eight study sites are given in Table 6. For Foote Creek Rim, combining all available study material gave an avoidance rate of 93.2%. At Altamont the estimated avoidance rate was 99.87% or, more likely, 99.73%, depending on the study plot size, although it is worth pointing out that the two estimates are probably too low for the following reason: the basic flight activity observations assume that all flights occur at random within the observation plot, but the Altamont studies point out that harriers (like most of the raptors on the site) fly disproportionately closer to the turbines (Thelander et al. 2003, Smallwood & Thelander 2004). This is probably due to increased prey abundance close to turbines, but it will mean that averaging out of flight observations across a larger plot area will underestimate the flight activity that brings a risk of collision since flights do not apparently occur at random.

At the six other sites, estimated avoidance rates were 100% since no harrier fatalities were recorded. At these sites there were higher harrier activity levels and collision risk exposure indices than at the two sites where harrier fatality was documented. The likelihood of detecting a harrier casualty will be dependent on a number of factors and not just harrier activity levels, however (and, as noted earlier, activity level may not be a reliable indication of fatality in harriers which, incidentally, undermines a fundamental assumption of CRMs). These additional factors include the scale of the study (duration and number of turbines within study), the rate at which carcasses disappear, observer efficiency at detecting carcasses and the search interval. Observer efficiency did not differ markedly between studies and as summarised by Erickson (2003) (see also the relevant study reports) carcass disappearance rate was also similar across sites, with the exception of Buffalo Ridge wind farm where carcass removal was relatively high. Here, however, the search interval was shorter than at most other sites (Table 2) which will tend to counteract the increased carcass disappearance rate. The scale of studies at Buffalo Ridge and Stateline was also relatively large and comparable with those studies where fatalities were found (Table 2). Although the other four studies (Vansycle, Klondike, Nine Canyon, NWTC) where no fatalities were found were individually relatively small in scale, in combination they were comparable with the larger studies (Table 3).[4]

As noted earlier, fatality estimates are potentially subject to sampling bias (as opposed to carcass search biases, which were largely accounted for in the available studies) and this will mean that avoidance rate estimates are subject to the same potential error. This will be pronounced if harrier deaths are relatively rare events, as appears to be the case. (Note that this could mean that the Foote Creek Rim estimates are too low as well as possibly meaning that some 100% estimates from elsewhere are too high; the Altamont study is probably the least biased due to its duration and number of turbines searched.) It is apparent, however, that for at least two wind farm studies (Buffalo Ridge, Minnesota: Johnson et al. 2000b; Stateline, Oregon/Washington: Erickson et al. 2004) due to harrier activity levels, search regime and number of turbines searched, sampling bias was probably less severe than smaller scale studies. Hence for at least these two of the six sites where no mortality was documented, if avoidance rates were not 100% then they were probably close to this value.

In other words, the evidence strongly indicates that harrier collisions are very rare events both due to flight behaviour and high true avoidance rates, and may occur on an accidental basis due to stochastic conditions. So in the absence of a substantially scaled study where the likelihood of collision is relatively high, because of an absolutely low but random probability of collision, sampling error is liable to produce estimated avoidance rates which are too low (e.g. Foote Creek Rim?) or slightly too high (e.g. Vansycle, Klondike, Nine Canyon, NWTC?). Unbiased estimates may therefore require studies of a substantial spatial scale and duration which are probably impractical and difficult to justify cost-effectively. A 'meta-analysis' incorporating several smaller scale studies may prove a practical alternative in this respect.[5]

Band et al. (2006) used an avoidance rate of 95% for hen harrier in the absence of any guiding empirical data, and a reasonable conclusion would be that this rate is too low

[4] According to the Band CRM, under a 95% avoidance rate about 5 harriers should have died in total through collision with the study turbines during the study period at the six sites where no fatalities were recorded.

[5] Taking all seven 'non-Altamont' studies, using a 99% avoidance the Band CRM would predict 1.2 harrier deaths should have been recorded by the study protocols, very close to the empirical measure after correction.

since available evidence is inclined to suggest that avoidance rates in this species are probably typically higher. The median of four empirical measures was about 99% (Altamont, Foote Creek Rim, Buffalo Ridge, Stateline), and a median rate utilising estimates from all eight studies would clearly be even higher. Hence an avoidance rate of 99% is probably more realistic.

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*Table 1. Summary of studies which have investigated displacement effects on hen harriers due to wind farms. Refer to text for the different types of study design. * Limited displacement of 100 m around turbines may have occurred in some situations.*

Study	Location	Study design	Effect?
Johnson et al. 2000a	Foote Creek Rim, Wyoming, USA	BACI	Yes
Johnson et al. 2000b	Buffalo Ridge, Minnesota, USA	BACI	No
Schmidt et al. 2003	Colorado, USA	IR	No
Kerlinger et al. 2005	California, USA	BA + IR	No
Kerlinger 2002	Searsburg, Vermont, USA	BA	No
Bergen 2001, Reichenbach 2003	Germany	BACI, IG	No
K. Handke, unpubl. data	N Germany	IG	No*
M. de Lucas, unpubl. data	SW Spain	IR	No

Table 2. Summary of the study protocols investigating harrier collision fatalities at eight USA wind farms. All studies corrected fatality estimates to account for search efficiency and carcass removal.

Site	Turbines searched	Study duration (months)	Search interval (d)	Kills/turbine/yr*	Reference
Altamont	685	62	7-35	0.0002	Smallwood & Thelander 2004, Thelander et al. 2003
Foote Creek Rim	69	36	28	0.006	Johnson et al. 2000a, Young et al. 2003a
Foote Creek Rim**	105	12	28	0	Young et al. 2003b
Buffalo Ridge***	21-50	48	14	0	Johnson et al. 2000b
Vansycle	38	12	28	0	Erickson et al. 2001, 2002
Stateline	124-153	29	14-28	0	Erickson et al. 2004
Klondike	16	12	28	0	Johnson et al. 2002, 2003
Nine Canyon	37	12	14-28	0	Erickson et al. 2002, 2003b
NWTC	10	12	14	0	Schmidt et al. 2003

*As given by reports after correction for missed carcasses. The carcass search regime could be complex at some sites because of changing search protocols due to, for example, new phases of turbine arrays being constructed and added to the searches. Hence, to avoid ambiguity, reported fatality rates after bias correction were taken from report annexes rather than undertaking novel calculations which may not have adequately corrected for study complications.

**A companion study examining the effect of UV painted turbine blades on fatalities (no effect found): the 69 turbines in the 'main' study were included in this companion study.

*** Osborn et al. (2000) also searched 50 of the 73 Phase I turbines at 7 day intervals between April 1994 and December 1995 and found no harrier corpses.

Table 3. Summary of harrier activity levels and proportion of flight observations at rotor swept height (RSH) for the eight study sites which were used to generate avoidance rate estimates.

Site	Mean activity*	Prop at RSH**	Reference
Altamont	0.014	0.200	Smallwood & Thelander 2004, Thelander et al. 2003
Foote Creek Rim	0.018	0.129	Johnson et al. 2000a, Young et al. 2003a
Foote Creek Rim	***	0.129	Johnson et al. 2000a, Young et al. 2003a
Foote Creek Rim	0.060	0.129	Young et al. 2003b (UV study)
Foote Creek Rim	0.018	0.129	Johnson et al. 2000a, Young et al. 2003a, b
Buffalo Ridge	0.104	0.065	Johnson et al. 2000b
Vansycle	0.099	0.100****	Erickson et al 2001, 2002
Stateline	0.044	0.100****	Erickson et al. 2004
Klondike	0.093	0.065	Johnson et al. 2002, 2003
Nine Canyon	0.110	0.100****	Erickson et al. 2002, 2003b
NWTC	0.288	0.100****	Schmidt et al. 2003

* Standardized for comparisons across studies: averaged across the year, n birds seen per plot of 800 m radius per 20 min (see Erickson et al. (2001, 2002) for further data and summary statistics for this standardized metric).

**Proportion of flights at rotor swept height (RSH).

***Calculated from the number of harriers seen during ‘instantaneous sampling’, every 10 min in a 40 min period.

****No data on proportion of flight activity at RSH presented in reports: value assumed on the basis of many studies at similar sites with similar turbines (see Whitfield & Madders 2006).

Table 4. An example of calculations used to estimate collision avoidance rate in the northern (hen) harrier: data from Foote Creek Rim, Wyoming.

1	**Northern harrier**		
2	Johnson et al 2000, Young et al 2003		
3	Plot area	201	ha, 800m radius circle plots J et al 2000
4	Obs time	2400	sec 40 min obs period J et al 2000
5	NH flying time	5.97	sec, see row 34-38
6	Prop time NH fly at rotor height	0.129	Appendix H, J et al 2000
7	Prop obs time NH fly at rotor height	0.000320888	
8	Prob rotor height flights per ha	1.59646E-06	
9	Flight risk area	54.19	ha, 50m around 69 turbines: metric cancels out later, so value immateri
10	Prop time NH fly at rotor height within flight risk area	8.65119E-05	
11	occupancy days per annum	365	d, not present all year but flying time/obs time calculated on this basis
12	flight hours per day	10	hr, incorporates turbine operation downtime 17% at 12 hr flight hr per d
13	occupancy	3650	hr/yr
14	NH occupancy at rotor swept heights in risk area	0.315768466	hr/yr
15		1136.766479	sec/yr
16	Flight risk volume	22759800	m3
17	N turbines	69	
18	Rotor diameter	42	Mitsubishi 600
19	Rotor depth	1.5	
20	Bird length	0.5	1.2m wingspan
21	Vol swept by rotor blades	191191.0457	
22	Bird occupancy of rotor swept volume	9.549274238	bird-sec per yr
23	Flight speed	8	m/sec
24	Time taken for transit through rotors	0.25	
25	N transits through rotors	38.19709695	per yr
26	BAND collision rate	13.70%	1.8 maxchord pitch 15 rotation 24 rpm, flapping flight
27	NH strikes (no avoidance)	5.233002283	
28	Avoidance rate	0.079113285	**92.09%**
29	NH strikes (with avoidance)	0.414	1 of 5 raptor fatalities were NH, 0.03 raptor kills/turb/yr Young etal
30			0 of 6 raptor fatalities in 1 yr were NH at 105 turbines Y et al UV study
31			**Incorporating this gives avoidance rate of 93.3%**
32			
33			
34			0.0428 obs per 40 min or 2400 sec count, Table 2 J et al 2000
35			0.887 obs were flying birds
36			1600m max linear extent across plot, av distance =1600 * pi/4 = 1257
37			8 m/s, 157 sec to cross plot
38			5.97 sec = 157x(0.887x0.0428) per 2400 sec of obs

Table 5. An example of calculations used to estimate collision avoidance rate in the northern (hen) harrier: data from Foote Creek Rim, Wyoming, employing instantaneous sampling of harrier presence which allowed proportion of time when harriers were seen to be calculated directly.

1	**Northern harrier**		
2	Johnson et al 2000, Young et al 2003		
3	Plot area	201	ha, 800m radius circle plots J et al 2000
4	Obs time	2400	sec 40 min obs period J et al 2000
5	Number NH per instantaneous sample	0.00275	Appendix E, J et al 2000. Every 10 min in 40 min session. Averaged across 4 seasor
6	Prop NH obs when flying	0.887	Appendix H, J et al 2000
7	Prop time NH fly at rotor height	0.129	Appendix H, J et al 2000
8	Prop obs time NH fly at rotor height	0.000314663	
9	Prob rotor height flights per ha	1.56549E-06	
10	Flight risk area	54.19	ha, 50m around 69 turbines: metric cancels out later, so value immaterial
11	Prop time NH fly at rotor height within flight risk area	8.48338E-05	
12	occupancy days per annum	365	d, not present all year but flying time/obs time calculated on this basis
13	flight hours per day	10	hr, incorporates turbine operation downtime 17% at 12 hr flight hr per d
14	occupancy	3650	hr/yr
15	NH occupancy at rotor swept heights in risk area	0.30964351	hr/yr
16		1114.716637	sec/yr
17	Flight risk volume	22759800	m3
18	N turbines	69	
19	Rotor diameter	42	Mitsubishi 600
20	Rotor depth	1.5	
21	Bird length	0.5	1.2m wingspan
22	Vol swept by rotor blades	191191.0457	
23	Bird occupancy of rotor swept volume	9.36404711	bird-sec per yr
24	Flight speed	8	m/sec
25	Time taken for transit through rotors	0.25	
26	N transits through rotors	37.45618844	per yr
27	BAND collision rate	13.70%	1.8 maxchord pitch 15 rotation 24 rpm, flapping flight
28	NH strikes (no avoidance)	5.131497816	
29	Avoidance rate	0.080678199	**91.93%**
30	NH strikes (with avoidance)	0.414	1 of 5 raptor fatalities were NH, 0.03 raptor kills/turb/yr Young etal
31			0 of 6 raptor fatalities in 1 yr were NH at 105 turbines Y et al UV study
32			**Incorporating this gives avoidance rate of 93.1%**

Table 6. Estimates of avoidance rates in the northern (hen) harrier at eight wind farms in USA: the estimate for Buffalo Ridge does not include the results of Osborn et al. (2000) which would also have indicated 100% avoidance.

Site	Avoidance rate	Reference
Altamont	99.87%*	Smallwood & Thelander 2004, Thelander et al. 2003
Altamont	99.73%**	Smallwood & Thelander 2004, Thelander et al. 2003
Foote Creek Rim	92.09%	Johnson et al. 2000a, Young et al. 2003a
Foote Creek Rim	91.93%***	Johnson et al. 2000a, Young et al. 2003a
Foote Creek Rim	100.00%	Young et al. 2003b (UV study)
Foote Creek Rim	93.2%****	Johnson et al. 2000a, Young et al. 2003a, b
Buffalo Ridge	100.00%	Johnson et al. 2000b
Vansycle	100.00%	Erickson et al. 2001, 2002
Stateline	100.00%	Erickson et al. 2004
Klondike	100.00%	Johnson et al. 2002, 2003
Nine Canyon	100.00%	Erickson et al. 2002, 2003b
NWTC	100.00%	Schmidt et al. 2003

*Assuming 139 ha study plot. Flight time estimates given by study.

**Assuming 297.5 ha study plot. Flight time estimates given by study.

***Using empirical measure of flight time proportion through instantaneous sampling.

****Main study and ‘UV study’ results combined, with no duplication of results common to both.

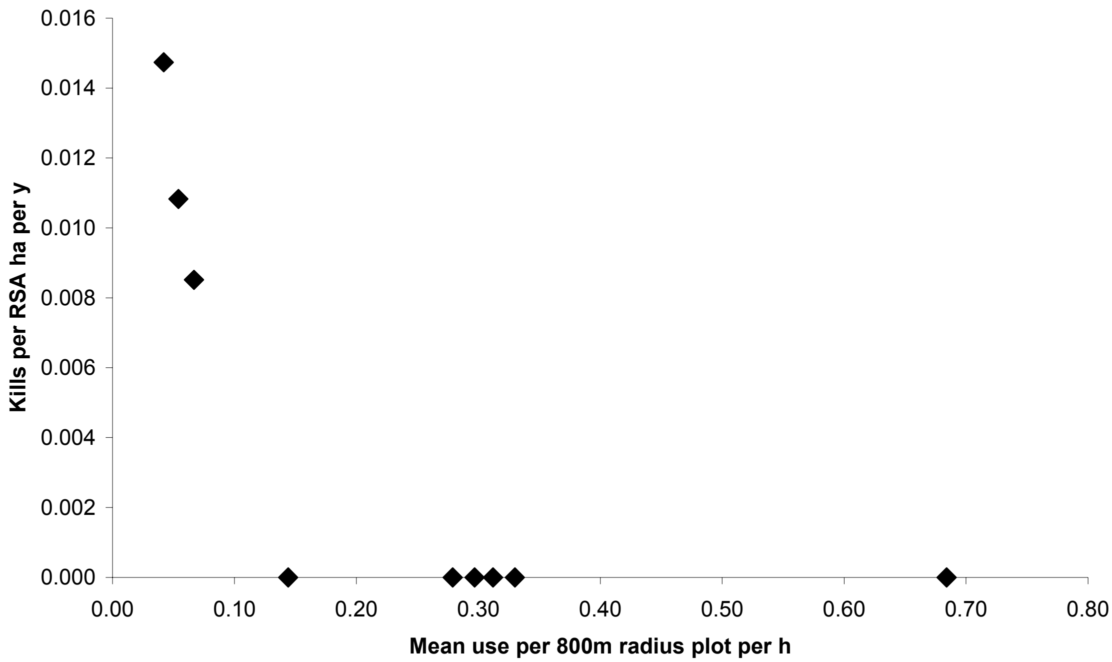

Fig. 1. The relationship between an index of hen harrier activity (mean number of sightings per 800 m circular plot per hour) and an index of mortality through collision with rotor blades (number of kills per hectare of Rotor Swept Area per year) at nine wind farm sites. Sources: Smallwood & Thelander (2004), Thelander et al. (2003), Erickson et al. (2001, 2002, 2003a, b), Johnson et al. (2000a, b, 2003), Schmidt et al. (2003), Lekuona & Ursúa (2005), Young et al. (2003a, b).

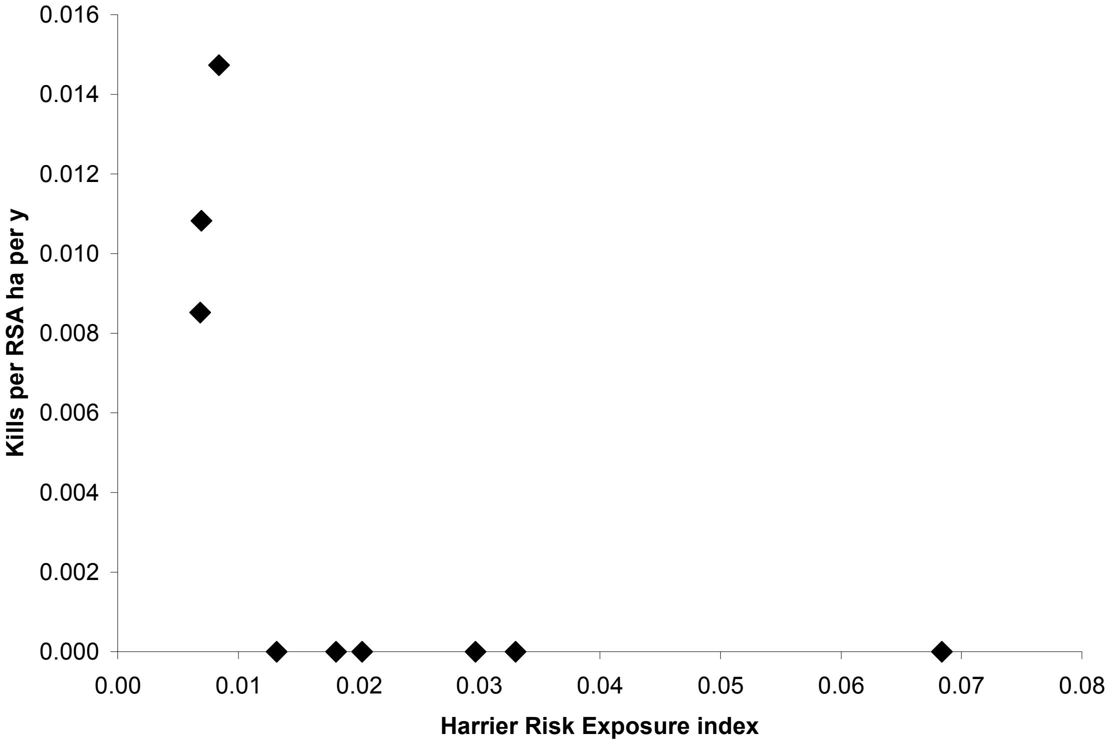

*Fig. 2. The relationship between an index of hen harrier exposure to collision risk (mean number of sightings per 800 m circular plot per hour * proportion of activity at rotor swept height) and an index of mortality through collision with rotor blades (number of kills per hectare of Rotor Swept Area per year) at nine wind farm sites. Sources: Smallwood & Thelander (2004), Thelander et al. (2003), Erickson et al. (2001, 2002, 2003a, b), Johnson et al. (2000a, b, 2003), Schmidt et al. (2003), Lekuona & Ursúa (2005), Young et al. (2003a, b).*