A review of the impacts of terrestrial wind farms on breeding and wintering hen harriers.

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1. INTRODUCTION

1.1 Purpose of work

Scottish Natural Heritage has commissioned a review of the impacts of terrestrial wind farms on breeding and wintering hen harriers. This is in order to assist in SNH's advice to developers, Scottish Government and others concerning onshore wind farm impacts on this species.

The main output will be an information note that will be published on the SNH web site. The product required of the contractor is a report that will be subject to further discussion and consultation. The final version will be edited by SNH in conjunction with the original authors. The final information note will only be formally released with the written agreement of all parties.

The principal outcome that SNH wishes to achieve is an unbiased evaluation of the effects and consequent impacts on wind farms on hen harriers, principally within Scotland (& GB) and Ireland. SNH wishes to reduce the uncertainty and ambiguity in developers', regulators' and conservation practitioners' understanding of impacts and how they may be mitigated where they are known to occur. SNH accepts that there may be residual uncertainties, and these will have to be addressed at a future revision of the information note. The review is intended to be as candid as is appropriate, on where uncertainties remain and what research and monitoring work is needed to address them.

1.2 Background

The development of onshore wind farms in the Scottish landscape has led to some concern around the impact on upland breeding birds, especially birds of prey, many of which have a poor (unfavourable) conservation status. The added impact of onshore wind farms has been seen as an additional pressure, which could make the recovery of the species to favourable status difficult, as many wind farm proposals are sited in areas used by breeding and wintering hen harriers. Even where development proposals do not overlap, they may be close to or contiguous, and overlap with at least some of the potential foraging range.

Despite there being a number of operational wind farms in existence, some of which overlap with areas used by hen harriers, there is still no clear consensus on the degree to which impacts are real and likely to add to the pressures on hen harrier populations. This has several consequences: uncertainties may mean that in the absence of information, regulatory authorities may wish to take a precautionary view on possible impacts and the consequences of those impacts. Secondly, at a very basic level, casework takes longer and staff resources are tied up making assessments when there is apparently little solid information on which to base such assessments.

However, there are, and have been, monitoring schemes at wind farm sites where hen harriers occur, and there is published information for other countries (such as USA) where closely related species also interact with onshore wind farms. The problem for SNH and other regulatory authorities is that much of this information is scattered, rarely in the published scientific literature and when it is available, often only published in non-peer reviewed reports. Some information is kept confidential, where, for whatever reason, it is virtually useless as a basis for making informed judgements on development proposals.

The purpose of this review is to collate the available information from the literature and from sites where post-consent monitoring has been undertaken so that a considered view can be presented on when and under what circumstances, wind farm developments are likely to be a problem for breeding and wintering hen harrier.

1.3 Methodology

The approach to this work is set out below. SNH envisage that it will include the following steps:

1. Identify any report, publication (hard copy or web based) or scientific paper that addresses the impacts of wind farms on hen harriers. Material that is confidential and cannot be disclosed should, in general be omitted as the veracity of the data and its claims cannot be verified.
2. Consult, as appropriate any other research worker, academic and/or conservation practitioner, on initial assessments, and to use such information, where appropriate to qualify or reinforce conclusions from the review of the varied literature that is obtained.
3. Consult with key staff in SNH and the Scottish Windfarm Bird Steering Group (SWBSG).
4. Draft an interim report for consultation.

2. POSSIBLE IMPACTS OF WIND FARMS ON HEN HARRIERS

2.1 Types of impact

Desholm (2006) summarised three hazard factors facing birds from wind farms.

1. a behavioural element, caused by birds avoiding the vicinity of the turbines as a behavioural response to a visual stimulus and/or sound stimulus;
2. a physical habitat element, where birds respond to destruction, modification or creation of habitat associated with turbine infrastructure construction;
3. a direct demographic element, resulting from mortality arising from physical collisions with the superstructures.

In the case of hen harriers these hazards may arise when they are breeding or while they are over-wintering. It is also possible that there may be hazards while they are moving between over-wintering and breeding sites. There is very little information about hazards while over-wintering or moving to and from over-wintering sites. Because the UK does not have recognised migration corridors for harriers it seems unlikely that wind farms would present significant hazards for large numbers during spring and autumn movements. Most of the over-wintering sites are in locations that are not currently subject to wind farm construction or plans. However, this could change in the future and evening flights at communal roosts are more likely to be at collision risk than the lower foraging flights.

The three impacts can be studied using different techniques.

a. If there is an avoidance of turbines this could be identified from detailed flight maps from vantage points. If there is avoidance it will have a scale, i.e. an avoidance distance. It is predicted that any avoidance/displacement effect would increase with proximity to the turbines.
b. If there are changes in harrier flight paths arising from habitat changes associated with the wind farm's construction these could be identified by comparing pre- and post-construction habitat usage maps. It is predicted that any responses to habitat change would reflect changes to the prey base. For example, if the vegetation is kept short there are likely to be fewer small mammals whilst a clear fell of conifer plantation may increase the prey base depending on the nature of post-felling management. In Ireland it is clear that hen harriers make good use of the early stages of second rotation forests (Wilson *et al* 2009).

Both a and b could lead to reductions in hen harrier productivity by reducing foraging success or increasing the energetic costs of foraging. These effects could only be detected if there is sufficient pre-construction information combined with suitable information from reference sites during the operational phase.

c. If there is collision mortality there may be population-level impacts depending on the level of mortality and the population's ability to buffer itself against a rise in mortality. Collision mortality may go unrecognised in the absence of nest watches and/or carcass searches. If there is significant collision mortality it is predicted that nest failure rates will be higher, possibly with more relays, and the regional population may begin to decline depending on the scale of any additional mortality.

2.2 Interactions between hen harriers and wind farms from the literature

One of the most interesting features of any literature searches for the impact of wind farms on hen harriers is the relative paucity of studies and examples of significant negative impacts. For example, in their critical review of the impacts of wind energy on grassland and shrub-steppe birds covering 24 studies published between 1998 and 2006, Mabey and Paul (2007) do not review a single study involving hen harriers even though it is listed as one of their grassland species.

There appear to be few documented cases of collision mortality. In a review by Kingsley and Whittam (2005) only six collisions are documented (two at the Altamont Wind Resource Area (Erickson *et. al.* 2001), one at Foote Creek Rim (Johnson *et. al.* 2001) and three at the Altamont Wind Resource Area (Smallwood and Thelander 2004)). Derby *et al* (2008) noted that "*Thus far, only three northern harrier fatalities at existing wind energy facilities have been reported in publicly available documents, despite the fact they are commonly observed during point counts at these projects*". However, at Altamont Pass Wind Resource Area Smallwood and Karas (2008) record seven northern harrier deaths (their Appendix) over a 17 year period between 1989 and 2007. Despite these deaths, northern harriers had the lowest death rate of all species summarised in Table 1 of Drewitt and Langston (2008). The estimate of 0.001 deaths per MW per year compares with an average of 1.94 for all raptors.

This low level of harrier mortality is supported by the results of the Stewart *et al* (2005) evidence-based review who found that hen harriers were in one of the least impacted groups. Although the sample was small it was possible to use meta-regression to investigate the data. They found that bird taxon had a significant impact on the effect of wind farms on bird abundance with a rank order (largest decline first) of Anseriformes (ducks), followed by Charadriformes (waders), Falconiformes and Accipitriformes (raptors) and Passeriformes (songbirds). Turbine number did not have a significant impact on bird abundance whilst turbine power had a very weak but statistically significant effect with low power turbines resulting in greater declines in abundance than high power turbines. They also found that the time since operations began had a significant, impact on bird abundance with longer operating times resulting in greater declines in abundance than short operating times. If this is a general characteristic, short term studies conducted soon after commissioning are less likely to detect any impacts. This may be relevant for some of the studies in the UK.

Johnson *et al* (2000) completed a comprehensive four year survey of the Buffalo Ridge Wind Farm Area (WFA). Phase 1 (25MW) was developed in 1994 and consists of 73 turbines. Phase 2 is a 143 turbine 107.25MW wind farm. This was completed in 1998 and, at that time, was the world's largest single wind farm project. The third phase, completed in 1999, is a 103.5 MW wind plant comprised of 138 turbines. Therefore, in total there are 354 turbines in the WFA. Based on frequency of occurrence, northern harriers were the fourth most frequently occurring species, being recorded in 30.0% of their surveys (their Table 8). This was, in general, one of the most frequently occurring species in each individual study area as well, although some differences did exist between areas. During summer surveys northern harriers were the third most frequently occurring species, being recorded in 19.9% of their surveys. Because of the size of wind farm area, and the relative abundance of northern harriers, this study should be a good guide to the possible impacts of wind farms on hen harriers. In the first year following construction (1998), the BACI analysis indicated that use of turbine point count plots was lower than expected for northern harrier. However, the area of reduced use occurred primarily close to turbines (< 100 m). On a large-scale basis (i.e., within the entire WRA) a BACI analysis was used to examine potential large-scale wind development effects at roadside plots. Northern harriers were the only grassland nesting species with lower than expected abundance at roadside plots during the 1998 breeding season. However, use of the Phase 2 and Phase 3 wind farms by northern harrier in 1999 was similar to expected use based on reference area values. These results suggest that, if there is any avoidance effect, it relatively small scale and possibly transient.

In Table 12 of Johnson *et al* (2000) northern harrier exposure indices were 0.048 and 0.030 (almost ten times lower than the maximum of between 0.3 and 0.4 for Franklin's gull). Their exposure index was calculated by multiplying a bias adjusted mean abundance (number per survey) and the proportion of all flying observations where the species was observed within the rotor-swept height of each of the turbines. One of the reasons for the low exposure index is the flight heights of the harriers. Their Appendix G lists the percentage of birds flying below turbine height during RLB surveys for two types of turbine (19.5 and 26 m above ground respectively) and these were 84% and 90% and with a further 2% and 1% above turbine height. Similarly, the Appendix G percentage of northern harriers flying below turbine height during point counts for the two turbine types were 92% and 94% respectively, and in each case 1% of flights were above turbine height. It should be expected that a low exposure index would result in few collisions. This is supported by the results of their carcass searches. During the 4-year study, 2,840 fatality searches were conducted on plots associated with operational turbines. Northern harriers were not one of the recorded fatalities despite their relative abundance.

As of May 2012 no hen harriers have been found or reported killed under German wind turbines. This based on information collated in an official website at the Ministry of Environment, Health and Consumer Protection of the Federal State of Brandenburg[1]. However, this may not be very informative about general risks to hen harriers because Germany has a small breeding hen harrier population that is restricted mainly to the North Sea islands where wind turbines are rare. Even though Germany has almost twenty times more turbines than Scotland (22,339 April 2012[2]) they are largely on agricultural land[3] in northern Germany that is unlikely to be used by hen harriers (Illner, 2011).

At areas such as Altamont the low harrier mortality rate is almost certainly related to flight behaviour since northern harriers appeared to be at low risk of collision despite spending a disproportionate amount of flying time within 50 m of the turbines (reported in Drewitt and Langston, 2008). Whitfield & Madders (2006a) suggest that the hen harrier's low susceptibility to collision is at least partly explained by the observations that harriers typically fly below the heights swept by rotor blades. For example, Smallwood and Thelander (2004, Table 8-3) recorded a mean height above ground of only 24.1 m. When this is combined with some small-scale (see below) and, more rarely, large-scale avoidance of rotor blades (Whitfield & Madders 2006b) it is unsurprising that few deaths are recorded for this species.

Garvin *et al* (2011), in a study of an American 87 turbine wind farm, found that raptor abundance post-construction was reduced by 47% compared to pre-construction levels. However, flight behaviour varied by species, but most individuals remained at a distance of at least 100 m from turbines and above the height of the rotor zone. In the case of harriers, they found evidence of a temporal lag in the possible displacement effect in response to windfarm construction. There was also no evidence of a rebound in subsequent years, although they suggest that it is possible that such a response may occur in the future. The northern harrier was the only species of conservation concern which declined post-construction in this American study. However, Garvin *et al* (2011) again concluded that this species appears to be at low risk of collision and appeared to show 100% avoidance of turbines.

The peer-reviewed study by Pearce-Higgins *et al* (2009) has had a significant impact on the assessment of possible impacts of wind farms on upland birds in the UK, including the hen harrier. Consequently, this study is considered in some detail. The study suggested that hen harriers avoided flying within 250 m of turbines, leading to a 53% reduction within 500 m of turbines. The monitoring data from the Scottish wind farms described in Section 3 of this report do not fully support either of these displacement observations and conclusions since harrier flights were observed close to turbines at five wind farms where there has been detailed monitoring. In addition, at Ben Aketil and Edinbane, activity has increased within the 500 m turbine buffer and birds are nesting relatively close to turbines.

[1] http://www.mugv.brandenburg.de/cms/detail.php/bb2.c.451792.de and http://www.mugv.brandenburg.de/cms/media.php/lbm1.a.2334.de/wka_vogel_de.xls for the spreadsheet

[2] http://windmonitor.iwes.fraunhofer.de/windwebdad/www_reisi_page_new.show_page?lang=eng&owa=Windenergieeinspeisung.daten%3Fp_lang=eng%26bild_id=273

[3] http://windmonitor.iwes.fraunhofer.de/windwebdad/www_reisi_page_new.show_page?page_nr=20&lang=en

Pearce-Higgins *et al* (2009) was a correlative study that considered the effects of turbines on a range of foraging birds, including hen harriers. It did not cover potential impacts such as loss of nesting sites, impacts of reduced foraging success on breeding output or the risk of collision by flying birds with turbines. They concluded that harrier density, within 500 m of a turbine, was reduced by 53%. However, the confidence interval for this reduction included 0 so it is evident that the effect was not clear cut. Indeed, in their Figure 1 there is no obvious decay in use with distance to the turbines. As will be shown later (section 3.2), usage may increase or decrease close to turbines depending on the metric used. However, there are some details in this study that may have clouded some interpretations of the results and subsequent recommendations for wind farm developments. We are grateful to Pearce Higgins for some detailed responses to a draft of this report. Many of the criticisms of the 2009 paper relate to the controls. For example, non-wind farm sites were smaller (range 180–268 ha) than wind farms (range 432–932 ha). In the case of hen harriers, the effects of turbines were examined out to a distance of 1 km. A 1 km buffer around a single turbine is 314 ha which is larger than the largest control site. Pearce-Higgins recognises there are such criticisms and notes that "*with the benefit of hindsight, our use of the term 'control' areas in the paper may not have been useful, because they were not used as control areas in the traditional sense, to compare changes on a wind farm with that of a control. Instead, they were used to reduce the level of correlation between environmental predictor variables and turbine distance. Most wind farms are located on hill tops, and therefore habitat and topography changes with increasing distance from those turbines. These sites were selected (from remote sensed data) to be similar to the turbine footprint of the relevant wind farm to reduce this artefact. To this end, their smaller size is entirely appropriate."* Some of these control site issues were also addressed in Pearce-Higgins *et al* (2012) where they note that, with respect to golden plover, "*some of the previous differences between wind farm and reference sites could have resulted from intrinsic initial differences in density*." Pearce-Higgins also suggests that the concerns raised by several consultants, that reference sites were not representative of the wind farms, are unwarranted since "*for most species we were able to conduct analyses using just the wind farm data to 500m (not affected by data from these 'controls') and the wind farm and non-wind farm data. With the exception of curlew, which showed greater avoidance than 500m, the results from all the other species were equivalent, suggesting that our approach was a good one and has not introduced systematic bias through poor 'control site selection'*. Nonetheless, the flight recording methodology is a concern for a species such as the hen harrier. The methods note that raptors were "*followed for a maximum of 1 min and then the same individual was not followed again until 5 min had elapsed*". It is clear from the flight maps from Ben Aketil and Edinbane (Section 3.2) that this could result in a significant bias in habitat use (either avoidance or an increase) depending on which fraction of a flight was recorded. In conclusion, Pearce-Higgins notes that "*the take home message of the 2009 and 2012 studies are evidence of widespread turbine avoidance for many upland bird species which are more consistent than track or transmission line avoidance and robust to various statistical checks....In relation to HH, the 2009 study suggests to me that across a range of sites there is evidence that hen harrier show reduced flight activity to 250m from the turbines, although this pattern may not be found at any one individual site. Depending on the relationship between activity and density, this may reduce habitat quality, and by c. 50 % within a 500m buffer around the turbines. It is unclear the extent to which this may significantly impact upon breeding territory quality. However, as recognised in our 2012 paper, detailed pre, during and post-construction monitoring is key to refine and improve these estimates of impact further, and the studies which you summarise here are good examples of that. I therefore suspect that you have summarised the impacts on hen harriers, as currently understood, pretty well, and think they show consensus for fine-scale avoidance from 100-250m distances which will reduce collision risk, but may reduce habitat quality. Levels of collision mortality appear low.* "

There is little evidence for an impact of wind farms on harrier nesting. One of the few reported examples is from Kerry in Ireland where O'Donoghue *et al* (2011) reported that the nesting location of a single harrier territory shifted further from a wind farm site after construction. There are unpublished reports of a decline in hen harriers in the vicinity of complex of wind farms on the Irish/Northern Ireland border, including the Lendrum Bridge wind farm. Over the period 2003-2011 there was a very marked decline in hen harrier occupancy and productivity from the surrounding 3-4 territories with no breeding attempts in 2011 although it is possible that there was a single failed attempt in 2012 (Wilson *pers comm*). It is not thought that the wind farm is the primary cause for these declines, rather they reflect other changes operating at the landscape scale. Elsewhere, in the Irish Republic, harriers have bred within 300m from turbines in Co. Kerry and 500m from turbines in Co. Tipperary, although the latter failed probably as a consequence of predation (Wilson *pers comm*). There are several other examples, from within the UK, where harriers have been recorded nesting close to operating turbines For example, at the Cruach Mhor Wind Farm in Argyll, harriers were first recorded nesting during the construction year (2003) and nesting has continued with a mean of 284 m to the closest turbine (range 131 - 476 m, 2003-2009) (Scottish Power Renewables, 2009). At Paul's Hill Wind Farm in NE Scotland nesting harrier numbers near the wind farm site were similar during operation (mean 2.4, 2006-2010) to before construction (mean 2.6, 1991-2003), and were higher during construction (mean 4.5, 2004-2005) with one nest at 110 m from construction activities (Forrest *et al*. 2011). A sample of 10 of the 28 turbines at Paul's Hill in NE Scotland were searched every fortnight over five years of operation and no harrier collision victims were found, despite 2-3 pairs nesting close to the wind farm (Forrest *et al*, 2011).

Madden and Porter (2007) report some monitoring data (2004-2007) from a wind farm in the Slieve Aughty Mountains, Ireland. At a landscape scale (within 5 km), between 10 and 11 pairs of harriers bred each year although none nested within the wind farm. As with other studies the majority of flights were low (<10 m over the bog) and some birds regularly passed within 50 m of turbines, including one within 10 m of a turbine base.

McMillan (2011) provides a detailed account of hen harrier nesting in the vicinity of the Ben Aketil and Edinbane wind farms. A new site was discovered only 500 metres from Ben Aketil's Turbine 3. This nest was successful in 2008 and successfully fledged a brood of 5 at the same location in 2009. McMillan (2011) reports that this "*nest was less than 200 metres from the windfarm access road and birds would certainly 'alarm' at anyone on the road*". Following construction works for a two turbine extension to Ben Aketil a pair of harriers attempted to breed in 2011. Unfortunately, the original breeding female and the clutch from a replacement female were killed on the nest by a fox (evidence from a nest camera).

The five turbine extension to the Edinbane wind farm was adjacent to the SK7 hen harrier territory. In accordance with a planning condition, work was completed on the closest turbine by the end of March 2010 and McMillan (2011) recorded both male and female hen harriers in this area. A male was seen displaying and escorting a young male off the territory. On several occasions the male was observed in the fenced hardwood plantation to the west of Turbine 6, and although a female was later seen in the area, no evidence of breeding was obtained. A successful nest site at Choisleadar was within 800 metres of turbines on the Edinbane site. Finally, in 2010 McMillan reports that the population of breeding hen harriers reached a similar level to what it had been pre-windfarm construction and this was sustained in 2011.

2.3 Conclusions

There are several clear conclusions from studies undertaken in different countries.

1. Hen harriers show some small scale avoidance of turbines leading to a small loss of potential foraging habitat.
2. Hen harriers appear to continue nesting successfully close to turbines.
3. Hen harrier flights tend to be lower than the turbine swept area.

4. A combination of the previous three conclusions is that collision mortality for hen harriers is unlikely to be large.

3. MONITORING STUDIES IN THE UK

3.1 Scale of possible impacts

Bright *et al* (2008) examined the spatial overlap between wind farms (at all stages of the planning process) and the location of birds from national and regional surveys. However, their analysis and conclusions were restricted to peatlands. They found the highest overlap between wind farms and bird species distribution was for hen harrier. The extent of the overlap depended on the planning stage of the wind farm: 2% of all hen harrier buffered areas overlapped with installed wind farms on peatland, rising to 6% of buffered areas for hen harrier and wind farms at all stages of the planning process (installed, approved, application and scoping). This percentage rose to 17% if the analysis was restricted to peatlands. They argue that the fact that 17% of hen harrier buffers on peatland overlapped with wind farms suggests a closer correspondence between hen harriers and wind farm development on peatland than in non-peatland habitats which may create cumulative impact problems.

However, it is also important to examine the concentrations of hen harriers in Scotland and the probability of significant wind farm developments. By far the largest part of the population is now on Orkney[4] (see section 3.2.5 for an account of wind farm-harrier interactions on Orkney). Other significant populations have been recorded on Arran, Mull, the Uists and Islay (Fielding *et al* 2011). Currently, there is no pressure from major wind farm developments in these locations. This is important because it means that a very significant part of the population should remain free from any wind farm impacts (unless significant risks develop for over wintering populations). Since these populations are also free from persecution (Fielding *et al* 2011) they should be capable of providing recruits for other populations across Scotland. The Perthshire population, where 43 pairs were recorded in 2011, has recently had a higher population of breeding harriers which coincides with the milder winters of the 1990s (Mattingley *pers comm*). This is one of the largest hen harrier populations in Mainland Scotland and should, perhaps, be monitored carefully to measure any effects of wind farms, and other factors, in that region. Perthshire also has a number of known harrier roost sites particularly in the Forest of Clunie SPA and, when winters are mild, East Scotland provides good wintering habitat for harriers especially females (Mattingley *pers comm*). The possible effects of wind farms on wintering hen harriers and, in particular the spatial association between the two, is poorly understood and is likely to remain so in the absence of extensive monitoring.

One of the difficult problems for predicting windfarm-hen harrier interactions is the apparent tendency for marked changes in hen harrier distributions at the scale of the wider landscape. This can act in both directions so, for example, a location currently free of hen harriers could see them appear following construction if the habitat is suitable. This could result in impacts that could not be predicted from any pre-construction surveying. Conversely, as with most of the hen harrier SPAs in Southern Scotland, they can disappear from large regions. It is not entirely clear what has caused the almost complete absence of hen harriers from Southern Scotland in 2012 (Thompson, *pers com*), although persecution has been implicated for their absence or reduced densities in some regions (Fielding *et al* 2011).

3.2 Monitoring schemes

There are four main extant post-construction monitoring schemes that we are aware of. Currently, we have access to the flight data for two of them: Ben Aketil and Edinbane. There are publications in the public domain relating to the other two, Cruach Mhor and Paul's Hill. Finally, there is a personal account of the situation on Orkney.

[4] http://www.birdwatch.co.uk/channel/newsitem.asp?c=11&cate=__11956

3.2.1 Ben Aketil

Two Ben Aketil turbines were constructed by mid-September 2007, rising to five by the start of October and nine by the 20th October. At the beginning of November 2007 all ten of the first phase was complete with eight functioning. An additional two turbines were installed during spring 2010 at the northern end of the string of turbines. The post-construction flight data collected by Atmos Consulting Ltd between 2008 and 2010 was made available to us and we have used it to investigate if there is any evidence for the small scale avoidance of turbines identified by Johnson *et al* (2000) for the northern harrier and also highlighted in the Pearce-Higgins *et al* (2009) correlative study.

The pre- and post-construction hen harrier flight data do not provide any qualitative indication of avoidance of turbines. Indeed it is striking how many flights cross the turbine string orthogonally as direct flights to and from the nesting area in the woodland (Figs 1 and 2). This becomes even more striking when the Atmos Consulting and Haworth Conservation data are combined (Fig. 3).

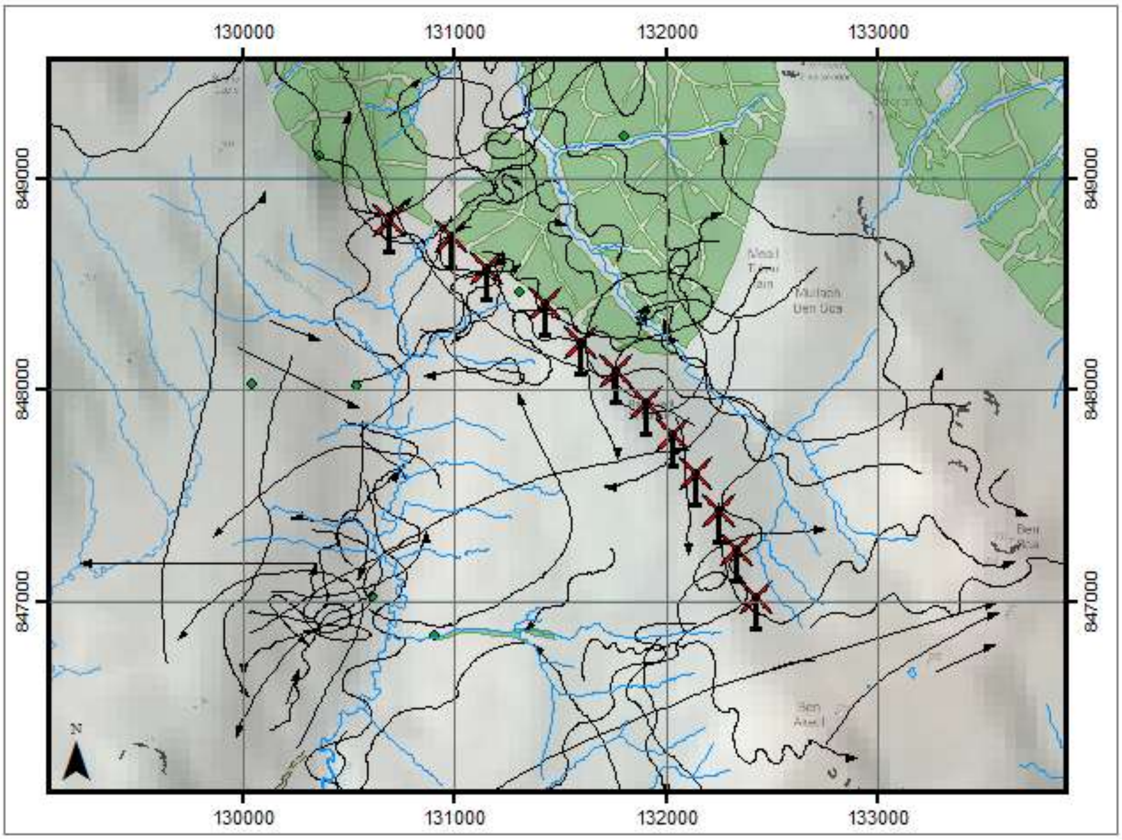

Fig 1. Atmos Consulting Ltd pre-construction hen harrier flight data (2002-2006). (Contains Ordnance Survey data © Crown copyright and database right 2010).

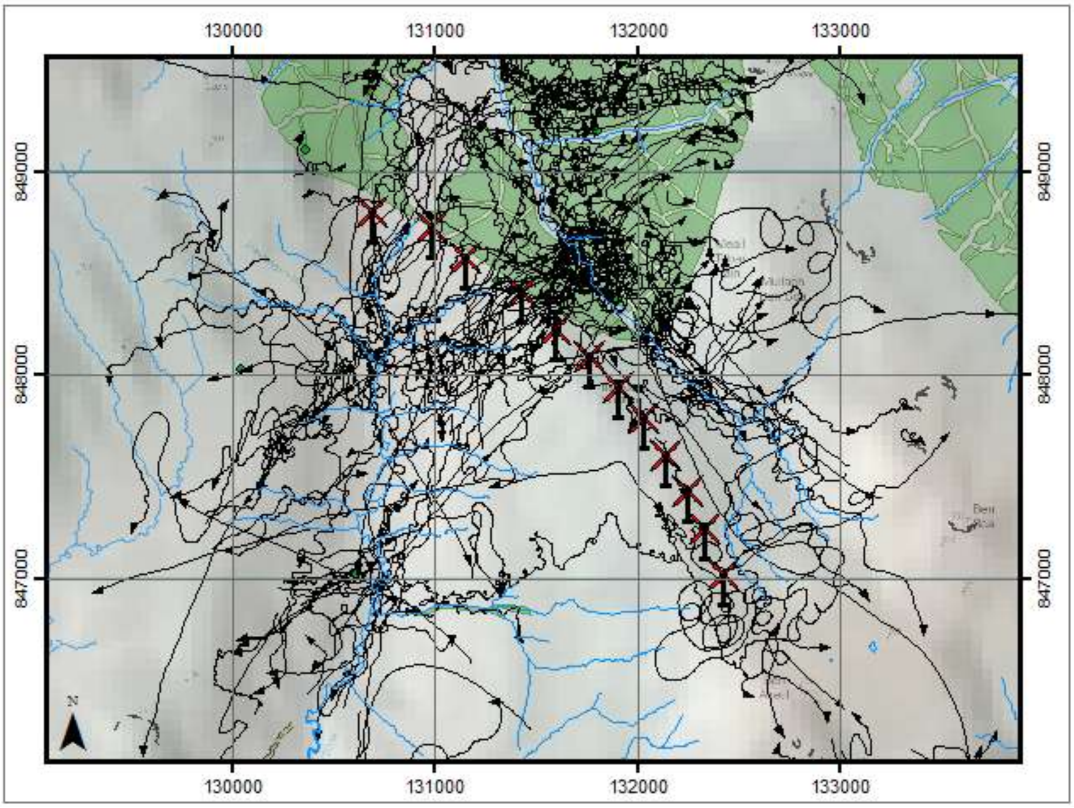

Fig 2. Atmos Consulting Ltd Post-construction hen harrier flight data (2008-2010). (Contains Ordnance Survey data © Crown copyright and database right 2010).

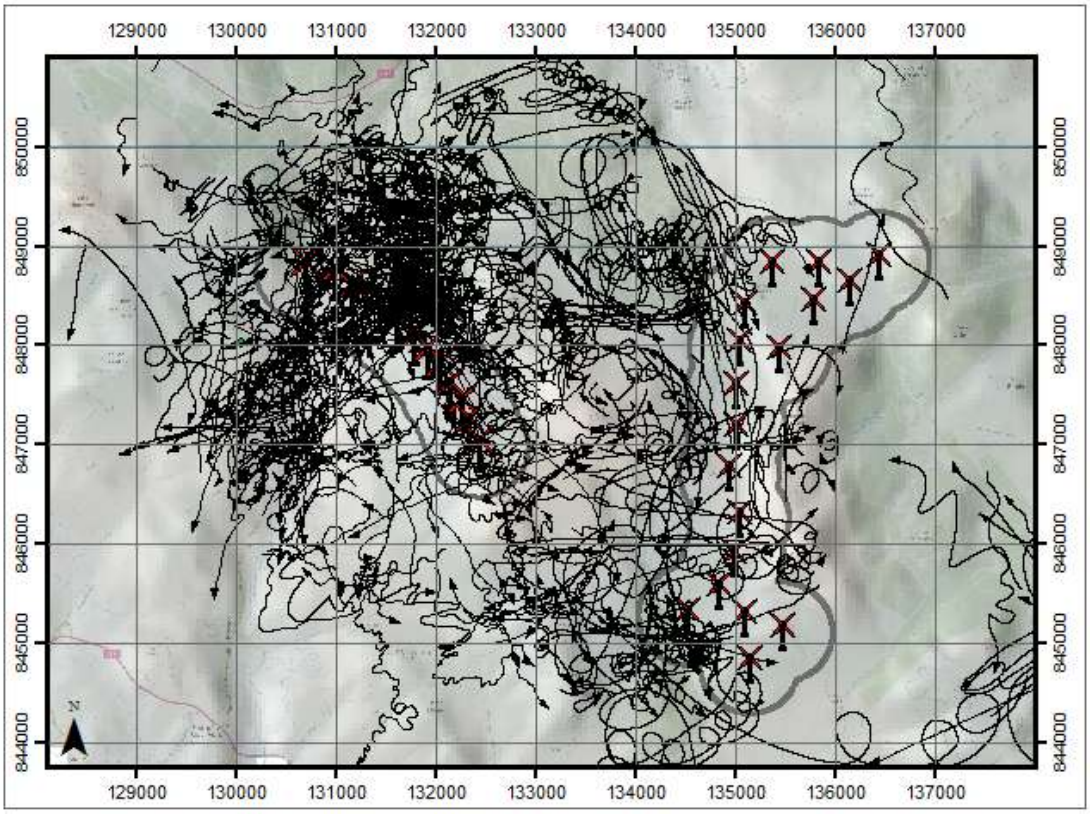

Fig 3. Post-construction hen harrier flights 2008-2011 (Atmos Consulting and Haworth Conservation data combined). (Contains Ordnance Survey data © Crown copyright and database right 2010).

It is also possible to analyse these data using a quantitative approach. If hen harriers do not fly close to turbines we should expect a reduction in the proportion of flight activity from that expected close to turbines. Because the aim of these analyses is to look for evidence of small scale avoidance the data are restricted to flights that passed within 500 m of a turbine (Fig. 4). The number of expected flights can be estimated from the relative areas of buffers drawn around the turbines. For example, if a 100 m buffer drawn around the turbines is 11% of the land area within a 500 m buffer drawn around the turbines we should expect at least 11% of the observed flight activity within the 100 m buffer.

Preference indices use an index to determine if resources are used in proportion to their availability. There is no agreement on the 'best' index. Allredge and Ratti (1992) reviewed the application of four methods, including preference indices, to resource selection analyses. They concluded that the choice of method depends upon which statistical hypothesis most closely matches the biological question, and how observations and individuals are weighted. Maclean *et al* (1998) compared six methods of analysing resource selection data. The methods gave different results for the same data because they used different assessments of availability and treated individuals differently. Only the method described by Neu *et al* (1974) method (an index) identified selection patterns consistent with known ecological requirements at all levels of habitat availability that they tested, i.e. the Neu results were scale-invariant. It is also appropriate for a design, such as this, in which individuals cannot be recognised.

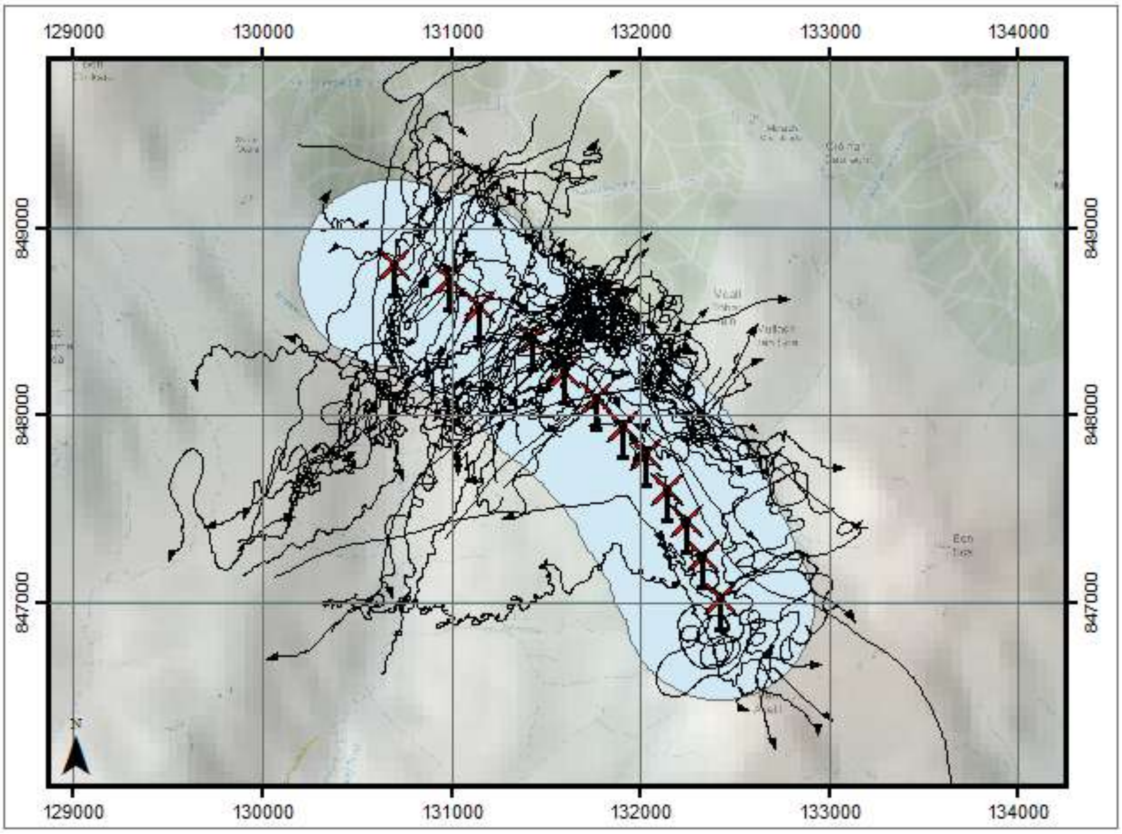

Fig 4. Post-construction hen harrier flights 2008-2011 that passed within 500 m of a turbine (Atmos Consulting data). (Contains Ordnance Survey data © Crown copyright and database right 2010).

We calculate Neu's index (SI) as the ratio of the used proportion to the available proportion, where the used proportion is the proportion of all flight activity within 500 m of the turbines that intersect a particular buffer and the available proportion is the area of a buffer as a proportion of the area of a 500 m turbine buffer. A selection index (SI) has a value of 1 when the observed level of activity matches the expected. If the level of activity exceeds the expected the value of SI will be greater than one, larger values indicating greater 'over-use'. If the level of activity is less than expected, for example as a consequence of avoidance, the value of SI will be less than one.

However, when concentric buffers are used the flight activity becomes cumulative, such that all of the flights within 100 m of a turbine must also be within 200 m of a turbine. If there is avoidance at 100 m this would be inherited by the 200 m buffer. Therefore, we calculated Neu's index in two ways.

1. The area of concentric buffers where each buffer has a fixed distance from the turbines: 50m, 100m, 200m, 300m, 400m and 500m.
2. The buffer area is restricted to a band between lower and upper radii. For example, the 50 m and 100 m concentric buffers have respective areas of 9.4 and 37.6 ha. However, the area of the band between 50 and 100 m is 37.6 - 9.4 = 28.2 ha.

Finally, it is possible to measure flight activity by a different metric: their number or their length within a buffer. We use both measures and both types of buffer resulting in four analyses.

Details of the calculations are in Appendix 1 and are summarised here by bar charts of Neu's index. A value above 1 indicates greater use than expected from the area while a value below 1 indicates less use than expected from the area i.e. displacement or avoidance.

Analysis 1: Concentric buffers, flight length

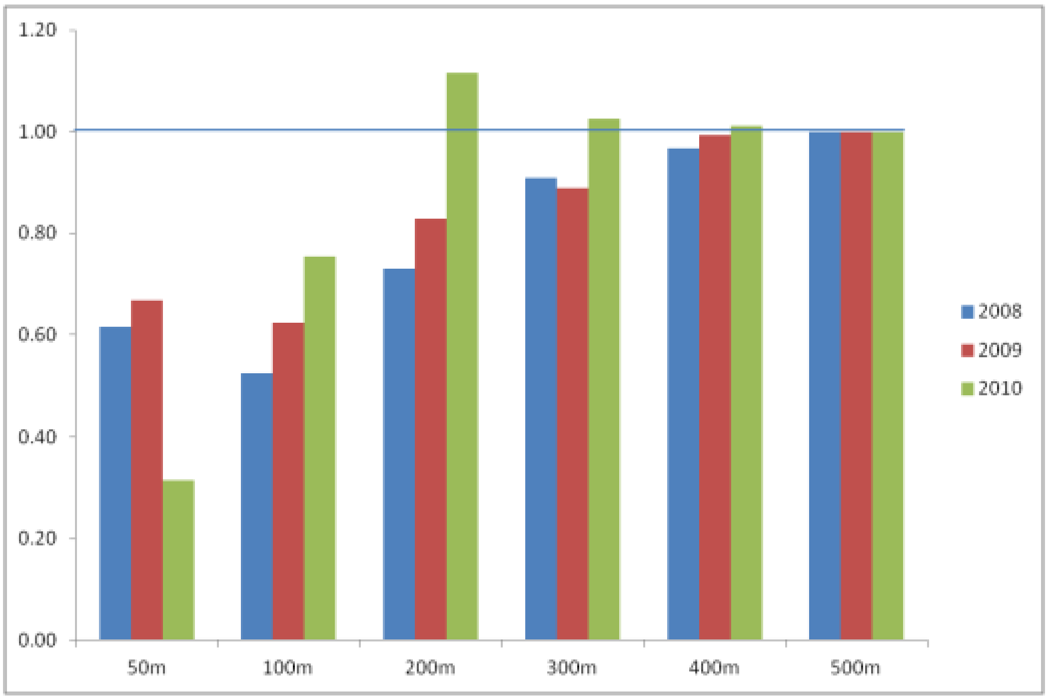

Figure 5 Selection Index for flight lengths (m) in buffers with increasing distances from turbines. These data are from the post-construction phase. The horizontal line at SI = 1.0 indicates that usage equals that expected from the buffer area.

There is some evidence of avoidance close to the turbines (up to 200 m in 2010) and this does not change over time. In the 50 m and 100 m buffers Neu's index is consistently below

1, indicating less use than expected from the area. Within the 200 m buffer, and beyond, the index is close to 1 indicating that usage is proportional to the area (Fig. 5).

Analysis 2: Concentric buffers, flight number.

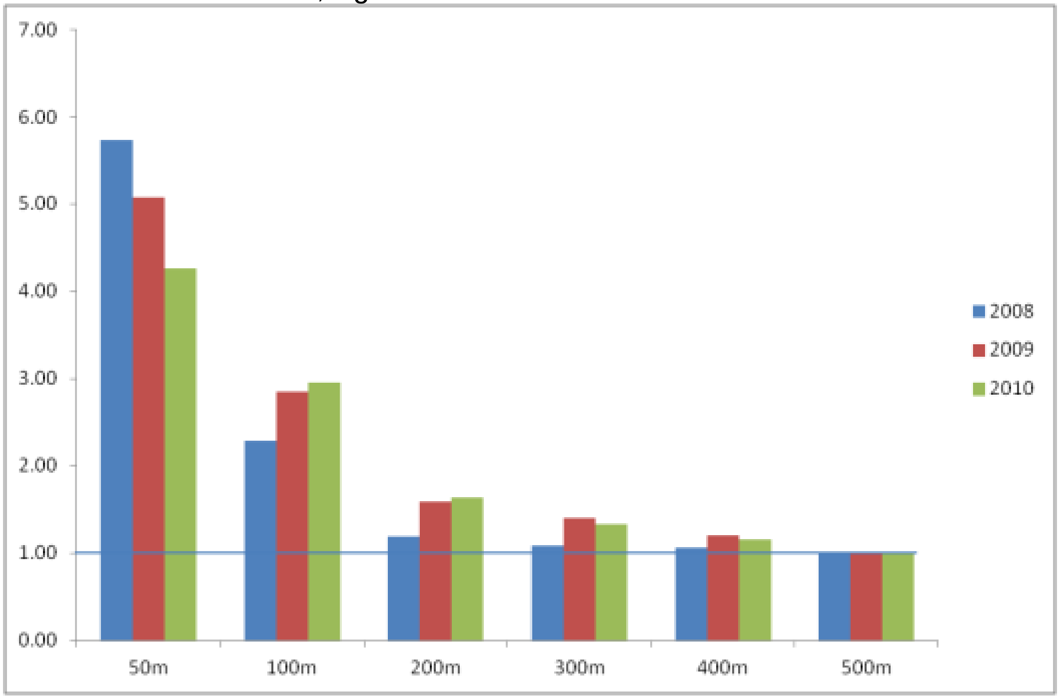

Figure 6 Selection Index for number of flights in buffers with increasing distances from turbines. These data are from the post-construction phase. The horizontal line at SI = 1.0 indicates that usage equals that expected from the buffer area.

Despite the evidence for displacement in the flight length calculations there is very marked evidence of excess flights close to turbines (Fig. 6). For example, 18 of the 150 flights (all years) passed within 50 m of turbine. The 50 m buffer is only 3% of the area of the 500 m buffer so only 0.03 x 150 = 4.5 flights are expected. This gives a Neu's index of 4.26. Therefore, is seems that hen harriers will fly close to turbines but they do so in relatively straight lines giving the shorter distances which provide evidence for displacement.

Analysis 3: Ring buffers, flight length.

The results are similar to the analysis with concentric buffers and are only summarised here. More details of the results are available in Annex 1. However, the avoidance effect close to the turbines no longer exists in the 100-200m band (Fig. A.1) and the indices are closer to 1 reinforcing the view that flight lengths are shorter than expected up to 100 m of a turbine and the importance of avoiding incorporating displacement at small distances into wider distance classes.

Analysis 4: Ring buffers, flight number

Again, the results in are similar to those in Fig. 6 (see Fig. A.2). In later years the evidence suggests that, if anything, flights are getting closer to turbines than expected. This is unlikely to be a direct effect of the turbines; rather it may be related to changes in nest locations and foraging patterns.

3.2.2 Edinbane

Haworth Conservation have been carrying detailed monitoring of Vattenfall Wind Power Ltd.'s Edinbane wind farm since 2007.

At Edinbane, preliminary construction of the wind farm commenced in early 2008, whilst main site works commenced during August 2008. Wind turbines started to arrive during late summer 2009 and construction was completed during June 2010. All turbine bases, for the original 13, had been completed by 20/06/2009, with the first turbine complete by July 15th. By the date of the survey on the 28th November 2009 the 13 were complete and construction started on the five bases for the later extension to 18 turbines. Work was completed by June 1010.

Bird observations have been collected, in and around the Edinbane wind farm by Ken Crane and Kate Nellist using three, four and, then later, five vantage points. Data collection started on 16th January 2007 using vantage points A, B and C. Vantage point D was added in January 2008 to record usage associated with a possible white-tailed eagle roost site. Vantage point E was added in January 2010 to provide better coverage of the adjacent Ben Aketil wind farm.

Over the five years of monitoring overall hen harrier activity has more than doubled (Table 1), primarily due to an increase in flights recorded from VP A (northern section of the Edinbane wind farm), while activity recorded from VP B (mainly Ben Aketil) has been relatively constant. Apart from 2008, relatively little hen harrier activity has been recorded from VP C (southern section of Edinbane). Surveying effort has been the same each year.

Spatial and temporal patterns of usage were investigated using a grid of cells 200 m by 200 m (4 ha). The total lengths of digitised flight lines that intersected each cell were calculated. Flights seen from VPs D and E were excluded from some analyses because these VPs were not used throughout the monitoring period. Similarly the total number of surveying hours per year was calculated for each grid cell by overlapping the viewsheds on to the grid. Usage is then expressed as kilometres of flight per 100 hours of observation.

Table 1. Summary of total fight lengths (km) recorded from the three main Vantage Points for three species over five years. A, B & C are the main vantage points.

Year	**A**	**B**	**C**	**All**
2007	7.9	35.0	6.5	49.4
2008	14.0	24.1	47.6	85.7
2009	45.8	44.0	10.2	100.0
2010	66.8	30.7	11.9	109.4
2011	64.2	28.8	7.6	100.6

Table 2. Relative use, measured as the percentage of summed length (km/100 hours) across 4 ha grid cells, with respect to 2007. Calculations are shown for all surveyed habitat (VPs A, B and C) and the areas enclosed by a 500 m radius buffer drawn around the turbines.

	All	Ben Aketil	Edinbane
2007	100.0	100.0	100.0
2008	210.3	467.4	353.7
2009	223.8	148.7	349.2
2010	157.5	161.7	267.3
2011	173.4	227.6	189.8

In addition to the overall increase in hen harrier flights there has been a marked increase in the percentage of flight activity that is within both wind farms (Table 2), although this does vary between years. For example, in 2011, the use of the entire area had increased to 173% of the use in 2007. This increase was larger in both wind farms so, for example, within the Ben Aketil wind farm 500 m buffer, flight activity was 228% larger than that in 2007. In fact, the reported results significantly underestimate the amount of hen harrier within the wind farms since on several monitoring days the Edinbane surveyors reported that there was "too much activity to record". Indeed, there is very little evidence that hen harriers avoid the wind farms and this is detailed in some of the field notes (Box 1).

Box 1. Descriptions of hen harrier flights that passes close to turbines.

10.40 Ml HH carrying prey <10 along fence N of VP towards turbines. Rose >100 as it continued over Gleann Eoghainn then dropped to 10-100 as it approached turbine 9 and flew round tower on west side, passing close to tower within blade's length but below tip. It continued to plantation edge and flew N over trees, lost between Red Burn and windfarm road 10.48.

11.20 Ml HH carrying prey flying 10-100 east of fence, similar place to previous sighting. Flew straight for turbine 11 and for approx a minute was seen flying in line with tower. As it flew near it dropped a little lower and flew wide round west side of tower, below but within length of rotating blade. Flew over plantation and lost low over Red Burn around area of junction with Allt nan Leacaich Bhain 11.25.

12.21 Ml HH carrying prey 10-100 from direction of Allt Ruairidh north of VP. Headed towards turbine 11, rose as it flew so that it was seen against turbine cockpit then dropped back 10-100, round east side of tower, passing close to tower. Flew over plantation and appeared to drop into treetops along E bank of Red Burn o/s 12.29.

11.02 Ml HH hunting <10 W side Gleann Eoghainn, flew W over fence, continued to burns N W of VP and began working its way S, still <10, until 11.06 it became hidden from my view by moorland surrounding VP. 11.08 Ml HH rising 10-100 carrying prey in talons over flat moor between burn and fence. Flew towards windfarm plantation, passing 10-100 between turbines 11 and 12 and continued over plantation, lost 11.16.

11.34 to 11.36 a ringtail HH circling 10-100 S side of Cruachan Glen Vic Askill and then steady glide 10-100 W between 2 working turbines o/s S of Ben Aketil.

The habitat utilisation analyses have been repeated for the Edinbane flight data. In order to simplify presentation of the data some of the results are shown for pre (2007, 2008) and post-construction (2010-2011) periods in Figs 7 and 8. Because of the similarity between the concentric and ring buffer results only the results for the concentric buffers are shown. Detailed results are in Annex 2.

Analysis 1: Concentric buffers, flight length.

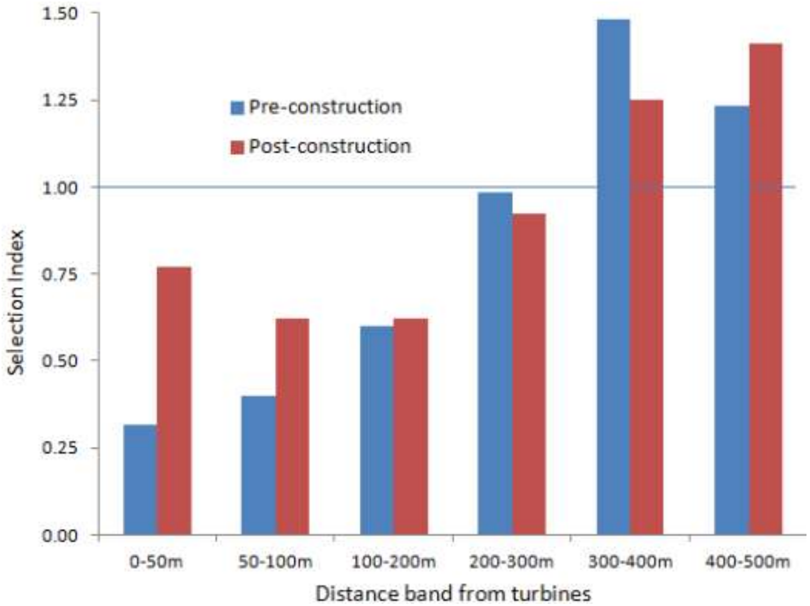

Figure 7 Selection Index for flight lengths (m) in buffered rings with increasing distances from turbines.

Analysis 2: Concentric buffers, flight number.

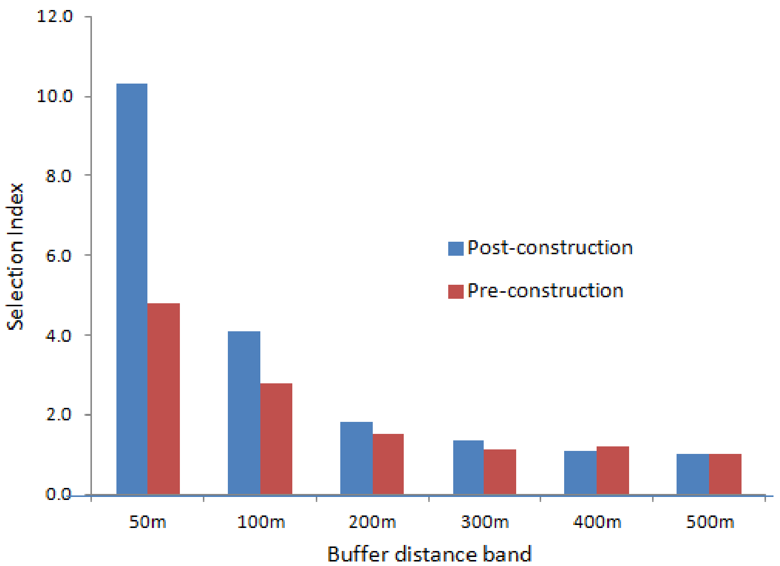

Figure 8 Selection Index for number of flights in buffered rings with increasing distances from turbines.

As with the Ben Aketil data there are more flights than expected close to the turbines and this is much more marked in the post-construction data. Again, as with the Ben Aketil data, flights are shorter than expected close to the turbines, but the effect is much reduced post-construction with usage approaching that expected within 50 m of the turbines.

The data from two wind farms, collected by different ecological consultancies on different dates shows a consistent pattern. The length of flight activity close to the turbines is less than expected but the number of flights is much larger than expected. Comparisons of the pre- and post-construction data at Edinbane suggest that the wind farm has not had a detrimental effect on harrier flight activity. Indeed, if anything, it has increased closer to the turbines. This agrees with the other analyses reported in the annual Edinbane monitoring reports (Fielding and Haworth 2012). Although there is an argument that data for these two wind farms should be treated as lacking independence given their proximity it is clear from the work with golden eagles (Haworth and Fielding 2012) that birds can behave differently at the two wind farms.

3.2.3 A critique of the analyses

During the peer review process for this report some concerns were raised about possible problems with the above analyses.

1. Proximity to nest
2. Bias in recording of flights

Problem 1 relates to the fact that the flight activity of hen harriers is positively correlated with proximity to a nest site and favoured foraging areas. This means that there will be spatial gradients of activity and there must be an assumption of more activity close to turbines if there is a nest site nearby meaning that distance to turbine and distance to nest site are confounded. Any increase in flight activity could be negatively correlated with proximity to turbines or positively correlated with proximity to a nest site.

Despite the assumptions of collision risk model no bird exhibits random flight. There will always be 'hotspots' and areas that are underused and there are sophisticated methods of dealing with these issues but they are outside of scope of this report if only because our effective sample size is one. More sophisticated analyses will require data from several wind farms. It is important to realise that flights by the same bird or pair are not independent of each other and cannot be used to generate a large sample size.

However, it is possible to think through the consequences of such correlations for the earlier analyses. The counteracting forces of avoidance of turbines and attraction to certain areas would be a significant issue if the distances to turbines and distances to nests or other 'hotspots' were correlated in some way. This is not the case for Ben Aketil. If the hen harrier nest site to the north of the turbines is buffered at 500 m the percentages of the 500 m nest buffer area in distance-to-turbine buffers are 18.9%, 18.3%, 14.4% and 15.3% respectively for 50 m, 100 m, 250 m and 500 m distances from the turbines. At 1000 m from the nest the percentages are 39.5%, 41.6%. 42.7% and 33.5% for the same distance-to-turbine buffers. The differences in the degree of overlap between distance-to-nest and distance-to-turbine are too small to account for gradients in flight activity in the vicinity of the turbines. If there is a nest effect at 500 m from the nest we might expect more activity closer to the turbines. While this is true for the number of flights it is not true for the amount of flight. However, the differences in percentages of the nest buffer are not large enough to account for the differences in the number of flights close to the turbines.

However, even if there is an increase in flight activity close to turbines, that is caused by proximity to the nest, this must also imply that there is no, or very little, avoidance of the turbines. Conversely, if there is avoidance of the turbines, despite the nest proximity this would be apparent in the results. We feel that the results clearly demonstrate some limited avoidance of turbines. Clearly, the presence of the turbines has not prevented the hen harriers from nesting close to them. Indeed, the evidence is that the nests are getting closer to turbines (see section 3.2.4 below) in this region of Skye.

Problem 2 relates to the difficulty of accurately recording flight lines onto maps. If there is no systematic bias in such recordings the net effect of mapping errors would be increased 'noise' but no bias, i.e. there would be no systematic movement of flight records away from or towards the turbines. However, it has been suggested that factors such as parallax may result in flights being placed closer to turbines than is justified. If true, this would result in an artificial increase in the number of flights recorded close to turbines. The only robust way of testing this criticism would be to trap breeding adults and attach GPS transmitters that would record actual positions. Such a study is currently being undertaken in Ireland and its results will assist in validating the truth of this criticism. However, in the absence of such evidence, it is also worth considering what the effects would be if it there is a recording bias.

First, what is the possible magnitude of any bias and could it be large enough to affect the conclusions? The Ben Aketil turbines are arranged in a string and many hen harrier flights cross this string (Figs. 3 & 4). The mean distance between turbines is 235 m (range 196 - 327 m). This suggests that, apart from the two turbines at the ends of the string, a bias greater than 50 m is unlikely when recording flights that pass between the turbines unless flights are consistently moved to the left or right. Secondly, given these inter-turbine distances the majority of flights passing between the turbines must be within 100 m of a turbine, i.e. there is a turbine to the left and right of the flight. In analyses 1 and 2 for Ben Aketil (Figs. 5 & 6, Appendix tables A.1.& A.2) the 100 m band includes all flights, including those within 50 m, and therefore it should not be much less susceptible to the recording bias, if any, in the 50 m buffer. Although, less extreme than at 50 m, the conclusions still stand, i.e. flight lengths are less than expected within 100 m of a turbine but there are more flights than expected.

In conclusion, we cannot rule either concern. Indeed, there is almost certainly some validity to both of them but the overall conclusions from these analyses are sufficiently robust to remain valid. There may be some merit in being cautious about the results at 50 m from the turbines but the conclusions are not predicated on those being true. The overall distribution of flights in Figs 2-4 is testament to the validity of the conclusions. we would, nonetheless, encourage others to explore alternative analysis options.

3.2.4 Breeding history of hen harriers in the vicinity of Ben Aketil - Edinbane wind farms

Surveys for breeding raptors in the general vicinity of the Edinbane windfarm have been undertaken each year between 2007 and 2011 by Bob McMillan. In 2007 eleven hen harrier territories were active with nine nests being located. Of these, six failed completely and three successful breeding attempts produced a total of ten young. In 2008 there were eleven active territories and ten nests were located. Of these, seven failed completely and three produced a total of nine young. In 2009 there were seven active territories and six nests were located. Of these five failed completely and two produced a total of nine young. In 2010 12 active territories were identified and nests found at ten. Ten young were fledged with the majority of failures thought to be due to fox predation. In 2011 13 active territories were identified and nests found at ten. Fifteen young were fledged.

As of mid July 2102 Bob McMillan reported that, although only two broods of three and five remained, both reached fledging. Two other broods had gone to fox intrusions. One of the sites has moved out of the adjacent forestry and on to moorland within 400 metres of a turbine. Last year the site was about 500 metres further west and it has therefore moved nearer the turbines rather than away from them.

3.2.5 Summary of the findings from the Ben Aketil and Edinbane data

There is some evidence of small scale (up to 100 m) displacement but only in terms of flight lengths, if anything there appear to be more flights than expected close to the turbines. This is reflected in the lack of any apparent landscape level impacts on hen harrier flights (Figs. 1-4). Clearly neither wind farm has been acting as a barrier to flights, particularly to and from the nest just north of the Ben Aketil turbine string. These conclusions agree with what appears to be the consensus, i.e. there is some small scale displacement of hen harrier activity but no significant large scale impacts.

3.2.6 Orkney

There are known hen harrier sites close to turbines and there appears to be have been no impact on nesting locations and no indications of mortality. There do not appear to be any detailed flight information. The following descriptions were provided by Andrew Upton.

At Burgar Hill there have been two or three turbines in place continuously since the early 1980s, increasing to five in late 2006 and then to six in late 2009. There was an established hen harrier site along the burn to the west, which was in use before the first turbines went up and has been occupied regularly since – there are usually one or two females in there each year, at distances down to around 500m from the nearest turbine. This year (2012) there are two females, one at about 450m and one at about 750m from the closest turbine.

Carcass searches have been carried out under the five older turbines at Burgar Hill for five consecutive summers from 2007 to 2011 and are continuing in 2012. Search intervals have varied, but average out at approximately every three weeks, April to August. In the three years (2009-2011) that he has been involved, plus 2012 to date, there have been no indications of harrier casualties. Three ringtail feathers were found about 75m from one turbine in July 2011 - a secondary, an upper wing covert and a tail feather - but there were no smaller feathers to indicate a collision impact or subsequent scavenging, so this was attributed to moult. Natural Research funded the previous two year's searches in 2007 and 2008, and they found no harrier casualties either.

At Hammars Hill five Enercon E44 turbines were constructed in late 2010, more than 1km from any recent regular harrier site. This year (2012), harriers are using a new site, with nest building taking place at 400-450m from the turbines, on a slope never previously known to have been occupied.

3.2.7 Cruach Mhor

Robson (2012) provided a summary of hen harriers in the vicinity of the Cruach Mhor wind farm. Cruach Mhor is in Argyll and has been operational since 2004 with 35 turbines. There are pre-consent surveys from 2001, prey density surveys annually (field vole, meadow pipit, skylark) and flight activity from VPs 2001, 2005 – 2007. Breeding success was monitored annually between 2003 and 2011.

Using the information from the plot of nest distances to the nearest turbine (Robson, 2012) it appears that during construction (2003, 2004) there were three and two nests respectively within 300 m of turbine locations. In 2005 and 2006, after the wind farm became operational, there were single nests within 300 m of a turbine with a further nest within 700 m during 2006. In 2007 there were two nests within 500 m. There are no data for 2008 but in 2009 and 2010 respectively, there were two and one nests within 300 m of a turbine. As with the Ben Aketil and Edinbane wind farms there is little evidence that turbines restrict harrier nesting attempts except, perhaps, at a distance of 0 m - 200/250 m.

Again, as with the previous three UK wind farms, there is no evidence for a decline in flight activity. In 2001 37.6% of the flight activity was <500m from the planned turbine locations rising to 40.9% between 2005-2007. There is little evidence from the flight map in Robson (2012) that hen harriers show much displacement by turbines but a fuller analysis that incorporates surveying intensity is needed to before definitive conclusions can be drawn.

3.2.8 Paul's Hill

Paul's Hill is a 28 turbine scheme in Moray, NE Scotland. Robinson and Lye (2012) provide a detailed account and analysis of hen harrier flight and nesting data within the vicinity of the wind farm. Paul's Hill was constructed between January 2004 and April 2006, before becoming operational in May 2006.

Paul's Hill wind farm is subject to a number of conditions under a section 75 agreement which are mainly related to the provision of long-term management to help conserve the local hen harrier population. Part of this work includes flight activity surveys from vantage points and nesting locations and success. Post-construction Monitoring has been undertaken from 2006 to the present and can be compared with baseline data collected in 2001 and 2002.

Robinson and Lye (2012) provide details of a statistical analysis of the hen harrier flight activity (log of metres of flight per hour per 250m grid square per year) using a GLM with a number of covariates. Neither of their null hypotheses could be rejected so they concluded that there was (a) no difference in flight activity levels between baseline and operational phase and (b) no difference in the average distance of flights from turbine locations differs during the baseline and operational phases. They did note that pre-construction flight variability was more variable and that post-construction flight activity was more condensed. However, the core of hen harrier flight activity area had remained the same.

Pre-development nest data (1991 – 2000) were provided by the local RSG and this was combined with baseline (2001 – 2002), pre-construction data (2003), construction (2004 – 2005) and post-construction data (2006 – 2011). Most nest sites were generally more distant than those for the four previous wind farms with a mean distance to turbines of approximately 1 km during both construction and operation. Nonetheless, the closest nests to turbines were 61m and 164m during construction and operation respectively. The 164 m distance to an operational turbine is closest of all five wind farms reviewed in this report.

Finally, a sample of ten of the Paul's Hill turbines were searched every fortnight over five years of operation and no harrier collision victims were found, despite 2-3 pairs nesting close to the wind farm (Forrest *et al*, 2011).

3.3 Summary of findings from UK wind farms

Despite the different wind farm layouts and differences in habitat and post-construction management there is no evidence from any of the monitored wind farms (Ben Aketil, Edinbane, Cruach Mhor, Paul's Hill or Orkney) that activity has decreases post-construction. Indeed, in most cases it appears to have increased and there is no evidence for a negative effect on nesting locations or productivity. The conclusion that harriers are only displaced at relatively small scales of between 0m - 100/200 m is also supported by observations at Altamont where the low harrier mortality rate was almost certainly related to flight behaviour since northern harriers appeared to be at low risk of collision despite spending a disproportionate amount of flying time within 50 m of the turbines (reported in Drewitt and Langston, 2008).

The data reviewed here do not provide any evidence of a barrier effect and any displacement, which appears to be mainly foraging flights rather than direct flights, is quite small scale. It should be unsurprising that foraging is reduced close to turbines if only because the presence of large areas of hard standings significantly reduces foraging opportunities. Arroyo *et al* (2009) investigated hen harrier foraging and found that the duration and spatial extent of male hunting intensity varied between sites and breeding periods, being lower during the nestling than the incubation period. Both sexes, but particularly males, selected areas of mixed heather and rough grass but avoided improved grassland. The effect of distance to the nest was large for females but very small for males, with females restricting most of their hunting to within 300–500 m of the nest. This has obvious implications for positive and negative management activities around wind farms.

3.4 Postscript

At the time of writing there have been recent confirmed reports of the two male hen harrier deaths (to May 2012) at a newly commissioned wind farm. The injuries appear inconsistent with a strike from a rotating turbine blade and may be more indicative of a collision with other wind farm infrastructure or a result of turbine slipstreams, which could have forced the birds into the ground or wind farm structures. The deaths of two hen harriers in such a short time, and in one location, seems unprecedented at a global scale. Nonetheless, collision risk calculations assume that some hen harriers will be killed by wind turbines so it should be unsurprising that some have been killed and, in general, such predicted deaths are factored into an assessment of the risks from wind farms.

However, there are two aspects of perhaps greater significance. First, the pre-construction work did not appear to identify any significant risk for hen harriers and secondly the apparent close temporal and spatial proximity of the possible deaths suggests there may be time and location specific factors at work and a detailed analysis of the events would obviously be useful. Given the sex of the birds, the timing and the proximity to good quality nesting habitat, it is probable that these birds were displaying, rather than foraging, when the collisions happened.

The two hen harrier deaths at this wind farm provide support for additional monitoring of this and all wind farms, at least for their first few years of operation. The locations and intensity of monitoring could be informed by information about general bird activity in the vicinity of the wind farm particularly during periods when birds may be displaying rather than foraging. However, it is clear from other Scottish and worldwide wind farms that hen harriers can and do forage in close proximity to operational turbines without any apparent adverse impacts.

4. POSSIBLE POPULATION LEVEL IMPACTS.

4.1 Introduction

Ultimately the significance of any wind effects on hen harriers should be measured at the population level. In particular, what impacts, if any, could wind farms have on the potential future population trajectory for the population? These effects can be modelled using standard population modelling techniques by examining two types of impact.

First there is the possible effect that wind farms have on productivity because of loss of nest sites and reduced foraging efficiency leading to fewer fledged young. Secondly, there are changes to survival rates caused by collision mortality. Although the current evidence suggests that it seems unlikely that either of these impacts will be large a range of scenarios can be modelled to identify possible thresholds beyond which impacts will become significant.

4.2 Model Structure

If a population is in a favourable status it should be capable of maintaining itself, or expanding, without a requirement for recruitment from other populations. At its simplest this is achieved when reproduction and survival are greater than the combined effects of mortality and dispersal to other populations. Fielding *et al* (2011) used software (Unified Life Models (ULM), version 4.5, Legendre and Clobert 1995) to build models and population trajectories were assessed from the value of lambda (ƛ). Lambda is the net birth rate per individual and in a stable population ƛ = 1, while a value > 1 indicates a population that should be growing and a negative value indicates that the population is declining and should, eventually, go extinct.

Irrespective of any behavioural ecological mechanism, such as polygyny, it is female productivity which ultimately drives a population's trajectory and, because our models take account of the proportion of successful females, the models will be robust and conservative. The population models used a three stage life cycle with pre-reproductive mortality. The basic Leslie matrix is:

$$\begin{matrix} 0 & f_j & f \\ S_1 & 0 & 0 \\ 0 & S_2 & S_v \end{matrix}$$

The top row (0 f_j f) are the number of *females* fledged per occupied site (0 for birds in their first year, f_j is number fledged by one year old females and f the number fledged by females aged 2+). Although this model allows for different values of f_j and f the field evidence suggests it is acceptable to use the same values for both. A review of available data by Fielding *et al* (2011) indicated that f varied from 0.36 to 2.00 across the thirteen Scottish NHZs, with an average of 0.838. Although there is evidence for a slight sex ratio bias (i.e. unequal numbers of males and females fledged, Etheridge *et al* 1997) our analyses assume, for simplicity, an equal sex ratio of fledged birds.

S_1, in the second row, is the survival of birds from fledging to age 1, S_2 (third row) is the survival from age 1 to 2 and S_v (third row) is the survival of birds aged two or more. Survival rates of female harriers in Wales have been estimated (Whitfield *et al* 2008) as 0.362 in the first year and 0.774 for adults (equivalent to S_2 and S_v in the model); equivalent reported values in Scotland are 0.361 (95% confidence limits 0.281–0.632) and 0.778 (0.570–0.984) on 'other [non-grouse] moorland' (Etheridge *et al* 1997) and 0.33 and 0.871 on Orkney (Rothery 1985). S_1 is generally about 40% of S_2 and S_v.

An example model definition file is given in Appendix 3.

The results from the population models (Fielding *et al* 2009; Appendix 5) clearly show that a stable or increasing hen harrier population requires a fledging rate (females per occupied site) above 0.5. If 50% of fledged young are assumed to be female this equates to a fledging rate of more than one per occupied site. The population fledging rate is a combination of the number of young fledged by successful nests and the proportion of nests that are successful. Since the mean fledging rates of successful nests reviewed by Fielding *et al* (2011) ranged from 2.37 to 3.59, a value of less than one per occupied site is indicative of a low proportion of successful nests, i.e. successful nests produce more offspring per nest than is needed for stability but too few nests are successful. For example, assuming the lowest mean number fledged per successful nest (2.37) a minimum of 42.2% of nests need to be successful to achieve a mean of one fledged young per occupied nest. At the highest rate (3.59) only 27.8% of nests need to be successful. Therefore, if the proportion of successful nests drops below these thresholds a population can only survive if there is continued immigration of breeding birds from other populations. If wind farms impact on foraging efficiency which, in turn, reduces productivity then the above information provides a mechanism by which likely impacts could be assessed. However, even if wind farms reduce productivity of neighbouring hen harriers it is difficult to imagine an operational windfarm which potentially reduced significantly the nesting success of more than one or two pairs.

It is also clear from Fielding *et al*. (2009, Appendix 5) that once the fledging rate per occupied site approached 1.6 (0.8 females) the population should be stable or increasing over the range of 'normal' juvenile and adult survival rates. The parameter elasticity values indicated, as for most large raptors, that survival rates were potentially more influential in affecting hen harrier population growth rates than breeding productivity. This result is expected given the findings from other animals and raptors (e.g. Whitfield *et al* 2004) with similar life history traits (i.e. relatively long lived with slow reproductive rates). Therefore, wind farm mortality would have to be significant to reduce survival rates to a level which significantly reduces the potential population growth rate. The evidence from windfarm studies in the UK and elsewhere is that this high level of mortality is unlikely although the recent deaths in Scotland highlight the potential for significant mortality when males are displaying.

In the example analyses below we use the models described in Fielding *et al* (2011) applied to a theoretical local population of 10 breeding pairs. This size was chosen to reflect the likely size at which an assessment would be made. In order for wind farms to have an impact at the national level the impacts would have to be orders of magnitude larger than anything currently recorded so this scenario is not modelled.

For example, assume a population of 10 pairs (productivity per pair = 0.838 females) and a 25 year wind farm mortality of approximately 0.5 birds colliding with a turbine (one hen harrier killed every 50 years). Assuming an equal sex ratio, this would mean that 0.25 females were killed (0.01 each year). The effect on adult female survivorship is minimal with a reduction from 0.774 (Fielding *et al* 2011) to 0.773. Using the population models from section 4.1 of Fielding *et al* (2011), the population is still capable of an annual 5.6% growth rate at this reduced level of adult survival. The revised adult survival rate is calculated assuming an annual adult mortality of 22.6% from 10 females (2.26), adding the additional annual predicted wind farm mortality of 0.01increases this to 2.27 females which is equivalent to an adult survival rate of 0.773. Even if the level of adult mortality was 50 times larger (one bird killed every each year or one female killed every two years (0.5 per year)) the population would still be capable of an annual growth rate of 1.4% with an adjusted adult female survival rate of 0.724 (1-2.76/10). The population would show a very slight decline (λ = 0.991) if the much higher collision mortality was combined with a reduction in productivity from 0.838 to 0.754 females per year (probably an inevitable consequence if either parent was killed).

4.3 Male-biased mortality?

There is an argument that the probability of wind farm mortality may be biased towards males as a consequence of their nest provisioning duties, i.e. they are more active and cover larger areas, and their display flights at the start of the breeding season. In terms of a female-based population mode, if most of the predicted additional mortality was in males it would be productivity, rather than female survival, that was affected. If a male is killed in a wind farm the female of the pair may be unable to provide both food for her young and nest protection resulting in probable nest failure and a reduction in the population's productivity. Assuming a mean of 0.838 females fledged per breeding attempt, the death of a male from a population of 10 breeding pairs might result in 7.54 (9 x 0.838 = 7.542) rather than 8.38 (10 x 0.838 = 8.38) females fledged that year. But, the first year survival rate for hen harriers is low at around 36% so the effects of this reduced productivity on the number of new breeding females in the next year would be small with a reduction from 3.02 (8.38 x 0.36) to 2.72 (7.54 x 0.36) individuals. It seems probable that a hen harrier population can tolerate a larger increase in male mortality than female mortality.

Indeed, even the death of one male per year may still allow a population to expand at an annual rate of approximately 3% compared with 5.6% in the absence of the additional mortality (assumes s1 = 0.362, s2 and Sv =0.774 and f = 0.838). Such a population would, however, require a small amount of male immigration or the establishment of some polygyny as on Orkney. It is likely that polygyny would reduce productivity for one or more of the females in the polygynous pairs but its effects on overall productivity would not be large if only one male in the population was polygynous with two females.

4.4 Conclusions

The conclusions from these modelling scenarios is that even if the effects of wind farms are much larger than the available evidence suggests it is unlikely that these effects would result in significant population level effects.

5. SUMMARY.

a. In Scotland, the main areas of hen harrier distribution are currently free of significant wind farm proposals. If this continues it is unlikely that wind farms will have a significant impact on the Scottish population irrespective of the level of threat to individual birds.
b. However, one of the difficult problems for predicting windfarm-hen harrier interactions is the apparent tendency for marked changes in hen harrier distributions at the scale of the wider landscape.
c. There are relatively few published studies and examples of significant negative impacts of wind farms on hen harriers.
d. There appear to be few documented cases of collision mortality (<10 prior to 2012).
e. Table 1 of Drewitt and Langston (2008) estimates that there were 0.001 deaths per MW per year compared with an average of 1.94 for all raptors.
f. During a 4-year study described by Johnson *et al* (2000), 2,840 fatality searches were conducted on plots associated with operational turbines. Harriers were not one of the recorded fatalities despite their relative abundance at the sites.
g. As of May 2012 no hen harriers have been found or reported killed under the more than 20,000 German wind turbines. However, there appears to be little overlap between turbines and hen harrier nesting sites.
h. A sample of 10 of the 28 turbines at Paul's Hill in NE Scotland were searched every fortnight over five years of operation during the breeding season and no harrier collision victims were found, despite 2-3 pairs nesting close to the wind farm.
i. Carcass searches were carried out at Burgar Hill (Orkney) for six consecutive summers from 2007 to 2012. Search intervals have varied, but average out at approximately every three weeks, April to August. This year to date, there have been no indications of harrier casualties.
j. The low levels of collision mortality appear to be at least partially related to the predominantly low flight heights of hen harriers.
k. Results from monitoring studies at the large Buffalo Ridge Wind Farm Area suggest that, if there is any avoidance effect, it relatively small scale and possibly transient.
l. The Pearce-Higgins *et* al (2009) study suggested that hen harriers avoided flying within 250 m of turbines, leading to a 53% reduction within 500 m of turbines.
m. Detailed monitoring at five Scottish wind farms does not support that level of avoidance but does suggest some small scale avoidance.
n. There is little evidence for an impact of wind farms on harrier nesting. One of the few reported examples is from Kerry in Ireland where O'Donoghue *et al* (2011) reported that the nesting location of a single harrier territory shifted further from a wind farm site after construction.
o. At other Scottish wind farms there is no evidence of such nesting displacements.
p. Detailed flight data were available for the Ben Aketil and Edinbane wind farms (Skye). A quantitative analysis of the flight data found some evidence of small scale (up to 100 m) displacement but only in terms of flight lengths, if anything there are more flights than expected close to the turbines. Neither wind farm has been acting as a barrier to flights, particularly to and from the nest just north of the Ben Aketil turbine string.
q. A description of the interactions between hen harriers and turbines on Orkney suggested no impacts on nesting activities and at Hammars Hill a previously unknown nesting site within 450m of new turbines was used in 2012. Detailed carcass searchers have not found any evidence of collisions.
r. At Cruach Mhor there is little evidence that turbines restrict harrier nesting attempts except, perhaps, at a distance of 200 - 250 m and as with the previous three UK wind farms, there is no evidence for a decline in flight activity compared with pre-construction activity.

s. A statistical analysis of flight data from the Paul's Hill wind farm concluded that there was no difference in flight activity levels between baseline and operational phase and no difference in the average distance of flights from turbine locations differs during the baseline and operational phases. Although pre-construction flight activity was more variable and post-construction flight activity was more condensed, the core of hen harrier flight activity area has remained the same.
t. At the time of writing there have been unconfirmed reports of the two hen harrier deaths at a newly commissioned wind farm. The injuries appear inconsistent with a strike from a rotating turbine blade and may be more indicative of a collision with other windfarm infrastructure. Collision risk calculations assume that some hen harriers will be killed by wind turbines so it should be unsurprising that some have been killed and, in general, such predicted deaths are factored into an assessment of the risks from wind farms.
u. However, if these deaths are confirmed, there are two aspects of perhaps greater significance. First, the pre-construction work did not appear to identify any significant risk for hen harriers and secondly the apparent close temporal and spatial proximity of the deaths suggests there may be time and location specific factors at work and a detailed analysis of the events would obviously be useful.
v. Population models investigated the possible effect that wind farms have on productivity resulting from the loss of nest sites and reduced foraging efficiency leading to fewer fledged young. Secondly, the models investigated the consequence of changes to survival rates caused by collision mortality. Finally, the models investigated the effects of a male-biased collision mortality
w. The conclusions from these modelling scenarios is that even if the effects of wind farms are much larger than the available evidence suggests it is highly unlikely that these effects would result in significant population level effects.

5.1 Conclusions

The overall conclusions from information covered in this review agree with what appears to be the global consensus, i.e. hen harriers experience some small scale displacement but generally there are no significant large scale impacts caused by wind farms. If the apparent recent deaths are confirmed a full investigation into any confounding factors would obviously be very helpful for other schemes.

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ANNEX 1: RESOURCE UTILIZATION CALCULATIONS FOR THE ATMOS CONSULTING LTD BEN AKETIL MONITORING DATA

Analysis 1.1: Concentric buffers, flight length

Table A.1. O is the observed flight length (m), SI is Neu's index calculated as O/Total length within the 500 m buffer. SSI is the standardised selection index

	Buffer size	50m	100m	200m	300m	400m	500m
	Area (ha)	9.4	37.6	108.76	178.68	253.48	334.08
Year	Proportion	0.03	0.11	0.33	0.53	0.76	1.00
2008	O	569	1947	7822	15994	24141	32879
	SI	0.62	0.53	0.73	0.91	0.97	1.00
	SSI	0.13	0.11	0.15	0.19	0.20	0.21
2009	O	789	2952	11333	19988	31630	42005
	SI	0.67	0.62	0.83	0.89	0.99	1.00
	SSI	0.13	0.12	0.17	0.18	0.20	0.20
2010	O	360	3455	14781	22295	31212	40689
	SI	0.31	0.75	1.12	1.02	1.01	1.00
	SSI	0.06	0.14	0.21	0.20	0.19	0.19
All	O	1717	8354	33937	58278	86984	115573
	SI	0.53	0.64	0.90	0.94	0.99	1.00
	SSI	0.11	0.13	0.18	0.19	0.20	0.20

Analysis 1.2: Concentric buffers, flight number

Table A.2. O is the observed number of flights, SI is Neu's index calculated as O/All Flights within the 500 m buffer. SSI is the standardised selection index

	Buffer size	50m	100m	200m	300m	400m	500m
	Area (ha)	9.4	37.6	108.76	178.68	253.48	334.08
Year	Proportion	0.03	0.11	0.33	0.53	0.76	1.00
2008	O	5	8	12	18	25	31
	SI	5.73	2.29	1.19	1.09	1.06	1.00
	SSI	0.46	0.19	0.10	0.09	0.09	0.08
2009	O	8	18	29	42	51	56
	SI	5.08	2.85	1.59	1.40	1.20	1.00
	SSI	0.39	0.22	0.12	0.11	0.09	0.08
2010	O	5	24	39	47	56	63
	SI	2.82	3.38	1.90	1.39	1.17	1.00
	SSI	0.24	0.29	0.16	0.12	0.10	0.09
All	O	18	50	80	107	132	150
	SI	4.26	2.96	1.64	1.33	1.16	1.00
	SSI	0.35	0.24	0.13	0.11	0.09	0.08

Analysis 1.3: Ring buffers, flight length

Table A 3. O is the observed flight length (m), SI is Neu's index calculated as O/Total length within the 500 m buffer. SSI is the standardised selection index

	Buffer size	50m	100m	200m	300m	400m	500m
	Area (ha)	9.4	28.2	71.1	69.9	74.8	80.6
Year	Proportion	0.03	0.08	0.21	0.21	0.22	0.24
2008	O	569	1378	5875	8172	8147	8738
	SI	0.62	0.50	0.84	1.19	1.11	1.10
	SSI	0.12	0.09	0.16	0.22	0.21	0.21
2009	O	789	2163	8381	8655	11642	10375
	SI	0.67	0.61	0.94	0.98	1.24	1.02
	SSI	0.12	0.11	0.17	0.18	0.23	0.19
2010	O	360	3095	11326	7514	8917	9477
	SI	0.31	0.90	1.31	0.88	0.98	0.97
	SSI	0.06	0.17	0.24	0.16	0.18	0.18
All	O	1717	6637	25583	24341	28706	28589
	SI	0.53	0.68	1.04	1.01	1.11	1.03
	SSI	0.10	0.13	0.19	0.19	0.21	0.19

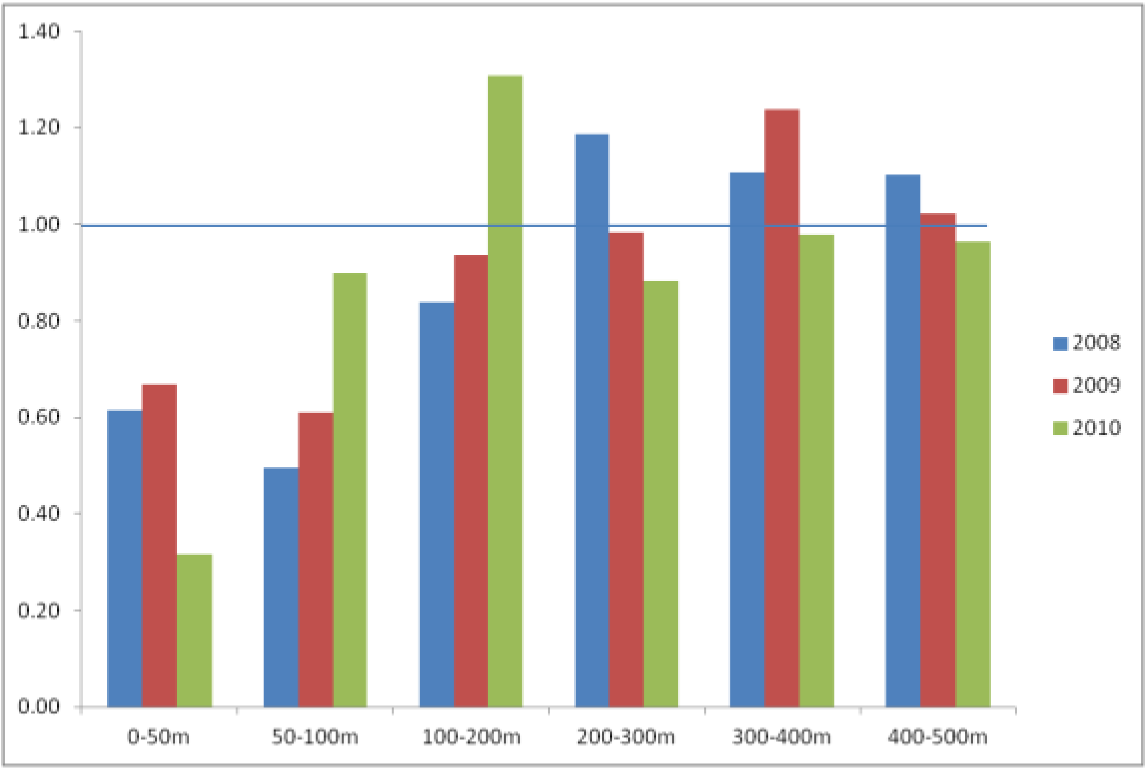

Figure A.1 Selection Index for flight lengths (m) in buffered rings with increasing distances from turbines. These data are from the post-construction phase. The horizontal line at SI = 1.0 indicates that usage equals that expected from the buffer area.

Analysis 1.4: Ring buffers, flight number

Table A. 4. O is the observed number of flights, SI is Neu's index calculated as O/All Flights within the 500 m buffer. SSI is the standardised selection index

	Buffer size	50m	100m	200m	300m	400m	500m
	Area (ha)	9.4	28.2	71.1	69.9	74.8	80.6
Year	Proportion	0.03	0.08	0.21	0.21	0.22	0.24
2008	O	5	3	4	6	7	6
	SI	5.73	1.14	0.61	0.92	1.01	0.80
	SSI	0.56	0.11	0.06	0.09	0.10	0.08
2009	O	8	10	11	13	9	5
	SI	5.08	2.11	0.92	1.11	0.72	0.37
	SSI	0.49	0.20	0.09	0.11	0.07	0.04
2010	O	5	19	14	8	9	7
	SI	2.87	3.63	1.06	0.62	0.65	0.47
	SSI	0.31	0.39	0.11	0.07	0.07	0.05
All	O	18	32	29	27	25	18
	SI	4.29	2.54	0.91	0.87	0.75	0.50
	SSI	0.44	0.26	0.09	0.09	0.08	0.05

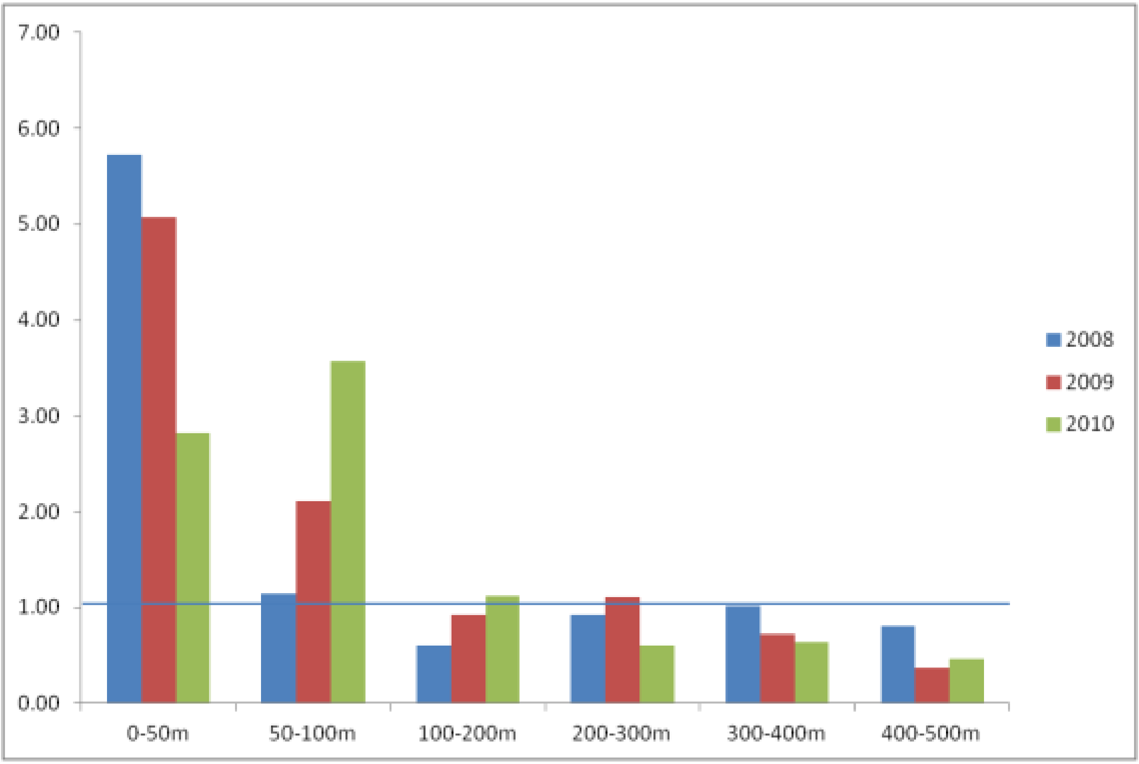

Figure A.2 Selection Index for number of flights in buffered rings with increasing distances from turbines. These data are from the post-construction phase. The horizontal line at SI = 1.0 indicates that usage equals that expected from the buffer area.

ANNEX 2: RESOURCE UTILIZATION CALCULATIONS FOR THE EDINBANE MONITORING DATA

Analysis 2.1: Concentric buffers, flight length

Table B.1. Observed flight length (m) and proportions in each buffer pooled over pre- and post-construction years. SI is Neu's index (used proportion/available proportion = proportion of all flight activity within a particular band/proportion of 500 m buffer area within the band. For example, 0-50 m pre-construction = (203/31558)/(14.1/696.9) = .0064/0.0202 = 0.318)

Year	0-50m	50-100m	100-200m	200-300m	300-400m	400-500m	0-500m
Area (ha)	14.1	42.4	168.3	180.8	14.8	143.5	696.9
Pre 07-08	203	767	4572	8066	9924	8026	31558
Post 10-11	489	1190	4729	7520	8312	9130	31370
Proportions							
Pre 07-08	0.006	0.024	0.145	0.256	0.314	0.254	
Post 10-11	0.016	0.038	0.151	0.240	0.265	0.291	
Area prop	0.020	0.061	0.241	0.259	0.212	0.206	
SI pre	0.318	0.399	0.600	0.985	1.483	1.235	
SI post	0.770	0.624	0.624	0.924	1.249	1.413	

Analysis 2.2: Concentric buffers, flight number

Table B.2. Observed number of flights (counted from the nearest turbine band, for example a flight in 300-400m and 400-500m bands would only count towards the former) and proportions in each buffer pooled over pre- and post-construction years. SI is Neu's index (used proportion/available proportion = proportion of all flights within a particular band/proportion of 500 m buffer area within the band.

Year	0-50m	50-100m	100-200m	200-300m	300-400m	400-500m	0-500m
Area (ha)	14.1	42.4	168.3	180.8	14.8	143.5	696.9
Pre 07-08	3	7	15	20	29	27	31
Post 10-11	5	8	14	19	21	23	24
Proportions							
Pre 07-08	0.097	0.226	0.484	0.645	0.935	0.871	
Post 10-11	0.208	0.333	0.583	0.792	0.875	0.958	
Area prop	0.02	0.061	0.241	0.259	0.212	0.206	
SI pre	4.8	3.7	2.0	2.5	4.4	4.2	
SI post	10.4	5.5	2.4	3.1	4.1	4.7	

ANNEX 3: EXAMPLE ULM MODEL DESCRIPTION FILE TITLE

Text following a { is a comment.

```
{Orkney hen harrier population model
{ 3 age classes, pre-breeding census.

{initial definition of the model, a Leslie matrix and a vector of the
number of individuals per stage
defmod hh(3)
mat : a
vec : w

defvec w(3)
n1, n2, n3

{If there are 43 females and they produce 0.364 young females per female
{there should be an initial stage 1 population of 16 individuals
{43*0.364 = 16
defvar n1 = 16

{First year birds are initially assumed to be 12.5% of the breeding
population of 43
defvar n2 = 5

{breeding females aged 2+ must be 38 (43-5)
defvar n3 = 38

defvar n = n1 + n2 + n3

{adult survival 0.778
defvar ads = 0.778

{ immature survival rate
defvar js = 0.362

{sd is 10% of the survival rate. This is used to generate noise for
{the Monte Carlo simulations
defvar jssd = js/10

{in this model immatures are not allowed to survive longer than adults
defvar jsmax = ads

{find an initial random value of S1 for this simulation
defvar sa = beta1f(js, jssd)

{and check that it isn’t larger than the maximum possible value,
{if it is reduce it to the maximum allowed
defvar s1 = if(sa>jsmax,jsmax,sa)

{2nd year survival rate
{2nd  survival rate standard deviation is 10% of adult survival rate
defvar imsd = ads/10

{set a maximum value that is 10% larger than the mean value.
defvar immsmax = ads+ads/10

{obtain a random value for 2nd year  survival
defvar sc = beta1f(ads, imsd)

{check that this value is smaller than the allowed maximum,
{if not then reduce it
```

```
defvar s2 = if(sc>immsmax,immsmax,sc)

{adult survival rate standard deviation is 10% of adult survival rate
defvar adsd = ads*0.1

{set a maximum value that is 10% larger than the mean value.
defvar adsmax = ads + ads*0.1

{estimate adult survival
defvar sv = beta1f(ads, adsd)

{check that it isn't too large
defvar v = if(sv>adsmax,adsmax,sv)

{fledged per occupied and sd
{make allowances for females only: = 0.729 * 0.5 = 0.364

{based on empirical data for this population the fecundity
{standard deviation is 20% of mean

defvar f = gaussf(0.364, 0.073)

{year 1 breeders
defvar  fj = f

{the Leslie matrix
defmat a(3)
 0,   fj,   f
 s1,  0,    0
 0,  s2,   sv
```