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University College Cork, Ireland Coláiste na hOllscoile Corcaigh

1	Hen Harrier Circus cyaneus population trends in relation to wind farms
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8	
9	SUMMARY
10	Capsule The data presented here demonstrate a considerable spatial overlap between wind farms and
11	the breeding distribution of Hen Harriers in Ireland, but evidence for a negative impact of wind farms
12	on their populations is weak.
13	Aim To assess the extent of the overlap between wind farms and breeding Hen Harriers and to
14	investigate their potential impact on Hen Harrier population trends.
15	Methods Data on Hen Harrier breeding distribution in 10km x 10km survey squares from national
16	surveys were used in conjunction with information on the location of wind farms to examine whether,
17	and to what extent, changes in Hen Harrier distribution and abundance between 2000 and 2010 were
18	related to wind energy development.
19	Results Of the sixty nine survey squares holding Hen Harriers during the 2010 breeding season, 28%
20	also held one or more wind farms. Data from 36 of the squares with breeding Hen Harriers during the
21	2000 survey revealed a marginally non-significant negative relationship between wind farm presence
22	and change in the number of breeding pairs between 2000 and 2010.
23	Conclusions A considerable overlap exists between Hen Harrier breeding distribution and the location
24	of wind farms in Ireland, particularly in areas between 200m and 400m above sea level. The presence
25	of wind farms is negatively related to Hen Harrier population trends in squares surveyed in 2000 and
26	2010, but this relationship is not statistically significant, and may not be causal. This is the first study

to assess the influence of wind energy development on Hen Harriers at such a large geographic andpopulation scale.

29

30 INTRODUCTION

31 Hen Harrier *Circus cyaneus* populations are declining across Europe, with some evidence of regional 32 declines over the past decade recorded for the moderately small Irish population (Irwin et al. 2011, 33 Ruddock et al. 2012, BirdLife International 2015). The species is listed on Annex 1 of the EU Birds 34 Directive (2009/147/EC) and is on the Amber list of species of conservation concern in Ireland (Colhoun and Cummins 2013). Their populations are protected in Ireland through the designation of 35 36 Special Protection Areas (SPAs) within which the Irish government is required to ensure that the 37 conservation status of Hen Harrier populations is favourable (Wilson et al. 2010). In many of the areas 38 where Hen Harriers breed, demands for wind-energy development are high, and these demands must 39 be met in compliance with environmental measures, including those aimed at protecting Hen Harrier 40 populations. In the absence of detailed information about the interactions between breeding Hen 41 Harriers and wind turbines, there are concerns that turbines could impact negatively on this species, 42 either by causing mortality or by reducing the availability or value of areas around them to Hen 43 Harriers (Fielding et al. 2011, Pearce-Higgins et al. 2009b, Ruddock et al. 2012).

44

45 In Ireland and Britain, Hen Harriers breed in moorland, young conifer plantations and other upland 46 habitats, typically between 100m and 400m above sea level (Ruddock et al. 2012, Watson 1977, 47 Wilson et al. 2009). Outside of the breeding season they range more widely across both upland and 48 lowland areas (Clarke and Watson 1990). Hen Harriers were once widespread in Ireland and Britain, 49 but their populations have decreased here, and across Europe, in response to changes in land use and 50 direct persecution (Burfield and von Bommel 2004, Ruddock et al. 2012, Sim et al. 2007). Hen Harriers 51 are now a species of conservation concern in Ireland (Colhoun and Cummins 2013) where breeding 52 productivity is lower than in other parts of their range (Irwin et al. 2011). Current estimates report a

breeding population of less than 172 pairs in the Republic of Ireland (Ruddock *et al.* 2012), and a
further 59 territorial pairs in Northern Ireland (Hayhow *et al.* 2013).

55

56 The susceptibility of this rare bird species to human-induced land use change presents significant 57 challenges for their conservation management, and compliance with legislation, in the context of on-58 going transformation of upland habitats. Among the land use changes that may affect Hen Harrier 59 populations are agricultural intensification, the establishment, maturation and harvesting of forest 60 plantations, fluctuations in prey populations (i.e. small mammals) and wind farm construction for 61 renewable energy generation (Amar et al. 2011, Amar and Redpath 2005, Fielding et al. 2011, Madders and Whitfield 2006, New et al. 2011, Pearce-Higgins et al. 2009a, Redpath et al. 2002). In particular, 62 63 the construction and operation of wind turbines can impact on Hen Harriers, and other birds, in a 64 range of ways (de Lucas et al. 2007, Drewitt and Langston 2006, Dai et al. 2015).

65

66 Many studies have reported on the proximal impacts of wind turbines on Hen Harriers and other 67 raptors through collision risk (Band et al. 2007, Chamberlain et al. 2006, de Lucas et al. 2008, Madders and Whitfield 2006, Balotari-Chiebao et al. 2016) and displacement during both the construction 68 (Pearce-Higgins et al. 2012) and the operational phases (Garvin et al. 2011, Madden and Porter 2007, 69 70 Pearce-Higgins et al. 2009a, Douglas et al. 2011). However, observed impacts vary widely between 71 different studies and there is a pressing need for more information on the potential ecological effects 72 of wind farms on Hen Harriers (Stewart et al. 2007, Wang et al. 2015, Tabassum et al. 2014). In 73 particular, a better understanding of population-level impacts of wind turbines on birds is crucial to 74 allow planners and policy makers to successfully balance renewable energy targets with effective 75 nature conservation (Hill et al. 1997, Tellería 2009a, Beston et al. 2016, Morinha et al. 2014). Masden 76 (2010) modelled the effects of wind farm developments on future Hen Harrier population trends in 77 Orkney and found that predicted declines in the population were linked to effects of habitat loss and 78 displacement rather than direct mortality. However, to date, no studies have investigated whether observed changes in Hen Harrier populations are related to wind energy development. Information
on the response of populations to changes in land use is essential to the conservation biology and
management of Hen Harriers, as it is to all vulnerable bird species.

82

Central to the concern over the impacts of wind energy development on Hen Harriers is the spatial overlap between wind farms and bird conservation interests in upland areas. This is partly because there are few economically competing land uses in many upland areas, and the potential to disturb or inconvenience large numbers of people is lower than in other parts of the country. Greater wind resources further increase the attractiveness of upland areas for wind farm construction (Bright *et al.* 2008a).

89

90 After over 20 years of wind energy development there are now 235 wind farms on the island of Ireland 91 including 17 wind farms in areas now designated as Hen Harrier Special Protection Areas (SPAs), with 92 a further 10 wind farms proposed for these areas. Effective and efficient regulation of wind energy 93 development in upland areas in part depends on achieving a comprehensive understanding of the 94 ways in which Hen Harriers respond to these developments. The vast majority of wind farms in Ireland have been developed since the turn of the 21st century, during which time four national surveys of 95 96 Ireland's Hen Harrier population have been carried out at five year intervals (Barton et al. 2006, Norriss 97 et al. 2002, Ruddock et al. 2012). This provides an excellent opportunity to assess the importance of 98 wind energy development as a factor in Hen Harrier population changes in Ireland.

99

The aim of this study was to determine whether the breeding Hen Harrier population across Ireland has been affected by wind farm developments in recent years. To date, very little research has been published on effects of wind farms on Hen Harriers on such a large population or geographic scale. In particular, this study focuses on the changes in Ireland's Hen Harrier population between 2000 and 2010 in relation to the construction of wind farm infrastructures during this period.

106 MATERIALS AND METHODS

107 In order to evaluate the large-scale effects of wind farms on Hen Harriers, two approaches were taken. 108 The first investigated the overlap between wind farms in Ireland and breeding sites of Hen Harriers. 109 The second part of this study examined whether changes in Hen Harrier population between 2000 and 110 2010 in Ireland were related to wind energy development during this time. As Hen Harrier distribution 111 is influenced by a range of environmental factors including elevation and habitat (Amar and Redpath 112 2002, Ruddock et al. 2012, Sim et al. 2007, Wilson et al. 2009), we also investigated the relative 113 importance of these factors in driving Hen Harrier numbers. We used data on Hen Harrier populations 114 from both the 2000 and 2010 National Breeding Hen Harrier Surveys (Norriss et al. 2002, Ruddock et 115 al. 2012) in combination with information on wind farms available on the Irish Wind Energy Associated 116 (IWEA) website.

117

118 Spatial overlap between wind farms and Hen Harriers

The scale used for this study was that of the 10km square. Geographical overlap was determined using ArcGIS 10.0 by overlaying the individual 10km x 10km squares (n=69) which held Hen Harriers during the 2010 National Hen Harrier Survey (Ruddock *et al.* 2012) and the locations of all wind farms across Ireland (as detailed on the Irish Wind Energy Association website (www.iwea.com) at the end of 2012). To determine the elevation overlap between Hen Harrier breeding sites and wind farms, elevations for breeding sites and wind farms were extracted from a digital elevation model of Ireland.

126

127 Hen Harrier population trends and wind energy development

128 Study area selection and Hen Harrier data

129 The numbers of confirmed pairs of breeding Hen Harriers from the National Surveys carried out in 130 2000 and 2010 (Norriss et al. 2002, Ruddock et al. 2012) were used to calculate the change in number 131 of breeding pairs per 10 km square during the 10 year interval between the two surveys. Data analysis 132 for this second part of the study was restricted to squares where Hen Harrier breeding pairs were 133 confirmed during the 2000 National Hen Harrier Survey. As survey effort varied considerably between 134 squares surveyed in 2000 (Ruddock et al. 2012), this approach made it possible to ensure that survey effort was sufficient to detect breeding pairs in all squares considered. This approach also ensures a 135 136 minimum standard of data from 2010, as survey effort was less variable among squares where Hen 137 Harriers had been previously recorded (Ruddock *et al.* 2012). To further ensure consistency of survey effort in the 2010 survey, we restricted our data analysis to squares that received three or more visits 138 139 during the 2010 survey. This selection of survey squares ensures that the data we used were of the 140 highest available quality, and that the resulting analysis would be robust. This resulted in a total of 36 141 squares being included in this part of the analysis (Fig. 1).

142

143 Wind turbines

The locations of all individual wind turbines constructed between the periods 2000 and 2010 in the 36 survey squares selected were identified from aerial photos, and plotted in ArcGIS 10.0. This was used to calculate the number of turbines constructed in each square between 2000 and 2010.

147

148 Forest cover

Total forest cover in the study squares up to 2010 was estimated from the 2007 Forest Service's Forest Inventory and Planning System (FIPS) and the inventory for the Coillte database. As well as total area of forest planted up to and including 2010, the changes in closed canopy forest and in pre-thicket forest cover between 2000 and 2010 were also calculated. The following categories of forest plantation were classified as pre-thicket habitat:

• First rotation plantations up to and including fifteen years of age.

• Second rotation plantations between three and fifteen years after planting.

- Forests classified in the Coillte database as "Under-developed", "Dead" and "Burned".
- 157

Private forests planted prior to 1998 often do not have a planting year recorded in the FIPS database, and even forests for which planting year is known can vary substantially in the rate at which they develop. Also, felling and replanting is typically not recorded in FIPS and there can be a considerable lag between these activities taking place and their being recorded in the Coillte database. In order to correct errors in forest classification arising from such discrepancies, data relating to all forested areas were verified visually using aerial photographs from 2000, 2005 and 2012.

164

165 Geographical position and elevation

The northing and easting of the centre of each 10km square were used to represent the geographical position of the square. A digital elevation model covering the island of Ireland was used to classify areas into three broad categories of elevation: 0 – 100m, 100 – 200m and 200 – 400m. Hen Harrier densities vary greatly between these elevation categories, being concentrated between 200m and 400m (Table 1).

171

172 Data analysis

173 Statistical analyses were carried out in R 2.13.1 statistical software package. Within the 36 10km 174 squares included in this analysis, the relationship between Hen Harrier breeding population change 175 and wind farms was tested using general linear models (GLMs). Because changes in the number of breeding Hen Harriers were normally distributed, Gaussian GLMs were used. Wind farm development 176 177 within the 10km squares was represented by two variables, the first being the number of turbines built in each square and the second being a binary variable that classified squares as either 'turbines 178 179 present' or 'turbines absent'. Moran's I (in R package ape) was used to test whether turbine numbers 180 or changes in numbers of Hen Harrier pairs were spatially autocorrelated.

182 Prior to running the GLMs, the relationship between the two turbine-related variables and the change 183 in number of breeding Hen Harriers between 2000 and 2010 were examined, in order to determine 184 whether turbine number or presence would be best to include in the models. In addition to turbines, 185 the initial model included: three grouping variables (categorising squares according to geographical 186 area, longitude and latitude); three continuous variables relating to the proportion of land area within 187 three elevation categories; two variables providing a more detailed characterisation of the 188 topographical environment (slope and terrain ruggedness, defined as the standard deviation of 189 elevation within the square, see White (2006)); the area of felled forest in 2000; the total area of forest 190 in 2010; the change between 2000 and 2010 in the area of closed canopy forest and pre-thicket forest; 191 and the suitability of surrounding areas outside the square measured as the percentage of land at 192 optimal Hen Harrier breeding elevations.

193

As well as these variables, the starting model also included interaction terms between these variables and turbine presence. Each of these interaction terms was tested prior to model selection in reduced models that included only the interaction term and the two component variables. Only interaction terms that were retained (according to AICc) in these reduced models were included in the 'full' model from which model selection proceeded.

199

200 **RESULTS**

201 Spatial overlap between wind farms and Hen Harriers

The 69 10km x 10km squares with confirmed breeding Hen Harriers in the Republic of Ireland in 2010 are shown in Fig. 1. Of a total of 69 squares found to be holding Hen Harriers during the 2010 breeding season, 28% of these (n = 19) also held one or more wind farms.

The observed overlap in spatial distribution of Hen Harriers and wind farms was not limited to a two dimensional surface distribution, but is also related to elevation (Fig. 2). Sixty seven per cent of Irish wind farms were located between 200m and 400m above sea level, an elevation band where up to 62% of all Hen Harrier territories were also found. Maximum Hen Harrier breeding densities also occurred at these elevations, with an average of 4.2 Hen Harrier pairs per 100km².

211

212 Hen Harrier population trends and wind farms

In the 36 Hen Harrier squares where sufficiently robust data were available for analysis there was no
evidence of spatial autocorrelation in either changes in the number of breeding pairs between 2000
and 2010 (Moran's I observed = -0.019, expected = -0.029, s.d. = 0.041, P = 0.82), or in the number of
turbines built during this time (Moran's I observed = -0.005, expected = -0.029, s.d. = 0.039, P = 0.47).
Analysis of turbine development in isolation from other sources of environmental variation indicated
that, in squares with wind farms, the number of turbines built was not related to the change in number
of breeding Hen Harriers (Fig. 3).

220

221 However, comparing squares with and without turbines, there appears to be a negative relationship 222 between turbine development and change in breeding Hen Harrier numbers (Fig. 4), although this 223 relationship is marginally non-significant (t=1.82, d.f. = 34, P = 0.077). Presence of turbines was 224 therefore selected as the most appropriate variable for inclusion in GLMs. As well as all variables 225 described in the methods, first-order interactions between turbine presence and each of five other 226 variables were also included in the starting model on which selection was carried out. These five 227 variables were: the proportion of the squares within each of three elevation categories (<100m; 100m 228 - 200m; and 200m - 400m), change in proportional cover of closed canopy forest and change in 229 proportional cover of pre-thicket forest.

231 The best model as selected by AICc included the proportion of land between 200m and 400m, the 232 presence of wind turbines within the square, the change in cover of pre-thicket forest, and the 233 interaction between land between 200m and 400m and the presence of wind turbines (Table 2). The 234 apparent effects of wind farm presence, pre-thicket cover and land between 200m and 400m in the 235 final model were all positive. However, the interaction between presence of wind farms and 236 proportion of land between 200m and 400m was negative (Table 2). This suggests that, although in 237 squares without wind farms the relationship between Hen Harrier change and proportion of land in 238 this elevation category was weakly positive, in squares with wind farms it was strongly negative (see 239 Fig. 5).

240

241 **DISCUSSION**

242 Spatial overlap between wind farms and Hen Harriers

243 One of the bird species for which potential impacts of wind farms have been of greatest concern is 244 the Hen Harrier. This concern is related to the rarity of Hen Harriers in Ireland and other parts of their range, the legal protection afforded to this species by the Birds Directive (2009/147/EC) and the spatial 245 246 overlap between the range of this species and the upland areas in which onshore wind farm 247 construction has been concentrated (Bright et al. 2008a). Wind farms are most commonly built in 248 upland areas because of strong wind currents and low human population densities. However, upland 249 areas are also home to some important bird populations, including those of the Hen Harrier, which is 250 most abundant in Ireland at elevations between 200m and 400m (Ruddock et al. 2012).

251

The results of this study show that, since 2000, wind farms have been built in 28% of 10km x 10km squares in the Irish uplands which were occupied by breeding Hen Harriers. In a study of sensitivity of 16 bird species to wind farm construction in Scotland, Hen Harriers were found to be one of only three species whose populations were likely to be negatively impacted by wind farms. This was, in large

part, due to a high overlap between Hen Harrier territories and areas within 2km of proposed or
existing wind farms (Bright *et al.* 2008a).

258

259 Such high levels of overlap are not uncommon for raptor species where breeding ranges can be 260 occupied by wind farms. Considerable overlap is reported for Egyptian vultures Neophron 261 percnopterus in Spain, where 33% of all territories were located within 15km of wind turbines (Carrete 262 et al. 2009). Also in Spain, 30% of squares occupied by Griffon Vultures Gyps fulvus were located within 263 10km of wind turbines (Tellería 2009b). In the Balkans most operational wind turbines are operating 264 within the highest conservation prioritisation zones for vulture conservation (Vasilakis et al. 2016). By 265 contrast the overlap of wind energy development with other bird species such as Common Scoters 266 Melanitta nigra is very low or negligible (Bright et al. 2008b). However, it must be noted that the 267 degree of overlap may vary substantially across a species' range. This is the case for White-tailed Sea 268 Eagles Haliaeetus albicilla in Europe. In parts of this species range, such as Norway, wind farms have 269 been built in areas with high breeding densities (Dahl et al. 2012). In contrast, the current distribution 270 of White-tailed Eagles in Scotland overlaps minimally with wind farms (Bright et al. 2008a) though, 271 given this species' recent rate of population growth in Scotland (Challis et al. 2015; Roos et al. 2015), 272 this overlap may increase in the future.

273

274 Further analyses revealed that this spatial overlap also occurs in relation to elevation. Although only 275 10% of land in Ireland is located between 200m and 400m above sea level, these areas hold 62% of 276 Hen Harrier territories and 67% of Irish wind farms. Hen Harrier breeding densities are also highest at 277 these elevations, with an average of 4.2 pairs per 100km² (Ruddock *et al.* 2012). These results highlight 278 how the areas which are suitable for Hen Harriers are also important for wind farms and the need for 279 a better understanding of the potential impacts of these developments. Although spatial overlap is 280 not always associated with negative impacts on birds (Fielding et al. 2006, Hernández-Pliego et al. 281 2015), where it does occur it affords a valuable opportunity to determine whether, and to what extent,

wind energy development is likely to conflict with bird conservation. Careful planning is required to minimise potential for negative impacts of development on conservation objectives (Balotari-Chiebao *et al.* 2016, Vasilakis *et al.* 2016). The findings of this study will be useful in providing guidance for future wind energy development in the identification of areas where development is least likely to conflict with Hen Harrier conservation. This is particularly important as the overlap in spatial distribution of Hen Harriers and wind farms is expected to increase as the wind energy sector continues to grow throughout the Hen Harrier's range to meet energy demands.

289

290 Hen Harrier population trends and wind farms

291 Hen Harrier populations have fluctuated significantly throughout their range over the past century. 292 Recent population trends suggest that the breeding population in Ireland has been relatively stable 293 over the last decade, with regional declines recorded in some areas (Barton et al. 2006, Norriss et al. 294 2002, O'Flynn 1983, Ruddock et al. 2012, Watson 1977). The availability of data on Hen Harrier 295 populations from the 2000 and 2010 National Surveys affords us the opportunity to investigate 296 whether, at the local scale of 10km, the deployment of wind energy facilities has been related to 297 changes in Hen Harrier breeding numbers. It is important to bear in mind that the relationships 298 identified in this study may not be causal. The environmental variables used to model changes in Hen 299 Harrier breeding numbers were not experimentally manipulated and are related to a large number of 300 other variables whose influence was not directly accounted for in this study. However, in the absence 301 of widely available before and after control impact studies, the relationships revealed by this 302 modelling method afford us a means of identifying factors that may impact on breeding Hen Harrier 303 numbers, and potential mechanisms for these impacts.

304

A negative relationship, approaching statistical significance, was identified between wind farm presence and change in the number of breeding pairs of Hen Harriers during the period from 2000 to 2010. However, the results of the GLM suggest that this relationship is also likely to be influenced by

308 other factors. The positive effects on Hen Harrier breeding numbers of changes in pre-thicket forest 309 cover and land between 200m and 400m suggest that changes in Hen Harrier populations in the 310 decade between 2000 and 2010 were also related to availability of suitable forest habitats and 311 possibly also to availability of habitat at appropriate elevations. Having taken these variables into 312 account, the effect in the model of wind turbine presence on breeding Hen Harrier numbers is positive. 313 However, this is countered by the highly significant negative effect of the interaction between turbine 314 presence and land area observed between 200m and 400m, for which there are a number of possible 315 reasons. Firstly, it is possible that areas suitable for turbines at medium elevations are intrinsically less 316 well suited to Hen Harriers than other areas at similar altitude. Much wind energy development has 317 taken place between 200m and 400m and it is possible that any negative interaction between Hen 318 Harriers and turbines was greatest at this elevation, as it is also the band of altitude that has most 319 frequently been occupied by breeding Hen Harriers across much of Ireland (Ruddock et al. 2012). 320 However, in squares with wind farms, turbine numbers were not negatively related to breeding 321 trends, suggesting that the negative interaction between turbine presence and mid-range elevations 322 is not directly caused by impacts of turbines such as collision mortality (Masden 2010). It may, 323 however, be caused by other impacts of wind farm development, such as disturbance during 324 prospection and surveys for new wind farms (Madders and Whitfield 2006) or displacement due to 325 habitat modification during construction activities (Masden 2010, Pearce-Higgins et al. 2012). It is also 326 possible that, in areas where there is more land suitable for wind turbine development, Hen Harriers 327 have been at higher risk of persecution (Whitfield and Madders 2005). Factors not investigated in this 328 analysis that could also impact on changes in Hen Harrier populations include changes in the 329 availability and quality of open habitats during the study period, disturbance by human activities, 330 changes in the intensity of farming practices, changes in forest plantations or changes in populations 331 of predators and prey.

332

333 Despite the large volume of work reporting on the impacts of wind farms on birds, published studies 334 relating changes in bird populations to wind energy development are scarce. Furthermore, much of 335 the work that has been undertaken on the impacts of wind farms remains unpublished and therefore 336 difficult to access. The current study provides a valuable insight into the factors influencing Hen Harrier 337 population trends. While this approach serves to underline the importance of on-going environmental 338 changes in upland habitats, it also reveals the complexity of factors affecting Hen Harrier population 339 trends. Species with reduced population numbers are particularly vulnerable to the cumulative effects 340 of factors which, in isolation, may not pose a threat at a population scale (Beston et al. 2016). In the 341 case of Hen Harriers in Ireland, the species is subject to direct persecution, transformation of breeding habitats, encroachment by increased developments in upland areas and, in some areas, increased 342 343 levels of predation (Barton et al. 2006, Ruddock et al. 2012, Wilson et al. 2012).

344

There are substantial political and economic pressures on regulators to allow wind energy developments to proceed in upland areas, many of which are important for Hen Harriers. This study sheds some light on how recent changes in Hen Harrier populations are related to this type of development, as well to other aspects of geography and land use. However, further research is urgently needed to improve our understanding of the individual and cumulative impacts of wind energy on Hen Harrier populations, in order to ensure that regulation of land use for Hen Harrier conservation is effective, but not excessively restrictive.

352

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TABLES

Elevation	Pairs	Density (100km ⁻²)	Area (km²)
0 – 100m	5	0.25	20.0
100 – 200m	42	1.90	22.3
200 – 400m	80	4.24	18.8
>400m	1	0.66	1.5

Table 1. Numbers and densities of confirmed breeding Hen Harrier pairs in 2010 in the 10km x 10kmsquares used in this study, in each of 3 elevation categories. Data are taken from Ruddock *et al.* (2012).

Table 2. Output summary for the final model describing change in number of breeding pairs of Hen Harriers in 36 10km squares as a function of altitudinal and land use related variables pertaining to these squares. The summary comprises estimates and standard errors for parameters retained in the model, with t-values and P-values for each. Forward and backward model selection proceeded from a fully specified model (see text for details) according to AICc score. AICc of null model = 141.35; AICc of final model = 123.20; AICc of next best model (as final model but including felling area in 2000) = 124.13.

	Estimate	SE	t	P value
Intercept	-0.66	0.38	-1.72	0.096
200-400m	3.48	1.29	2.71	0.011
Wind farms	2.26	0.74	3.07	0.0045
Pre-thicket change	19.13	7.97	2.40	0.023
200-400m*Wind farms	-7.67	1.70	-4.51	<0.0001

LEGENDS TO FIGURES

Figure 1. Spatial overlap between the distribution of Hen Harriers at a 10km square scale in the Republic of Ireland as recorded during the 2010 National Survey and wind farms. Hen Harriers were recorded in all grey squares. Light grey squares had wind farm development as of 2012 (n = 19) and dark grey squares did not (n = 50).

Figure 2. Frequency of occurrence (%) of wind farms and Hen Harrier territories (2010 breeding season) in 10km squares, and average Hen Harrier breeding densities in these squares, within different ranges of elevation.

Figure 3. Change in number of breeding Hen Harriers between 2000 and 2010 plotted against the number of wind turbines built, in the eleven squares that experienced turbine development during this period. This relationship was not statistically significant (Pearson's r = 0.41, n = 12, P = 0.18).

Figure 4. Change in number of breeding Hen Harriers between 2000 and 2010, in the 11 squares that experienced wind turbine development during this period and the 25 squares where no turbines were built. On average, Hen Harriers declined by over 1 pair per square more in squares with turbines than in squares with no turbines, but this difference was marginally non-significant (t = 1.82, d.f. = 34, P = 0.077).

Figure 5. The relationship between change in the number of Hen Harrier pairs between 2000 and 2010 and the proportion of land between 200m and 400m in 12 squares where wind turbines were built during this period (above) and in 25 squares where there was no wind energy development during this time (below). See Table 2 for full details of the model output.