



Title	Hen Harrier Circus cyaneus population trends in relation to wind farms
Author(s)	Wilson, Mark W.; Fernández-Bellon, Darío; Irwin, Sandra; O'Halloran, John
Publication date	2016-12-02
Original citation	Wilson, M. W., Fernández-Bellon, D., Irwin, S. and O'Halloran, J. (2017) 'Hen Harrier Circus cyaneus population trends in relation to wind farms', Bird Study, 64(1), pp. 20-29. doi:10.1080/00063657.2016.1262815
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://dx.doi.org/10.1080/00063657.2016.1262815 Access to the full text of the published version may require a subscription.
Rights	© 2016, Taylor & Francis. This is an Accepted Manuscript of an article published by Taylor & Francis in Bird Study on 02/12/2016, available online: http://dx.doi.org/10.1080/00063657.2016.1262815
Embargo information	Access to this article is restricted until 12 months after publication by the request of the publisher
Embargo lift date	2017-12-02
Item downloaded from	http://hdl.handle.net/10468/3747

Downloaded on 2018-08-23T18:36:07Z

1 **Hen Harrier *Circus cyaneus* population trends in relation to wind farms**

2

3 Mark Wilson¹, Darío Fernández-Bellon¹, Sandra Irwin¹ and John O'Halloran¹

4

5 ¹School of Biological, Earth and Environmental Sciences, University College Cork, Enterprise Centre,
6 North Mall, Cork.

7 Corresponding author: s.irwin@ucc.ie

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

27 to assess the influence of wind energy development on Hen Harriers at such a large geographic and
28 population 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
35 (Colhoun and Cummins 2013). Their populations are protected in Ireland through the designation of
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

53 breeding population of less than 172 pairs in the Republic of Ireland (Ruddock *et al.* 2012), and a
54 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
62 and Whitfield 2006, New *et al.* 2011, Pearce-Higgins *et al.* 2009a, Redpath *et al.* 2002). In particular,
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
68 and Whitfield 2006, Balotari-Chiebao *et al.* 2016) and displacement during both the construction
69 (Pearce-Higgins *et al.* 2012) and the operational phases (Garvin *et al.* 2011, Madden and Porter 2007,
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

79 observed changes in Hen Harrier populations are related to wind energy development. Information
80 on the response of populations to changes in land use is essential to the conservation biology and
81 management of Hen Harriers, as it is to all vulnerable bird species.

82

83 Central to the concern over the impacts of wind energy development on Hen Harriers is the spatial
84 overlap between wind farms and bird conservation interests in upland areas. This is partly because
85 there are few economically competing land uses in many upland areas, and the potential to disturb or
86 inconvenience large numbers of people is lower than in other parts of the country. Greater wind
87 resources further increase the attractiveness of upland areas for wind farm construction (Bright *et al.*
88 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
95 have been developed since the turn of the 21st century, during which time four national surveys of
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

100 The aim of this study was to determine whether the breeding Hen Harrier population across Ireland
101 has been affected by wind farm developments in recent years. To date, very little research has been
102 published on effects of wind farms on Hen Harriers on such a large population or geographic scale. In
103 particular, this study focuses on the changes in Ireland's Hen Harrier population between 2000 and
104 2010 in relation to the construction of wind farm infrastructures during this period.

105

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**

119 The scale used for this study was that of the 10km square. Geographical overlap was determined
120 using ArcGIS 10.0 by overlaying the individual 10km x 10km squares (n=69) which held Hen Harriers
121 during the 2010 National Hen Harrier Survey (Ruddock *et al.* 2012) and the locations of all wind
122 farms across Ireland (as detailed on the Irish Wind Energy Association website (www.iwea.com) at
123 the end of 2012). To determine the elevation overlap between Hen Harrier breeding sites and wind
124 farms, elevations for breeding sites and wind farms were extracted from a digital elevation model of
125 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
135 effort was sufficient to detect breeding pairs in all squares considered. This approach also ensures a
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
138 effort in the 2010 survey, we restricted our data analysis to squares that received three or more visits
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*

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

147

148 *Forest cover*

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

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

- 155 • Second rotation plantations between three and fifteen years after planting.
- 156 • Forests classified in the Coillte database as "Under-developed", "Dead" and "Burned".

157

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

164

165 *Geographical position and elevation*

166 The northing and easting of the centre of each 10km square were used to represent the geographical
167 position of the square. A digital elevation model covering the island of Ireland was used to classify
168 areas into three broad categories of elevation: 0 – 100m, 100 – 200m and 200 – 400m. Hen Harrier
169 densities vary greatly between these elevation categories, being concentrated between 200m and
170 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
176 breeding Hen Harriers were normally distributed, Gaussian GLMs were used. Wind farm development
177 within the 10km squares was represented by two variables, the first being the number of turbines
178 built in each square and the second being a binary variable that classified squares as either 'turbines
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.

181

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

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

199

200 **RESULTS**

201 **Spatial overlap between wind farms and Hen Harriers**

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

205

206 The observed overlap in spatial distribution of Hen Harriers and wind farms was not limited to a two
207 dimensional surface distribution, but is also related to elevation (Fig. 2). Sixty seven per cent of Irish
208 wind farms were located between 200m and 400m above sea level, an elevation band where up to
209 62% of all Hen Harrier territories were also found. Maximum Hen Harrier breeding densities also
210 occurred at these elevations, with an average of 4.2 Hen Harrier pairs per 100km².

211

212 **Hen Harrier population trends and wind farms**

213 In the 36 Hen Harrier squares where sufficiently robust data were available for analysis there was no
214 evidence of spatial autocorrelation in either changes in the number of breeding pairs between 2000
215 and 2010 (Moran's I observed = -0.019, expected = -0.029, s.d. = 0.041, P = 0.82), or in the number of
216 turbines built during this time (Moran's I observed = -0.005, expected = -0.029, s.d. = 0.039, P = 0.47).
217 Analysis of turbine development in isolation from other sources of environmental variation indicated
218 that, in squares with wind farms, the number of turbines built was not related to the change in number
219 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.

230

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
245 range, the legal protection afforded to this species by the Birds Directive (2009/147/EC) and the spatial
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

252 The results of this study show that, since 2000, wind farms have been built in 28% of 10km x 10km
253 squares in the Irish uplands which were occupied by breeding Hen Harriers. In a study of sensitivity of
254 16 bird species to wind farm construction in Scotland, Hen Harriers were found to be one of only three
255 species whose populations were likely to be negatively impacted by wind farms. This was, in large

256 part, due to a high overlap between Hen Harrier territories and areas within 2km of proposed or
257 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,

282 wind energy development is likely to conflict with bird conservation. Careful planning is required to
283 minimise potential for negative impacts of development on conservation objectives (Balotari-Chiebao
284 *et al.* 2016, Vasilakis *et al.* 2016). The findings of this study will be useful in providing guidance for
285 future wind energy development in the identification of areas where development is least likely to
286 conflict with Hen Harrier conservation. This is particularly important as the overlap in spatial
287 distribution of Hen Harriers and wind farms is expected to increase as the wind energy sector
288 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

305 A negative relationship, approaching statistical significance, was identified between wind farm
306 presence and change in the number of breeding pairs of Hen Harriers during the period from 2000 to
307 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 prospecting 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
342 habitats, encroachment by increased developments in upland areas and, in some areas, increased
343 levels of predation (Barton *et al.* 2006, Ruddock *et al.* 2012, Wilson *et al.* 2012).

344

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

352

353 **ACKNOWLEDGEMENTS**

354 The authors wish to thank all of the fieldworkers who collected data for the National Hen Harrier
355 surveys included in this study, many in a voluntary capacity, and particularly Marc Ruddock and Allan
356 Mee, Golden Eagle Trust; Tony Nagle, Irish Raptor Study Group; and David Tierney and David Norriss,
357 National Parks & Wildlife Service for organising these surveys. We would also like to express our
358 gratitude to all landowners who allowed access to study sites for this work, and National Parks and

359 Wildlife Service (NPWS) staff for their contribution to this research. We also thank Barry O'Mahony,
360 Paul Troake, Geoff Oliver, Barry O'Donoghue, Tony Nagle and Gyr Penn for assisting with fieldwork
361 undertaken by University College Cork. Forest Cover data were provided to this study by the Forest
362 Service and Coillte. This research was funded by several members of the Irish Wind Energy Association,
363 the Department of Agriculture, Food & the Marine, and the National Parks and Wildlife Service.
364 Research was carried out under licence issued by NPWS in accordance with the Wildlife Act, 1976.

365

366 REFERENCES

- 367 **Amar, A., Davies, J., Meek, E., Williams, J., Knight, A. & Redpath, S.** 2011. Long-term impact of
368 changes in sheep *Ovis aries* densities on the breeding output of the hen harrier *Circus cyaneus*.
369 *J. Appl. Ecol.* **48**: 220-227.
- 370 **Amar, A. & Redpath, S.** 2002. Determining the cause of the hen harrier decline on the Orkney Islands:
371 an experimental test of two hypotheses. *Anim. Conserv.* **5**: 21-28.
- 372 **Amar, A. & Redpath, S.** 2005. Habitat use by Hen Harriers *Circus cyaneus* on Orkney: implications of
373 land use change on this declining population. *Ibis* **147**.
- 374 **Balotari-Chiebao, F., Brommer, J.E., Niinimäki, T. & Laaksonen, T.** 2016. Proximity to wind-power
375 plants reduces the breeding success of the white-tailed eagle. *Anim. Conserv.* **19**: 265-272.
- 376 **Band, W., Madders, M. & Whitfield, D.P.** 2007. Developing field and analytical methods to assess
377 avian collision risk at wind farms. In De Lucas, M., Hanss, G. & Ferrer, M. (eds.) *Birds and wind*
378 *farms: Risk assessment and mitigation*. Quercus.
- 379 **Barton, C., Pollock, C., Norriss, D.W., Nagle, T., Oliver, G.A. & Newton, S.** 2006. The second national
380 survey of breeding Hen Harriers *Circus cyaneus* in Ireland. *Irish Birds* **8**: 1-20.
- 381 **Beston, J.A., Diffendorfer, J.E., Loss, S.R. & Johnson, D.H.** 2016. Prioritizing Avian Species for Their
382 Risk of Population-Level Consequences from Wind Energy Development. *PLoS ONE* **11**:
383 e0150813.

384 **BirdLife International** 2015. European Red List of Birds. Luxembourg: Office for Official Publications
385 of the European Communities.

386 **Bright, J. A., Langston, R.H.W., Bullman, R., Evans, R., Gardner, S. & Pearce-Higgins, J.W.** 2008a. Map
387 of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. *Biol.*
388 *Conserv.* **141**: 2342-2356.

389 **Bright, J.A., Langston, R.H.W., Pearce-Higgins, J.W., Bullman, R., Evans, R. & Gardner, S.** 2008b.
390 Spatial overlap of wind farms on peatland with sensitive areas for birds. *Mires & Peat* **4**: 1-12.

391 **Burfield, I. & von Bommel, F.** 2004. *Birds in Europe: Population estimates, trends and conservation*
392 *status. Conservation Series No. 12*, BirdLife International, Cambridge, UK.

393 **Carrete, M., Sánchez-Zapata, J.A., Benítez, J.R., Lobón, M. & Donázar, J.A.** 2009. Large scale risk-
394 assessment of wind-farms on population viability of a globally endangered long-lived raptor.
395 *Biol. Conserv.* **142**: 2954-2961.

396 **Challis, A., Wilson, M.W., Holling, M., Roos, S., Stevenson, A. & Stirling-Aird, P.K.** 2015. Scottish
397 Raptor Monitoring Scheme Report 2014. Published for Scottish Raptor Monitoring Scheme,
398 by BTO Scotland, Stirling.

399 **Chamberlain, D.E., Rehfisch, M.R., Fox, A.D., Desholm, M. & Anthony, S.** 2006. The effect of
400 avoidance rates on bird mortality predictions made by wind turbine collision risk models. *Ibis*
401 **148**: 198-202.

402 **Clarke, R. & Watson, D.** 1990. The Hen Harrier *Circus cyaneus* Winter Roost survey in Britain and
403 Ireland. *Bird Study* **37**: 84-100.

404 **Colhoun, K. & Cummins, S.** 2013. Birds of conservation concern in Ireland. *Irish Birds* **9**: 523-544.

405 **Dahl, E. L., Bevanger, K., Nygård, T., Røskoft, E. & Stokke, B.G.** 2012. Reduced breeding success in
406 white-tailed eagles at Smøla windfarm, western Norway, is caused by mortality and
407 displacement. *Biol. Conserv.* **145**: 79-85.

408 **Dai, K., Bergot, A., Liang, C., Xiang, W.-N. & Huang, Z.** 2015. Environmental issues associated with
409 wind energy – A review. *Renew. Energ.* **75**: 911-921.

410 **de Lucas, M., Janss, G.F.E. & Ferrer, M.** 2007. *Birds and wind farms: risk assessment and mitigation,*
411 *Quercus.*

412 **de Lucas, M., Janss, G.F.E., Whitfield, D.P. & Ferrer, M.** 2008. Collision fatality of raptors in wind farms
413 does not depend on raptor abundance. **45:** 1695-1703.

414 **Douglas, D.J.T., Bellamy, P.E. & Pearce-Higgins, J.W.** 2011. Changes in the abundance and distribution
415 of upland breeding birds at an operational wind farm. *Bird Study* **58:** 37-43.

416 **Drewitt, A.L. & Langston, R.H.W.** 2006. Assessing the impacts of wind farms on birds. *Ibis* **148:** 29-42.

417 **Fielding, A., Haworth, P., Whitfield, P., McLeod, D. & Riley, H.** 2011. A conservation framework for
418 Hen Harriers in the United Kingdom. JNCC Report 441. Joint Nature Conservation Committee,
419 Peterborough.

420 **Fielding, A.H., Whitfield, D.P. & McLeod, D.R.A.** 2006. Spatial association as an indicator of
421 the potential for future interactions between wind energy development and golden eagle
422 *Aquila chrysaetos* in Scotland. *Biol. Conserv.* **131:** 359-369.

423 **Garvin, J.C., Jennelle, C.S., Drake, D. & Grodsky, S.M.** 2011. Response of raptors to a windfarm. *J.*
424 *Appl. Ecol.* **48:** 199-209.

425 **Hayhow, D.B., Eaton, M.A., Bladwell, S., Etheridge, B., Ewing, S.R., Ruddock, M., Saunders, R.,**
426 **Sharpe, C., Sim, I.M.W. & Stevenson, A.** 2013. The status of the Hen Harrier, *Circus cyaneus,*
427 in the UK and Isle of Man in 2010. **60:** 446-458.

428 **Hernández-Pliego, J., de Lucas, M., Muñoz, A.-R. & Ferrer, M.** 2015. Effects of wind farms on
429 Montagu's harrier (*Circus pygargus*) in southern Spain. *Bio. Conserv.* **191:** 452-458.

430 **Hill, D., Hockin, D., Price, D., Tucker, G., Morris, E. & Treweek, J.** 1997. Bird disturbance: improving
431 the quality and utility of disturbance research. *J. Appl. Ecol.* **34:** 275-288.

432 **Irwin, S., Wilson, M.W., Kelly, T.C., O'Mahony, B., Oliver, G., Troake, P., Ryan, B., Cullen, C.,**
433 **O'Donoghue, B. & O'Halloran, J.** 2011. The breeding biology of Hen Harriers in Ireland over a
434 five year period. *Irish Birds* **9:** 165-172.

- 435 **Madden, B. & Porter, B.** 2007. Do wind turbines displace Hen Harriers *Circus cyaneus* from foraging
436 habitat? Preliminary results of a case study at the Derrybrien wind farm, County Galway. *Irish*
437 *Birds* **8**: 231-236.
- 438 **Madders, M. & Whitfield, D.P.** 2006. Upland raptors and the assessment of wind farm impacts. *Ibis*
439 **148**: 43-56.
- 440 **Masden, E.A.** 2010. *Assessing the cumulative impacts of wind farms on birds. PhD thesis.* PhD,
441 University of Glasgow.
- 442 **Morinha, F., Travassos, P., Seixas, F., Martins, A., Bastos, R., Carvalho, D., Magalhães, P., Santos, M.,**
443 **Bastos, E. & Cabral, J.A.** 2014. Differential mortality of birds killed at wind farms in Northern
444 Portugal. *Bird Study* **61**: 255-259.
- 445 **New, L.F., Buckland, S.T., Redpath, S. & Matthiopoulos, J.** 2011. Hen Harrier management: insights
446 from demographic models fitted to population data. *J. Appl. Ecol.* **48**: 1187-1194.
- 447 **Norriss, D.W., Marsh, J., McMahon, D. & Oliver, G. A.** 2002. A national survey of breeding Hen
448 Harriers *Circus cyaneus* in Ireland 1998-2000. *Irish Birds* **7**: 1-10.
- 449 **O'Flynn, W. J.** 1983. Population changes of the Hen Harrier in Ireland. *Irish Birds* **2**: 337-343.
- 450 **Pearce-Higgins, J.W., Grand, M.C., Beale, C.M., Buchanan, G.M. & Sim, I.M.W.** 2009a. International
451 importance and drivers of change of upland bird populations. In Bonn, A., Allott, T., Hubacek,
452 K. & Stewart, J. (eds.) *Drivers of environmental change in the uplands.* Routledge, Abingdon,
453 UK.
- 454 **Pearce-Higgins, J.W., Stephen, L., Douse, A. & Langston, R.H.W.** 2012. Greater impacts of wind farms
455 on bird populations during construction than subsequent operation: results of a multi-site and
456 multi-species analysis. *J. Appl. Ecol.* **49**: 386-394.
- 457 **Pearce-Higgins, J.W., Stephen, L., Langston, R.H.W., Bainbridge, I.P. & Bullman, R.** 2009b. The
458 distribution of breeding birds around upland wind farms. *J. Appl. Ecol.* **46**: 1323-1331.
- 459 **Redpath, S., Amar, A., Madders, M., Leckie, F. & Thirgood, S.** 2002. Hen Harrier foraging success in
460 relation to land use in Scotland. *Anim. Conserv.* **5**: 113-118.

461 **Roos, S., Dobson, A., Noble, D., Haworth, P., Fielding, A., Carrington-Cotton, A., Etheridge, B. &**
462 **Wernham, C.** 2015. Raptors in Scotland – a methodology for developing trends and indicators.
463 Scottish Natural Heritage Commissioned Report No. 542.

464 **Ruddock, M., Dunlop, B.J., O'Toole, L., Mee, A. & Nagle, T.** 2012. Republic of Ireland Hen Harrier
465 Survey 2010. Irish Wildlife Manual No. 59. National Parks and Wildlife Service, Department of
466 Arts, Heritage and the Gaeltacht, Dublin, Ireland.

467 **Sim, I.M.W., Dillon, I.A., Eaton, M.A., Etheridge, B., Lindley, P., Riley, H., Saunders, R., Sharpe, C. &**
468 **Tickner, M.** 2007. Status of the Hen Harrier *Circus cyaneus* in the UK and Isle of Man in 2004,
469 and a comparison with the 1988/89 and 1998 surveys. *Bird Study* **54**: 256-267.

470 **Stewart, G.B., Pullin, A.S. & Coles, C.F.** 2007. Poor evidence-base for assessment of windfarm impacts
471 on birds. *Environ. Conserv.* **34**: 1-11.

472 **Tabassum, A., Premalatha, M., Abbasi, T. & Abbasi, S.A.** 2014. Wind energy: Increasing deployment,
473 rising environmental concerns. *Renew. Sust. Energ. Rev.* **31**: 270-288.

474 **Tellería, J.** 2009a. Wind power plants and the conservation of birds and bats in Spain: a geographical
475 assessment. *Biodivers. Conserv.* **18**: 1781-1791.

476 **Tellería, J.L.** 2009b. Overlap between wind power plants and Griffon Vultures *Gyps fulvus* in Spain.
477 *Bird Study* **56**: 268-271.

478 **Vasilakis, D.P., Whitfield, D.P., Schindler, S., Poirazidis, K.S. & Kati, V.** 2016. Reconciling endangered
479 species conservation with wind farm development: Cinereous vultures (*Aegypius monachus*)
480 in south-eastern Europe. *Biol. Conserv.* **196**: 10-17.

481 **Wang, S., Wang, S. & Smith, P.** 2015. Ecological impacts of wind farms on birds: Questions,
482 hypotheses, and research needs. *Renew. Sust. Energ. Rev.* **44**: 599-607.

483 **Watson, D.** 1977. *The Hen Harrier*, T & A D Poyser.

484 **White, K.S.** 2006. Seasonal and sex-specific variation in terrain use and movement patterns of
485 mountain goats in southeastern Alaska. In Wishart, B. & Pybus, M. (eds.) *Biennial symposium*
486 *of the northern wild sheep and Goat council*. NWSGC, Cody, Wyoming, USA.

- 487 **Whitfield, D.P. & Madders, M.** 2005. A review of the impacts of wind farms on hen harriers. Natural
488 Research Information Note 1. Natural Research Ltd., Banchory.
- 489 **Wilson, M.W., Irwin, S., Norriss, D.W., Newton, S.F., Collins, K., Kelly, T.C. & O'Halloran, J.** 2009. The
490 importance of pre-thicket conifer plantations for nesting Hen Harriers *Circus cyaneus* in
491 Ireland. *Ibis* **151**: 332-343.
- 492 **Wilson, M.W., Irwin, S., O'Donoghue, B., Kelly, T.C. & O'Halloran, J.** 2010. The use of forested
493 landscapes by Hen Harriers in Ireland. COFORD Connects. Environment No. 10.
- 494 **Wilson, M.W., O'Donoghue, B., O'Mahony, B., Cullen, C., O'Donoghue, T., Oliver, G., Ryan, B.,
495 Troake, P., Irwin, S., Kelly, T.C., Rotella, J.J. & O'Halloran, J.** 2012. Mismatches between
496 breeding success and habitat preferenes in Hen Harrier *Circus cyaneus* breeding in forested
497 landscapes. *Ibis* **154**: 578-589.

TABLES

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

Elevation	Pairs	Density (100km ²)	Area (km ²)
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 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.