

Title	Anthropogenic pressures within the breeding range of the Hen Harrier Circus cyaneus in Ireland
Authors	Caravaggi, Anthony;Irwin, Sandra;Lusby, John;Ruddock, Marc;Mee, Allan;Nagle, Tony;O'Toole, Lorcán;O'Neill, Shane;O'Halloran, John
Publication date	2020-03-27
Original Citation	Caravaggi, A., Irwin, S., Lusby, J., Ruddock, M., Mee, A., Nagle, T., O'Toole, L., O'Neill, S. and O'Halloran, J. (2020) 'Anthropogenic pressures within the breeding range of the Hen Harrier Circus cyaneus in Ireland', Bird Study, 66(4), pp. 461-470. doi: 10.1080/00063657.2020.1725420
Type of publication	Article (peer-reviewed)
Link to publisher's version	10.1080/00063657.2020.1725420
Rights	© 2020, British Trust for Ornithology. All rights reserved. This is an Accepted Manuscript of an item published by Taylor & Francis in Bird Study on 27 March, 2020, available online: https:// doi.org/10.1080/00063657.2020.1725420
Download date	2025-07-05 14:13:18
Item downloaded from	https://hdl.handle.net/10468/9856



University College Cork, Ireland Coláiste na hOllscoile Corcaigh

- 1 Original Research Paper
- 2 Anthropogenic pressures within the breeding range of the Hen Harrier (*Circus cyaneus*)
- 3 in Ireland
- 4 Anthony Caravaggi<sup>1,2</sup>, Sandra Irwin<sup>1</sup>, John Lusby<sup>3</sup>, Marc Ruddock<sup>4</sup>, Allan Mee<sup>5</sup>, Tony
- 5 Nagle<sup>6</sup>, John O'Halloran<sup>1</sup>\*
- <sup>6</sup> <sup>1</sup> School of Biological, Earth and Environmental Sciences, University College Cork,
- 7 Distillery Field, North Mall, Cork, Ireland, T23 XA50.
- <sup>2</sup> University of South Wales, 9 Graig Fach, Pontypridd, UK CF37 4BB.
- <sup>3</sup> BirdWatch Ireland, Unit 20, Block D, Bullford Business Campus, Kilcoole, Co. Wicklow,
- 10 Ireland, A63 RW83.
- <sup>4</sup> Golden Eagle Trust Ltd, 12 Ely Place, Dublin 2, Ireland, D02 T651.
- <sup>5</sup> Ardpatrick, Kilmallock, Co. Limerick, Ireland.
- <sup>6</sup> The Rookery, Ballyfeard, Co. Cork, Ireland.
- 14 \*Corresponding author: j.ohalloran@ucc.ie
- 15
- Keywords: raptor; human impacts; upland conservation; bird of prey; land management;
   policy
- 18
- 19 Word count (excluding references, table and figure): XXXX
- 20
- 21 Short title: Impacts on Hen Harrier breeding habitat
- 22
- 23 Summary
- 24 Capsule

Patterns in the frequency and co-occurrence of anthropogenic pressures associated with
suitable breeding habitat for Hen Harriers demonstrates the need for specific, focussed

27 management and policy options aimed at mitigating impacts on this threatened population.

28 Aims

To describe anthropogenic pressures and threats in the upland breeding range of Hen Harriersand to explore their potential impacts on the declining Hen Harrier population.

31 Methods

We used text mining, mixed effects models, Principal Component Analysis and clustering methods to explore anthropogenic pressures on suitable breeding and foraging habitats for Hen Harriers in Ireland, based on the 2015 national breeding Hen Harrier survey data.

#### 35 **Results**

Mixed-effects models described a strong influence of agriculture, forestry, predator activity and recreational activities on survey areas that contained Hen Harrier territories. Cluster analyses described three discrete pressure clusters and showed consistent co-occurrence of independent pressures.

### 40 Conclusions

41

Areas of suitable habitat for Hen Harriers in the uplands overlap with areas that experience
anthropogenic pressures known to negatively impact on this vulnerable bird species.
Combined with clear evidence for the co-occurrence of multiple pressures at regional scale,
this demonstrates a clear need for statutory agencies to consider the potential cumulative

46 impacts of individual pressures when developing conservation strategies for Hen Harriers.

47

48

## 49 Introduction

Many species, worldwide, are threatened by anthropogenic pressures that require intervention 50 51 to mitigate or eliminate their negative impacts (Wilcove et al. 1998; Carroll et al. 2015; Di Minin et al. 2016). Such pressures can result in stress responses or reduced fitness in wildlife 52 that, in some cases, has severe impacts on individuals or populations (Wilcove et al. 1998; 53 54 Taylor & Knight 2003; Johnson et al. 2005; Ciuti et al. 2012; Coetzee & Chown 2016). 55 Conservation processes typically aim to prevent species population declines and extinctions (Soule 1985). However, conservation policy must also be cognisant of the sustainable 56 management of environmental resources and other activities of economic and social 57 importance including commercial forestry, agriculture and recreation (Young et al. 2005; 58 59 Kareiva & Marvier 2012; Kennedy et al. 2016; Vangansbeke et al. 2017) 60 Human activities in the vicinity of breeding birds can lead to increased rates of nest desertion (White & Thurow 1985), and reduced rates of site occupancy (Webber et al. 2013), 61 62 territory establishment (Bötsch et al. 2017), breeding success (Balotari-Chiebao et al. 2016) and survival (Ruhlen et al. 2003; including illegal killing, e.g. Smart et al. 2010). 63 Quantifying the extent and ecological relevance of each of these impacts informs our 64 understanding of human-wildlife interactions and underpins conservation and resource 65 66 management processes. It is essential, therefore, that human activities that have the potential 67 to affect wildlife, particularly vulnerable species of conservation concern, are properly assessed and understood, so that appropriate measures can be developed to facilitate 68 69 conservation and sustainable land and resource use.

Hen Harriers (*Circus cyaneus*) are medium-sized raptors that nest largely upland
areas, typically heather moorland in Britain (Redpath et al. 1998; Amar et al. 2008; Watson
2017), during the summer breeding season. Upland habitats in Ireland have been subjected to

73 degradation and land-use change and, in the absence of their preferred open heath and blanket 74 bog nesting habitat. As a result of a large-scale afforestation programme in the Republic of Ireland from the 1950s and the conversion of 'traditional' open habitats to forest, Hen 75 76 Harriers in Ireland are frequently associated with young (i.e. pre-thicket) conifer plantations that provide them with areas for nesting and foraging (Wilson et al. 2009; Irwin et al. 2012; 77 Wilson et al. 2012; Ruddock et al. 2016). Anthropogenic impacts such as afforestation and 78 79 forest management (NPWS 2015), landscape degradation and land-use change (Wilson et al. 2009; Wilson et al. 2012), livestock grazing (O'Rourke & Kramm 2009), illegal burning 80 81 (Renou-Wilson et al. 2011), peat extraction (O'Riordan et al. 2015), recreation (Hynes & Buckley 2007) and wind energy development (Wilson et al. 2017) could have important 82 implications for breeding Hen Harriers. It should be noted that the level of persecution 83 84 observed in Britain (e.g. Redpath et al. 2010; Murgatroyd et al. 2019) is not observed in Ireland as there are no areas that are managed solely for driven grouse shooting. However, 85 raptors are known to migrate within the British Isles (Mead, 1973) and persecution of Hen 86 87 Harriers in Britain could have hitherto undescribed impacts on the Irish population. The Hen Harrier population in Ireland is of national conservation concern (Colhoun & Cummins 88 2013), with a population of between 108 and 157 breeding pairs recorded in the most recent 89 national survey (Ruddock et al. 2016). The species is listed under Annex I of the European 90 91 Commission Birds Directive (2009/147/EC) that requires Member States to designate Special 92 Protection Areas (SPAs) for their survival and reproduction. Six Hen Harrier SPAs containing important breeding areas for the species were designated in Ireland in 2007. 93 Hen Harrier conservation research in Ireland to date has focussed on the impacts of 94 95 afforestation (Irwin et al., 2012; Wilson et al., 2009, 2012) and wind farm development 96 (Fernández-Bellon et al., 2015; Wilson et al., 2017) on their populations, as required to inform conservation management. Due to the targeted nature of previous research, very little 97

98 information is available in the published literature regarding the broader range of anthropogenic pressures that might impact breeding Hen Harriers and associated foraging and 99 breeding habitat. Furthermore, previous research has considered how individual pressures 100 101 impact separately and in specific contexts while consideration of the synergies between pressures is lacking. To address these gaps, we explored data on anthropogenic pressures 102 affecting Hen Harriers within their breeding range in Ireland, with the aim of deriving 103 104 information that would inform conservation and management processes for this threatened species. 105

106

## 107 Materials and methods

108 The 2015 National Survey of Breeding Hen Harrier in Ireland was conducted between April and August 2015 in suitable Hen Harrier habitat in upland areas, largely, but not exclusively, 109 between 200m and 600m above sea level (asl) and within the Hen Harrier breeding range 110 (Ruddock et al. 2016). Survey squares of  $10 \text{ km}^2$  (n = 268) were defined using the Irish 111 National Grid (Fig. 1a). Anthropogenic activities that could potentially impact on breeding 112 113 Hen Harriers ('pressures' from hereon) were recorded from vantage points within each survey square during each of 4-6 dedicated watches per square, during the breeding season. 114 Where sites were occupied, vantage points were a minimum of 500 m from nests sites. 115 116 Vantage points were identified *a-priori* based on habitat suitability, topographical constraints and the potential for observers to cause disturbance to breeding birds (Ruddock and Whitfield 117 2007; Philip Whitfield et al. 2008). Hen Harrier territories (n = 100, across 54 survey 118 119 squares) were recorded where identified; occupancy was based on observations of Hen Harrier breeding behaviour and the repeated presence of birds (Ruddock et al., 2016). Data 120 were collected by staff, members and volunteers from the National Parks & Wildlife Service 121

(NPWS), BirdWatch Ireland (BWI), Irish Raptor Study Group (IRSG), Golden Eagle Trust
(GET), university researchers, and independent commercial and voluntary ornithological
surveyors

Pressures were divided into 47 discrete categories (Appendix I) aligned with the EU 125 Birds Directive (2009/147/EC) reporting matrix. The frequency of occurrence of each 126 127 pressure within 2 km of vantage point locations was recorded within each survey square. Initial exploration of the data revealed extreme outliers, therefore we adopted a precautionary 128 approach and applied consistent thresholds throughout. Values for individual pressures that 129 130 occurred beyond two standard deviations (SDs) from the mean were replaced with the maximum value as defined by the aforementioned threshold, rounded to the nearest whole 131 integer. This allowed us to capture the prevalence of each pressure at each location while 132 133 mitigating over-inflation. The sum frequency of each pressure was calculated (i) across all survey squares where the total number of recorded pressures was >0 (n=146; Appendix II); 134 (ii) across squares located within SPA boundaries only (n=24); and (iii) across squares where 135 confirmed Hen Harrier territories were present (n=54). It was necessary to account for 136 variation in survey effort as the number of visits made to vantage points varied between 137 138 observers. Therefore, a Pressure Index (PI) was created, where the total number of pressures 139 was divided by the total number of visits (Ruddock et al. 2016). PI scores were normalised 140 between 0 and 1 to facilitate comparisons between sites. General Linear Models (GLMs) 141 were used to investigate differences between PI scores - with zero counts removed and remaining data log transformed to meet model assumptions - where PI was the dependent 142 variable and the location of vantage points relative to SPA boundaries (inside/outside) and 143 144 confirmed Hen Harrier territories (present/absent) were explanatory variables. Models explored each category (SPA boundaries and Hen Harrier territories) independently as well as 145 part of a fully-factorial model that included an interaction term. 146

Principal Component Analysis (PCA; Jolliffe & Cadima, 2016) and linear mixed-147 effects models were used to investigate relationships between the presence/absence of Hen 148 Harrier territories and pressure categories. Data were Box Cox transformed to remove 149 150 skewness, centred and standardised to have a  $\bar{x} = 0$  and  $\sigma = 1$  prior to analysis. Principal Components (PCs) that cumulatively accounted for >50% of the variance were retained for 151 inclusion in models. The presence/absence of Hen Harrier territories (Fig. 1b) was entered as 152 153 a binary dependent variable, retained PCs were included as explanatory variables and surveyor identity was included as a random variable. Model permutations were ranked using 154 155 the Akaike Information Criterion (AIC); the top subset of models was found within  $\Delta AIC \leq 2$ units (Burnham & Anderson 2002). 156

Cluster analysis was used to quantify associations between individual pressure 157 categories across all survey squares. The various methods that comprise cluster analyses 158 provide a means of classifying multivariate data into subgroups according to the similarity of 159 their attributes, thus revealing the underlying structure (Everitt et al. 2009). We calculated the 160 distance of each recorded pressure from the cluster's mean using a Euclidean distance index 161 and applied the Ward error sum of squares hierarchical clustering method (Ward 1963) to the 162 163 resultant data. The optimal number of clusters  $(k_t)$  was identified using average silhouettes 164 (Kaufman & Rousseeuw 1990) and Approximately Unbiased (AU) p-values with multiscale 165 bootstrap resampling (B = 10,000) where clusters with  $p \ge 0.95$  were strongly supported 166 (Suzuki and Shimodaira 2006). All data analyses and plotting were carried out using the statistical programme R (R Core Team 2017), specifically the packages *cluster* (Maechler et 167 al. 2018) and pvclust (Suzuki and Shimodaira 2015), dendextend (Galili 2015), nlme 168 169 (Pinheiro et al. 2017) and caret (Kuhn 2017). Data are subject to data-sharing agreements and, therefore, cannot be redistributed. However, R code used for data exploration and 170 analyses are available at http://doi.org/10.5281/zenodo.3549584. 171

172

#### 173 **Results**

174 A total of 2,873 individual pressure occurrences were recorded during this study. There were

no anthropogenic pressures recorded in 45% of survey squares. The most frequently recorded

- 176 pressures across all survey squares were *forest management and use* (13% of occurrences),
- 177 *paths, tracks, forest roads* (11%), *uncontrolled burning* (6%) and *wind energy production*
- 178 (6%). Similar pressures were recorded inside and outside of SPA boundaries: *forest*
- 179 *management and use* (14% and 11% of occurrences, respectively), *paths, tracks, forest roads*
- (10%, 0%), forest planting on open ground (0%, 8%), *uncontrolled burning* (6.6%, 7%) and
- 181 *wind energy production* (9.5%, 7%). The most frequently recorded pressures associated with
- 182 confirmed Hen Harrier territories were *loss of habitat features* (13.7%), *dispersed habitation*
- 183 (10.5%), paths, tracks, forest roads (9.2%) and forest management (8.1%). In contrast,
- 184 pressures at vantage points not associated with Hen Harrier territories were *forest*
- 185 *management and use* (16%), off-road motorised driving (12%), *forest planting on open*
- 186 *ground* (11%), and *mechanical removal of peat* (11%).
- Pressure Indices varied between survey squares (Fig. 1c) and only one survey square had a PI > 0.5. Survey squares where vantage points occurred within SPAs had a maximum PI of 0.22 ( $\bar{\mathbf{x}} = 0.08 \pm 0.07$ ), which was significantly higher than those outside SPAs (t =0.028;  $\beta = -0.44 \pm 0.20$ ; P = 0.03). Survey squares where vantage points were associated with Hen Harrier territories had a maximum PI of 0.42 ( $\bar{\mathbf{x}} = 0.10 \pm 0.09$ ; Appendix I), which was significantly higher than those that were not associated with territories (t = 0.038;  $\beta = -0.39 \pm$ 0.19; P = 0.04; Table 1).
- Both silhouette and AU clustering methods supported three discrete clusters ( $P \ge$ 0.05). The largest cluster (*ii*) consisted of 25 pressure categories while the smallest (*iii*) was

the most distinct and consisted of five pressure categories. One sub-cluster was statisticallysupported (*iv*) and was comprised of 17 pressure categories (Fig. 2).

A total of seven Principal Component axes, accounting for >50% of the total variance, 198 were retained for inclusion in mixed-effects models investigating the relationship between the 199 presence/absence of Hen Harrier territories and associated pressures. The top subset of 200 models ( $\Delta AIC \leq 2$ ) included PC1, PC2 and PC3. PC1 accounted for the greatest proportion of 201 202 total variance (20%); loadings were most strongly weighted towards aspects of agricultural and forestry activity and predators; PC2 (8%) was weighted towards forest management and 203 204 site access; and PC3 was weighted towards forest clearance and recreational activities (Table 2). The best approximating model was positively influenced by PC1 and PC3, and negatively 205 206 influenced by PC2 (Table 2). It should be noted that PC1 includes nest destruction, predation 207 by birds and predation by mammals. These pressures can only occur where Hen Harriers nest, hence the observed positive association is to be expected. 208

209

### 210 Discussion

211 Our results show that suitable Hen Harrier breeding habitats in Ireland are subjected to a wide range of anthropogenic pressures that could have significant implications for this 212 vulnerable species. The number and variety of pressures recorded demonstrates the potential 213 214 of disturbance to prospecting Hen Harriers early in the breeding season and/or to foraging Hen Harriers once territories have been established (e.g. González et al. 2006). Furthermore, 215 the co-occurrence of pressures as described by cluster analyses demonstrates the considerable 216 217 potential for cumulative effects. Anthropogenic impacts are not homogenous in their severity or extent. This is certainly true in the current study, where some pressures will have more 218 severe consequences for Hen Harriers or will act at different spatial scales. However, there is 219

a dearth of quantitative data on the impacts of described pressures on Hen Harriers. Our
results highlight the importance of managing pressures in an integrated manner rather than on
an individual basis. This provides support for the effective management of suitable breeding
areas to minimise the potential impact of anthropogenic pressures on vulnerable Hen Harrier
populations.

225 Planted forests and the presence of tracks or roads were recorded at high frequencies in all survey squares across Ireland. Large areas of Irish upland habitat have been afforested 226 227 in recent decades and total forest cover is expected to continue to increase from the current 228 11% to as much as 18% in the next 30 years (NPWS 2015). In the absence of their traditional 229 open heath and blanket bog habitat, Hen Harriers in Ireland are frequently associated with young (i.e. pre-thicket) conifer plantations that provide areas that Hen Harriers use for 230 231 nesting and foraging (Wilson et al. 2009; Irwin et al. 2012; Wilson et al. 2012; Ruddock et al. 2016). Hen Harriers cannot use use closed-canopy forests for breeding or foraging, therefore 232 the maturation of the existing forest estate threatens to deprive Hen Harriers of already scarce 233 breeding habitat, while further increases in forest cover could also lead to increased habitat 234 fragmentation and subsequently reduce the capacity of the landscape to support breeding 235 236 pairs. Recreational activities were also strongly associated with survey squares containing 237 Hen Harrier territories. Systematic reviews have demonstrated that recreational activities can 238 negatively impact breeding birds (e.g. Steven et al. 2011; Larson et al. 2016) including above-ground foragers (Bötsch et al. 2017) and upland species such as Golden Plovers 239 (Pluvialis apricarius; Finney et al. 2005). Thus, there exists the potential for disturbance of 240 prospecting Hen Harriers early in the breeding season and/or foraging Hen Harriers once 241 242 territories have been established.

243 Mammalian and avian predators were among the factors strongly associated with Hen
244 Harrier territories. O'Donoghue (2010) attributed 55% of all nest failures in south and west

Ireland in 2007 and 2008 to predation events and foxes (Vulpes vulpes) have been observed 245 depredating Hen Harrier chicks via remote-sensing camera traps (Irwin et al. 2012; 246 Fernández-Bellon et al. 2017). Other potential predators of Hen Harrier nests in Ireland 247 include Pine Marten (Martes martes), American Mink (Neovison vison), Stoat (Mustela 248 erminea), Raven (Corvus corax) and Hooded Crow (Corvus corone corvix) (Picozzi, 1984; 249 Fernández-Bellon et al., 2018a). These predators can have substantial negative impacts on 250 251 ground-nesting birds (Paton 1994) as eggs and young chicks are particularly vulnerable to predation when parents are absent. Populations of generalist predators may be bolstered by 252 253 changes in land-use and management, including afforestation and other forms of habitat fragmentation (e.g. Prestt, 1965; Haydon & Harrington, 2000; Chalfoun et al. 2002; Twining 254 et al. 2019). However, data on the abundance and activity of upland predators in Ireland are 255 256 scarce; efforts to investigate such may be of considerable benefit to the conservation of Hen Harriers. 257

It is notable that wind energy production was recorded more frequently within SPA 258 boundaries than outside but was rarely recorded in survey squares that contained breeding 259 Hen Harriers (3.3%) in this study, perhaps indicating avoidance of wind farms for breeding 260 261 purposes (also see Wilson et al. 2017). Indeed, windfarm construction activity has been implicated in the desertion of traditional breeding sites in Ireland (O'Donoghue et al. 2011). 262 263 The construction and operation of wind turbines can have both lethal and sub-lethal impacts 264 on birds (Drewitt & Langston 2006; Marques et al. 2014; Wilson et al. 2015; Balotari-Chiebao et al. 2016; Smith & Dwyer 2016; Fernández-Bellon et al. 2018; Thaker et al. 2018). 265 The Republic of Ireland is committed to EU targets on renewable energy including a national 266 267 target of 40% electricity from renewables by 2020, which is likely to involve the construction of additional wind farms (DCCAE 2010). Wind energy developments tend to be upland-268 focussed and future, large-scale expansion may pose a threat to breeding Hen Harriers. A bird 269

sensitivity mapping tool has been developed to guide the siting of future wind energy
developments in Ireland in relation to the distribution of species of conservation concern,
including Hen Harrier (McGuinness et al. 2015). However, there is as yet no mandatory
obligation on developers to use this tool.

The timing of disturbance events may be a key consideration and many sources of 274 disturbance may already be present at the onset of breeding, when pairs are establishing 275 276 territories. Furthermore, other pressures such as peat extraction or illegal burning may not occur until after laying and, hence, can impact on parental care and, ultimately, breeding 277 278 success. Current mitigation measures for Hen Harriers in Ireland adopt a reactive approach where circular 'High Likelihood Nesting Areas' (HNLA, formerly Red Areas) of high 279 280 sensitivity to Hen Harriers, that contain nesting pairs and with a radius of 1.2 km, are added 281 to the HNLA network when new breeding pairs are identified (NPWS 2015). Forestry operations that may cause disturbance are regulated within these HNLAs during the breeding 282 season (Forest Service 2012). However, the protection afforded by HNLAs only applies to 283 284 known pairs within the SPA network. Therefore, all other pairs that are outside of the SPA network (>50% of the breeding population; Ruddock et al. 2016), remain vulnerable to direct 285 disturbance from forest management activities during the nesting season. Moreover, breeding 286 Hen Harriers have been recorded travelling as far as 11 km from active nests (Irwin et al. 287 288 2012; Arroyo et al. 2014) and human activities and impacts in the wider landscape can have 289 impacts on the physiology (Abbasi et al. 2017) and mortality (Ferrer & Hiraldo 1993) of birds. Human activities within the foraging range of breeding Hen Harriers could result in 290 patch avoidance and/or stress-related responses in foraging birds, potentially keeping them 291 292 away from the nest for longer periods of time and subsequently increasing chick vulnerability. It is possible that Hen Harriers in Ireland have the capacity to develop a 293 294 tolerance for human activities during the breeding season. However, given their small

population size and conservation status, the precautionary principle suggests that human
activities should be strictly regulated in areas of suitable Hen Harrier breeding and foraging
habitat, particularly during key breeding months. Furthermore, pressures and their potential
impacts on breeding Hen Harriers must be placed in a broader context that includes the
timing of pressure occurrence, the composition of the wider landscape and the conservation
of suitable habitat.

The pressures described herein represent potential disturbances to Hen Harriers 301 throughout their breeding cycle and therefore may have important consequences for long-302 303 term population persistence or recovery. Recent research suggests that the same pressures impact another upland bird of prey, the Short-eared Owl (Asio flammeus), across their 304 European range (Fernández-Bellon, unpubl. data). Thus, we recommend the following 305 306 actions to enhance conservation benefits for Hen Harriers and other sensitive upland species and habitats: i) restrict forestry activities within the known hen Harrier range during the Hen 307 Harrier breeding season (April – August) by using targeted surveys to detect Hen Harrier 308 presence, thereby ensuring that forest management activities can be undertaken in areas that 309 do not hold Hen Harriers during the summer months; ii) quantify the abundance and activity 310 311 of upland predators and explore options for predator control, where appropriate; iii) 312 discourage recreation and non-licensed forestry-related activities in areas known to hold Hen 313 Harriers, throughout the breeding season, supported by a programme of community engagement, awareness-raising and upland signage; and iv) improve lines of communication 314 between the relevant stakeholders so that potentially damaging activities can be identified at 315 316 the earliest stages.

Failure to mitigate anthropogenic disturbances in upland areas of potentially suitable
Hen Harrier breeding habitat, whether inside or outside of SPAs, could have negative
consequences for this already vulnerable population. To date, none of the SPAs in the Hen

320 Harrier Natura 2000 network possess management plans, one of the key requirements of such sites, over a decade on from designation in 2007, and a Hen Harrier Threat Response Plan, 321 initiated by the National Parks & Wildlife Service in the Republic of Ireland in 2016 with 322 wide stakeholder consultation, has yet to be published. Furthermore, connecting multiple 323 pressures is a key issue for conservation management, and Hen Harrier conservation policies 324 must comprehensively account for cumulative anthropogenic impacts at regional level. 325 326 Successful mitigation and management would represent a significant step towards the conservation of Hen Harriers in Ireland and serve as an example for upland conservation 327 328 initiatives in Europe.

329

## 330 Acknowledgments

331 The authors thank the many people who collected data for the 2015 National Survey of

332 Breeding Hen Harrier in Ireland and members of the stakeholder and scientific steering

333 groups for the Supporting Hen Harriers in Novel Environments (SHINE) research project at

334 UCC. The SHINE research project was funded by the Department of Agriculture, Food & the

335 Marine. We also thank the Editor and two anonymous reviewers whose feedback helped

improve this manuscript.

337

#### 338 **References**

Abbasi, N.A., Arukwe, A., Veerle, L.B.J., Eulaers, I., Mennilo, E., Ibor, O.R., Frantz,
A., Covaci, A. & Malik, R.N. 2017. Oxidative stress responses in relationship to persistent
organic pollutant levels in feathers and blood of two predatory bird species from Pakistan. *Sci. Total. Environ.* 580: 26–33.

Amar, A., Arroyo, B., Meek, E., Redpath, S. & Riley, H. 2008. Influence of habitat on
breeding performance of Hen Harriers *Circus cyaneus* in Orkney. *Ibis* 150: 400–404.

- Arroyo, B., Leckie, F., Amar, A., McCluskie, A. & Redpath, S. 2014. Ranging behaviour
  of Hen Harriers breeding in Special Protection Areas in Scotland. *Bird Study* 61: 48–55.
- Balotari-Chiebao, F., Brommer, J.E., Niinimaki, T. & Laaksonen, T. 2016. Proximity to
  wind-power plants reduces the breeding success of the white-tailed eagle. *Anim. Conserv.* 19:
  265–272.
- Bötsch, Y., Tablado, Z. & Jenni, L. 2017. Experimental evidence of human recreational
  disturbance effects on bird-territory establishment. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 284: 20170846.
- Burnham, K. & Anderson, D. 2002. Model selection and multi- model inference: a
   practical information-theoretic approach. New York: Springer.
- Carroll, C., Rohlf, D.J., Li, Y.-W., Hartl, B., Phillips, M.K. & Noss, R.F. 2015.
  Connectivity conservation and endangered species recovery: a study in the challenges of defining conservation-reliant species: *Conserv. Lett.* 8: 132–138.
- 358 **Chalfoun, A.D., Thompson, F.R. & Ratnaswamy, M.J.** 2002). Nest predators and 359 fragmentation: a review and meta-analysis. *Conserv. Biol.* **16**: 306–318.
- Ciuti, S., Northrup, J.M., Muhly, T.B., Simi, S., Musiani, M., Pitt, J.A. & Boyce, M.S.
  2012. Effects of humans on behaviour of wildlife exceed those of natural predators in a
  landscape of fear. *PLOS ONE* 7: p.e50611.
- 363 Coetzee, B.W.T. & Chown, S.L. 2016. A meta-analysis of human disturbance impacts on
   364 Antarctic wildlife. *Biol. Rev.* 91: 578–596.
- 365 Colhoun, K. & Cummins, S. 2013. Birds of conservation concern in Ireland. *Irish Birds* 9:
   523–544.
- 367 Department of Communications, Climate Action & Environment [DCCAE]. 2010. The
   368 national renewable energy action plan: Submitted under Article 4 of Directive 2009/28/EC.
   369 Dublin, Ireland.
- 370 Di Minin, E., Slotow, R., Hunter, L.T.B., Montesino Pouzols, F., Toivonen, T., Verburg,
- P.H., Leader-Williams, N., Petracca, L. & Moilanen, A. 2016. Global priorities for
  national carnivore conservation under land use change. *Sci. Rep.* 6: 23814.
- 373 Drewitt, A.L. & Langston, R.H.W. 2006. Assessing the impacts of wind farms on birds.
  374 *Ibis* 148: 29–42.
- Everitt, B., Landau, S. & Leese, M. 2009. *Cluster analysis*. 4th ed. London : New York:
  Arnold ; Oxford University Press.
- Fernández-Bellon, D., Irwin, S., Wilson, M. & O'Halloran, J. 2015. Reproductive output
  of Hen Harriers Circus cyaneus in relation to wind turbine proximity. *Irish Birds* 10: 143–
  150.
- 380 Fernández-Bellon, D., Wilson, M., Irwin, S., Kelly, T.C., O'Mahony, B. & O'Halloran,
- **J.** 2018a. Video evidence of siblicide and cannibalism, movement of nestlings by adults, and interactions with predators in pasting her herrier. *I. Partor Pag.* **52**: 203–200
- interactions with predators in nesting hen harriers. *J Raptor Res.* **52**: 393-399

- **Fernández-Bellon, D., Wilson, M., Irwin, S. & O'Halloran, J.** 2018b. Effects of
- development of wind energy and associated changes in land use on bird densities in upland areas. *Conserv. Biol.* **33**: 413-422.
- Ferrer, M. & Hiraldo, F. 1993. Evaluation of management techniques for the Spanish
  Imperial Eagle. *Biol. Conserv.* 63: 436-442.
- Finney, S.K., Pearce-Higgins, J.W. & Yalden, D.W. 2005. The effect of recreational
  disturbance on an upland breeding bird, the golden plover *Pluvialis apricaria*. *Biol. Conserv.*
- **121**: 53–63.
- Galili, M. 2015. dendextend: an R package for visualizing, adjusting, and comparing trees of
  hierarchical clustering. *Bioinformatics* 31: 3718–3720.
- González, L.M., Arroyo, B.E., Margalida, A., Sánchez, R. & Oria, J. 2006. Effect of
  human activities on the behaviour of breeding Spanish imperial eagles (*Aquila adalberti*):
  management implications for the conservation of a threatened species. *Anim. Cons.* 9: 85-93.
- Hayden, T. & Harrington, R. 2000. *Exploring Irish mammals*. Town House and Country
  House Ltd, Dublin.
- Hynes, S. & Buckley, C. 2007. Recreational pursuits on marginal farm land: a discretechoice model of Irish farm commonage recreation. *Econ. Soc. Rev.* 38: 63–84.
- 400 Irwin, S., Wilson, M., Kelly, T.C., O'Donoghue, B., O'Mahony, B., Oliver, G., Cullen,
- 401 C., O'Donoghue, T. & O'Halloran, J. 2008. Aspects of the breeding biology of Hen
  402 Harriers Circus cyaneus in Ireland. *Irish Birds*. 8: 331-334.
- 403 Irwin, S., Wilson, M., O'Donoghue, B., O'Mahony, B., Kelly, T. & O'Halloran, J. 2012.
- 404 *Optimum scenarios for Hen Harrier conservation in Ireland.* Cork: Department of
- Agriculture, Food and the Marine by the School of Biological, Earth and Environmental
  Sciences, University College Cork.
- Johnson, C.J., Boyce, M.S., Case, R.L., Cluff, H.D., Gau, R.J., Gunn, A. & Mulders, R.
  2005. Cumulative effects of human developments on Arctic wildlife. *Wildlife Monogr.* 160:
- 409 1–36.
- Jolliffe, I.T. & Cadima, J. 2016. Principal component analysis: a review and recent developments. *Philos. Tran. R. S. A.* 374: 20150202.
- 412 Kareiva, P. & Marvier, M. 2012. What is conservation science? *BioScience* 62: 962–969.
- 413 Kaufman, L. & Rousseeuw, P.J. 1990. *Finding Groups in Data*. Hoboken, NJ, USA: John
  414 Wiley & Sons, Inc.
- 415 Kennedy, C.M., Miteva, D.A., Baumgarten, L., Hawthorne, P.L., Sochi, K., Polasky, K.,
- 416 Oakleaf, J.R., Uhlhorn, E.M. & Kiesecker, J. 2016. Bigger is better: Improved nature
- 417 conservation and economic returns from landscape-level mitigation. *Sci. Adv.* 2: e1501021–
  418 e1501021.
- Kuhn, M. 2017. *caret: Classification and regression training*. Available at: https://CRAN.R project.org/package=caret

- 421 Larson, C.L., Reed, S.E., Merenlander, A.M. & Crooks, K.R. 2016. Effects of recreation
- 422 on animals revealed as widespread through a global systematic review. *PLOS ONE* 11(12), p.
- 423 e0167259.
- 424 Maechler, M., Rousseuw, P. Struyf, A., Hubert, M. & Hornik, K. 2018. *cluster: Cluster* 425 *Analysis Basics and Extensions*. Available at: https://CRAN.R-project.org/package=rgdal.
- 426 Marques, A.T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M.J.R., Fonseca, C.,
- 427 Mascarenhas, M. & Bernardino, J. 2014. Understanding bird collisions at wind farms: An
- updated review on the causes and possible mitigation strategies. *Biol. Conserv.* **179**: 40–52.
- 429 Mc Guinness, S., Muldoon, C., Tierney, N., Cummins, S., Murray, A., Egan, S. &
- 430 Crowe, O. 2015. Bird Sensitivity Mapping for Wind Energy Developments and Associated
- 431 *Infrastructure in the Republic of Ireland*. BirdWatch Ireland, Kilcoole, Wicklow. #
- 432 Mead, C.J. 1973. Movements of British raptors. *Bird Study.* 20: 259-286.
- 433 Murgatroyd, M., Redpath, S.M., Murphy, S.G., Douglas, D.J., Saunders, R. & Amar, A.
- 2019. Patterns of satellite tagged hen harrier disappearances suggest widespread illegal
  killing on British grouse moors. *Nat. Commun.* 10: 1094.
- 436 National Parks & Wildlife Service [NPWS] 2015. *Hen Harrier conservation and the* 437 *forestry sector in Ireland*. Dublin, Ireland: National Parks & Wildlife Service.
- 438 O'Donoghue, B. 2010. The Ecology and Conservation of Hen Harriers (*Circus cyaneus*) in
  439 Ireland. PhD thesis. University College Cork.
- 440 O'Donoghue, B., O'Donoghue, T.A. & King, F., 2011. The Hen Harrier in Ireland:
  441 conservation issues for the 21st century. *Biol. Env. Proc. R. Irish Acad.* 111B: 83-93
- 442 O'Riordan, M., Mahon, M. & McDonagh, J. 2015. Power, discourse and participation in
- 443 nature conflicts: the case of turf cutters in the governance of Ireland's raised bog
  444 designations. *J. Env. Policy Plann.* 17:127-145.
- 445 O'Rourke, E. & Kramm, N. 2009. Changes in the management of the Irish Uplands: A
  446 case-study from the Iveragh Peninsula. *Eur. Countryside* 1: 53-66.
- 447 Philip Whitfield, D., Ruddock, M. & Bullman, R. 2008. Expert opinion as a tool for
  448 quantifying bird tolerance to human disturbance. *Biol. Conserv.* 141: 2708–2717.
- Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. & R Core Team. 2017. *nlme: Linear and Nonlinear Mixed Effects Models*. Available at: https://CRAN.R-project.org/package=rgdal.
- 451 **Prestt, I.** 1965. An enquiry into the recent breeding status of some of the smaller birds of
  452 prey and crows in Britain. *Bird Study* 12: 196-221.
- 453 **R Core Team 2017**. *R: A language and environment for statistical computing*. Vienna,
- 454 Austria.: R Foundation for Statistical Computing. Available at: https://www.R-project.org/.
- 455 Redpath, S.M., Madders, M., Donnelly, E., Anderson, B., Thirgood, S., Martin, A.,
- 456 McLeod, D. 1998. Nest site selection by Hen Harriers in Scotland. *Bird Study* 45: 51–61.

- 457 Redpath, S.M., Amar, A., Smith, A., Thompson, D.B. & Thirgood, S. 2010. People and
- 458 nature in conflict: can we reconcile hen harrier conservation and game management. In
- 459 Baxter J. & Galbraith, C.A. (eds) Species Management: Challenges and Solutions for the 21st
- 460 *Century*, 335-350. Stationery Office Books, Edinburgh.
- 461 Renou-Wilson, F., Bolger T., Bullock C., Convery F., Curry J., Ward S., Wilson D. &
- 462 Müller C. 2011. BOGLAND: Sustainable Management of Peatlands in Ireland Final
- 463 *Report.* Johnstown Castle, Co Wexford, Ireland: Environmental Protection Agency.
- 464 Ruddock, M., Mee, A., Lusby, J., Nagle, T., O'Neill, S. & O'Toole, L. 2016. *The 2015*
- 465 *National Survey of Breeding Hen Harrier in Ireland*. Irish Wildlife Manuals No. 93. National
- 466 Parks and Wildlife Service, Department of the Arts, Heritage and the Gaeltacht, Dublin,467 Ireland.
- 468 Ruddock, M. & Whitfield, D.P. 2007. A review of disturbance distances in selected bird
   469 species. Inverness, UK: Scottish Natural Heritage.
- 470 Ruhlen, T.D., Abbott, S., Stenzel, L.E. & Page, G.W. 2003. Evidence that human
  471 disturbance reduces Snowy Plover chick survival. *J. Field Ornithol.* 74: 300-305.
- 472 Smart, J., Amar, A., Sim, I.M., Etheridge, B., Cameron, D., Christie, G. & Wilson, J.D.
- 2010. Illegal killing slows population recovery of a re-introduced raptor of high conservation
  concern–the red kite *Milvus milvus*. *Biol. Conserv.* 143: 1278-1286.
- 475 Smith, J.A. & Dwyer, J.F. 2016. Avian interactions with renewable energy infrastructure:
  476 An update. *The Condor* 118: 411–423.
- 477 Soule, M.E. 1985. What is conservation biology? *BioScience* 35: 727–734.
- 478 Steven, R., Pickering, C. & Castley, J.G. 2011. A review of the impacts of nature based
  479 recreation on birds. *J. Env. Manage*. 92: 2287–2294.
- 480 Suzuki, R. & Shimodaira, H. 2006. Pvclust: an R package for assessing the uncertainty in
  481 hierarchical clustering. *Bioinformatics*. 22: 1540–1542.
- Taylor, A.R. & Knight, R.L. 2003. Wildlife responses to recreation and associated visitor
   perceptions. *Ecol. Appl.* 13: 951–963.
- Thaker, M., Zambre, A., Bhosale, H. 2018. Wind farms have cascading impacts on
  ecosystems across trophic levels. *Nat. Ecol. Evol.* 2: 1854–1858.
- 486 Twining, J.P., Montgomery, I., Fitzpatrick, V., Marks, N., Scantlebury, D.M. & Tosh,
- 487 **D.G.** 2019. Seasonal, geographical, and habitat effects on the diet of a recovering predator
  488 population: the European pine marten (*Martes martes*) in Ireland. *Euro. J Wildlife Res.* 65:
  489 51.
- 490 Vangansbeke, P., Blondeel, H., Landuyt, D., De Frenne, P., Gorissen, L. & Herheyen, K.
  491 2017. Spatially combining wood production and recreation with biodiversity conservation.
  492 *Biodivers. Conserv.* 26: 3213–3239.
- Ward, J.H. 1963. Hierarchical grouping to optimize an objective function. J. Am. Stat.
  Assoc. 58: 236–244.

- 495 Watson, D. 2017. *The Hen Harrier*. London, UK: Bloomsbury Natural History.
- Webber, A.F., Heath, J.A. & Fischer, R.A. 2013. Human disturbance and stage- specific
  habitat requirements influence snowy plover site occupancy during the breeding season. *Ecol. Evol.* 3: 853-863.
- White, C.M. & Thurow, T.L. 1985. Reproduction of Ferruginous Hawks exposed to
   controlled disturbance. *The Condor* 87: 14–22.
- 501 Wilcove, D.S., Rothstein, D., Phillips, A. & Losos, E. 1998. Quantifying threats to 502 imperiled species in the United States. *BioScience* **48**: 607–615.
- Wilson, M.W., Fernández-Bellon, D., Irwin, S. & O'Halloran, J. 2017. Hen Harrier
   *Circus cyaneus* population trends in relation to wind farms. *Bird Study*. 64: 20-29.
- 505 Wilson, M.W., Irwin, S., Norriss, D.W., Newton, S.F., Collins, K., Kelly, T.C. &
- 506 O'Halloran, J. 2009. The importance of pre- thicket conifer plantations for nesting Hen
- 507 Harriers *Circus cyaneus* in Ireland. *Ibis* **151**: 332-343.
- 508 Wilson, M.W., O'Donoghue, B., O'Mahony, B., Cullen, C., O'Donoghue, T., Oliver, G.,
- **Solution Ryan, B., Troake, P., Irwin, S., Kelly, T.C., Rotella, J.J. & O'Halloran, J.** 2012.
- 510 Mismatches between breeding success and habitat preferences in Hen Harriers *Circus*
- 511 *cyaneus* breeding in forested landscapes. *Ibis* **154**: 578-589.
- 512 Young, J., Watt, A., Nowicki, P., Alard, D., Clitherow, J., Henle, K., Johnson, R.,
- 513 Laczko, E., McCaracken, D., Matouch, S., Niemela, J. & Richards, C. 2005. Towards
- sustainable land use: identifying and managing the conflicts between human activities and
- 515 biodiversity conservation in Europe. *Biodivers. Conserv.* **14**: 1641–1661.

516

## Appendix I

Pressure codes and descriptions. Reproduced from Ruddock et al. (2016). Adapted from the EU Birds Directive reporting matrix (http://cdr.eionet.europa.eu/help/birds\_art12).

Code	Description of pressure
A1	Modification of cultivation practices
A2	Agricultural intensification
A3	Mowing / cutting of grassland
A4	Abandonment / lack of mowing
A5	Intensive grazing
A6	Non-intensive grazing
A7	Abandonment of pastoral systems, lack of grazing
A8	Fertilisation (agricultural)
A9	Removal of hedges and copses or scrub
B1	Forest planting on open ground (increase in forest area, planting e.g. on grassland, heathland)
B2	Forest and plantation management & use
B3	Forest replanting (i.e. replanting on forest ground after clear-cutting)
B4	Forest clearance (clear-cutting, removal of all trees)
B5	Thinning of tree layer
B6	Fertilisation (forestry)
B7	Other forest activities (e.g. erosion due to forest clearing, fragmentation)
C1	Hand cutting of peat
C2	Mechanical removal of peat
C3	Wind energy production
D1	Paths, tracks, cycling tracks (includes non-paved forest roads)
D2	Roads, motorways (all paved/ tarred roads)
D3	Utility and service lines (e.g. power-lines, pipelines)
D4	Aircrafts or flightpaths
D5	Improved access to site
E1	Urbanisation, residential and commercial development
E2	Dispersed habitation (i.e. little or no human disturbance)
F1	Nest destruction
F2	Illegal killing (e.g. shooting, trapping, poisoning)
G1	Human intrusions and disturbances
G2	Outdoor sports and leisure activities, recreational activities
G3	Walking, horse-riding and non-motorised vehicles
G4	Motorised vehicles
G5	Off-road motorised driving
G6	Other outdoor sports and leisure activities
G7	Military manoeuvres
H1	Pollution (e.g. water pollution, fly-tipping)
J1	Natural fires
J2	Controlled burning (e.g. strip burning for grouse management)

- J3 Uncontrolled burning (e.g. widespread unmanaged or malicious burning)
- J4 Modification of water levels or waterbodies
- J5 Reduction or loss of specific habitat features (e.g. removal of hedgerows, deep heather, scrub, walls, drains)
- J6 Reduction of prey availability
- J7 Anthropogenic reduction of habitat connectivity (i.e. fragmentation such as by removal of large areas of habitat or creation of barriers between habitats)
- K1 Interspecific faunal relations predation (by other birds e.g. crows)
- K2 Interspecific faunal relations predation (by mammals e.g. foxes)
- X No pressures recorded
- O Other pressures not listed above; noted pressures included bracken encroachment, cattle, drainage, helicopter training, quarrying and shooting.

# Appendix II

Summary data for all survey squares where the total number of pressures was >0. SPA =
location of survey site relative to Special Protection Area (SPA) boundaries: 1 = inside; 0 =
outside. PI = standardised Pressure Index (see main text).

Site number	Total number of pressures	Total number of observer visits	Total number of Hen Harrier territories	SPA	PI
1	1	5	0	0	0.01
2	10	45	0	0	0.02
3	22	16	0	0	0.10
4	8	10	0	0	0.06
5	10	9	0	0	0.08
6	23	8	0	0	0.21
7	5	3	0	0	0.12
8	4	8	0	0	0.04
9	12	6	0	0	0.15
10	34	17	1	0	0.15
11	14	14	3	0	0.07
12	16	14	1	0	0.08
13	19	22	1	0	0.06
14	9	2	0	0	0.33
15	2	3	0	0	0.05
16	4	3	0	0	0.10
17	9	12	1	0	0.06
18	17	35	2	1	0.04
19	9	11	2	0	0.06
20	2	3	0	0	0.05
21	6	30	2	0	0.01
22	7	12	0	0	0.04
23	8	10	1	0	0.06
24	3	5	1	0	0.04
25	6	43	1	0	0.01
26	15	13	1	1	0.09
27	23	78	1	1	0.02
28	10	8	0	0	0.09
29	4	8	0	0	0.04
30	3	13	0	0	0.02
31	3	6	0	0	0.04
32	18	31	0	0	0.04
33	9	9	0	0	0.07
34	20	78	3	1	0.02
35	9	29	0	0	0.02
36	2	6	0	0	0.02
37	2	2	0	0	0.07

38	6	3	0	0	0.15
39	6	5	0	0	0.09
40	5	82	2	1	0.00
41	7	10	1	1	0.05
42	1	44	1	0	0.00
43	13	142	7	1	0.01
44	5	3	0	0	0.12
45	16	21	0	0	0.06
46	3	3	0	0	0.07
47	3	2	0	0	0.11
48	24	8	0	0	0.22
49	3	1	0	0	0.22
50	5	2	0	0	0.19
51	6	11	0	0	0.04
52	19	10	0	0	0.14
53	9	9	0	0	0.07
54	6	2	0	0	0.22
55	26	5	0	0	0.39
56	1	8	0	0	0.01
57	65	23	1	1	0.21
58	95	32	2	1	0.22
59	6	1	0	0	0.44
60	17	3	0	0	0.42
61	122	60	2	1	0.15
62	59	11	0	0	0.40
63	17	11	1	0	0.11
64	6	2	0	0	0.22
65	33	17	1	0	0.14
66	56	40	2	1	0.10
67	68	62	2	1	0.08
68	2	5	0	0	0.03
69	13	79	5	1	0.01
70	17	60	4	1	0.02
71	17	4	0	0	0.31
72	81	50	2	0	0.12
73	1	5	0	0	0.01
74	54	25	0	0	0.16
75	40	21	2	1	0.14
76	8	34	2	1	0.02
77	2	31	0	0	0.00
78	2	43	2	1	0.00
79	33	17	0	0	0.14
80	9	8	0	0	0.08
81	4	1	0	0	0.30

82	2	2	0	0	0.07
83	40	50	2	0	0.06
84	5	12	1	0	0.03
85	54	12	0	0	0.33
86	5	7	0	0	0.05
87	48	36	2	1	0.10
88	2	1	0	0	0.15
89	113	143	5	0	0.06
90	3	1	0	0	0.22
91	74	21	3	0	0.26
92	14	9	0	0	0.12
93	150	60	2	1	0.19
94	19	11	1	0	0.13
95	53	25	2	0	0.16
96	35	15	2	1	0.17
97	73	14	1	0	0.39
98	11	11	0	0	0.07
99	21	26	1	1	0.06
100	5	11	1	0	0.03
101	11	17	1	0	0.05
102	20	5	0	0	0.30
103	15	4	1	0	0.28
104	15	25	0	0	0.04
105	23	10	0	0	0.17
106	6	5	0	0	0.09
107	4	3	0	0	0.10
108	13	11	0	0	0.09
109	5	20	2	0	0.02
110	8	17	1	1	0.03
111	31	15	1	0	0.15
112	85	15	3	0	0.42
113	7	3	0	0	0.17
114	2	9	0	0	0.02
115	26	9	0	0	0.21
116	5	54	2	1	0.01
117	14	4	0	0	0.26
118	2	3	0	0	0.05
119	16	24	0	0	0.05
120	15	9	0	0	0.12
121	6	8	0	0	0.06
122	9	11	0	0	0.06
123	6	8	0	0	0.06
124	4	6	0	0	0.05
125	11	4	0	0	0.20

126	14	7	0	0	0.15
127	8	9	0	0	0.07
128	8	4	0	0	0.15
129	27	19	0	0	0.11
130	10	16	0	0	0.05
131	10	16	0	0	0.05
132	4	2	0	0	0.15
133	13	10	0	0	0.10
134	54	4	0	0	1.00
135	2	1	0	0	0.15
136	14	12	1	1	0.09
137	9	13	0	0	0.05
138	18	10	0	0	0.13
139	6	3	0	0	0.15
140	86	79	1	0	0.08
141	9	8	1	0	0.08
142	23	21	3	0	0.08
143	1	3	0	0	0.02
144	100	23	1	0	0.32
145	1	3	0	0	0.02
146	1	16	0	0	0.00

## **Appendix III**

Linear mixed-effects model results for pressures – expressed as Principal Components (PC) - associated with confirmed Hen Harrier territories (present/absent). Factors retained in the top subset of *n* models ( $\leq \Delta 2$  AIC) are highlighted. Constituent pressures along with pressure codes and associated loadings (coefficients; in parentheses) are given. Pressure codes are taken and descriptions are abbreviated from those given in Ruddock et al. (**2016**; see Appendix I). Regression coefficients ( $\beta \pm SE$ ) and significance of contributory PCs are given, where \* = p < 0.05, \*\* = p < 0.01, and \*\*\* = p < 0.001. For constituent pressures in PC1-3, see Table 2 in the main text.

Principal Component					
(% variance explained)	Pressure	β	± SE	t	
PC1		0.025	0.007	3.52	**
PC2		-0.046	0.009	-5.05	***
PC3		0.044	0.011	-3.91	**
PC4	Non-intensive grazing (A6; 0.51)	0.010	0.013	0.78	
(5%)	Agricultural fertilisation (A8; 0.32)				
	Urbanisation, residential and commercial development(E1; 0.50)				
PC5	Hand cutting of peat (C1; -0.40)	-0.004	0.014	-0.27	
(5%)	Aircrafts or flightpaths (D4; -0.30)				
	Reduction of prey availability (J6; -0.52)				
	Other pressures not listed (O; -0.38)				
PC6	Agricultural intensification (A2; 0.27)	-0.005	0.014	-0.38	
(4%)	Hand cutting of peat (C1; -0.25)				
	Roads, motorways (D2; 0.34)				
	Dispersed habitation, i.e. little or no human disturbance (E2; 0.37)				
	Off-road motorised driving (G5; -0.38)				
	Other outdoor sports and leisure activities (G6; 0.29)				
PC7	Hand cutting of peat (C1; 0.29)	0.006	0.015	0.41	
(4%)	Dispersed habitation, i.e. little or no human disturbance (E2; 0.28)				
	Pollution (H1; 0.26)				
	Modification of water levels or waterbodies (J4; 0.27)				

Reduction of prey availability (J6; -0.27) Other pressures not listed (O; -0.32)

**Table 1.** General Linear Model (GLM) results for regional differences in pressures on Hen Harrier breeding habitat - expressed as a Pressure Index (PI; log transformed). s = Special Protection Areas (SPA; inside/outside); r = confirmed territories (present/absent). Regression coefficients ( $\beta \pm$  SE) and significance of contributory variables are given, where \* = p < 0.05.

Model	Variable	t	$\beta$ (± SE)		
$PI \sim r$	r	0.038	$-0.39 \pm 0.19^{*}$		
$PI \sim s$	S	0.028	$-0.44 \pm 0.20^{*}$		
$\mathrm{PI} \thicksim r + s + r^*s$	S	-0.515	$-0.14 \pm 0.28$		
	r	-0.683	$-0.16 \pm 0.23$		
	$s^*r$	-1.128	$-0.46 \pm 0.40$		

**Table 2**. Linear mixed-effects model results for pressures – expressed as Principal Components (PC) - associated with confirmed Hen Harrier territories (present/absent). Models were evaluated according to their Akaike's Information Criterion (AIC) value. Factors retained in the top subset of *n* models (<  $\Delta 2$  AIC) are highlighted. Constituent pressures along with pressure codes and associated loadings (coefficients; in parentheses) are given. Pressure codes are taken and descriptions are abbreviated from those given in Ruddock et al. (**2016**; see **Appendix I**). Regression coefficients ( $\beta \pm SE$ ) and significance of contributory PCs are given, where \* = p < 0.05, \*\* = p < 0.01, and \*\*\* = p < 0.001. For constituent pressures in PC4-7, see Appendix III.

Principal Component					
(% variance explained)	Pressure	β	± SE	t	
PC1	Abandoned pastoral systems (A7; 0.29)	0.025	0.007	3.52	**
(21%)	Removal of hedges, copse and scrub (A9; 0.29)				
	Forest replanting (B3; 0.27)				
	Nest destruction (F1; 0.29)				
	Controlled burning (J2; 0.27)				
	Predation by birds (K1; 0.31)				
	Predation by mammals (K2; 0.26)				
PC2	Forest management and use (B2; -0.28)	-0.046	0.009	-5.05	***
(10%)	Forest clearance (B4; -0.30)				
	Thinning of tree layer (B5; -0.26)				
	Paths, tracks, forest roads (D1; -0.35)				
	Roads, motorways (D2; -0.33)				
	Natural Fires (J1; -0.30)				
PC3	Dispersed habitation (E2; -0.32)	0.044	0.011	-3.91	**
(7%)	Outdoor sport, leisure and recreation (G2; -0.35)				
	Walking, horse-riding, cycling (G3; -0.42)				
	Motorised vehicles (G4; -0.29)				
	Off-road driving (G5; -0.32)				
	Other outdoor sports and leisure (G6; -0.30)				

PC4	0.010 0.013 0.78
PC5	-0.004 0.014 -0.27
PC6	-0.005 0.014 -0.38
PC7	0.006 0.015 0.41

**Figure 1.** Maps of Ireland showing (**a**) survey squares and Special Protection Areas (SPAs, as indicated by grey polygons), (**b**) the total number of confirmed Hen Harrier territories per square, and (**c**) pressure indices derived from cumulative observations of pressures within each survey square. See Appendix II for square-specific data.

**Figure 2.** Relationships between pressures associated with potentially suitable breeding habitat for Hen Harriers. Pressure codes are taken and descriptions abbreviated from those given in Ruddock et al. (2016). Dashed grey rectangles indicate outermost clusters identified via the silhouette method and multiscale bootstrapping (10,000 iterations; Approximately Unbiased [AU]  $p \le 0.05$ ).  $\bigcirc$  = clusters supported at AU  $p \le 0.05$ . For detailed pressure definitions, see **Appendix I**.









Height

**Code Description of pressure**