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The influence of habitat edge on a ground nesting bird species: hen harrier *Circus cyaneus*

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Anthropogenic-source habitat fragmentation leads to increased habitat edge in the environment, with potential negative consequences for wildlife. We examine the influence of increased edge on a ground nesting bird of conservation concern, the hen harrier *Circus cyaneus*. Using eight years of data collected in the Slieve Bloom Mountains Special Protection Area, central Ireland, and an average breeding population of ten pairs, we investigate how habitat fragmentation and edge influences hen harrier nest site selection, breeding success and productivity. We also used a deterministic population matrix model to assess population breeding trends and to simulate population growth rate responses to increased habitat edge by varying demographic parameters such as productivity and juvenile survival. Our results show that habitat edge had a significant effect on nest site selection, breeding success and productivity. Hen harriers were more likely to nest in areas of high edge/area ratio, but this was associated with lower breeding success and productivity, suggesting a possible ecological trap. This mismatch between nest site selection and breeding output may be linked to this species' high reproductive site fidelity. Our population matrix indicated a population increase, whereas population monitoring indicates population stability. Our simulations suggest that increased edge will have a negative effect on population growth rate, providing a greater understanding of the relationship between hen harrier population trends and changing habitat configuration. These results highlight the importance of contiguous habitats and the need for appropriate land use management in protected upland areas for breeding raptors. Minimising habitat fragmentation and forest edge to create larger blocks of uniform peatland habitat should be an integral part of the conservation management of hen harrier breeding areas both in Ireland and in similar breeding habitats such as those in Britain.

Keywords: afforestation, ecological trap, edge effect, fragmentation, habitat configuration, land use change, population matrix model, predation, raptors, site fidelity

The definition for habitat fragmentation is diverse (Fahrig 2003), but it generally refers to the conversion of continuous habitats to smaller, fragmented mosaics by human activities (Wilcox 1980, Andren 1994). This results in increased habitat edge – the boundary between two different habitat types – which can be detrimental to certain animal species (Reino et al. 2009, Douglas et al. 2014, Pfeifer et al. 2017). Ground nesting bird species in particular are known to respond negatively to increased edge (Batary and Baldi 2004). Across Europe, population declines of many ground nesting birds have been linked to intensification of agriculture and forestry practices (Chamberlain et al. 2000, Wretenberg et al. 2006, Reino et al. 2009, Douglas et al. 2014). Many of these declines are associated with increased habitat edge as new patches are inserted into the existing landscape (Douglas et al. 2014). This highlights the potential impact of edge effects on the demographic patterns of ground nesting birds.

The hen harrier *Circus cyaneus* is a ground nesting species that may be significantly affected by habitat changes and increased edge as a result of its breeding biology (Angelstam 1986, Manolis et al. 2002, Batary and Baldi 2004). The hen harrier is a Species of European Conservation Concern (Fielding et al. 2011, Staneva and Burfield 2017) and listed on Annex I of the EU Birds Directive (2009/147/EC). The latest EU bird status report categorises this species as Near

Threatened (BirdLife International 2015). Breeding hen harriers are associated with open or scrub-dominated habitats (Cramp 1980) and unenclosed pre-thicket forestry (Wilson et al. 2012a, Ruddock et al. 2016). In much of the UK, hen harriers prefer to nest in tall ('rank') heather *Calluna vulgaris*, (Bibby and Etheridge 1993, Redpath et al. 1998). On the island of Ireland, however, hen harriers have been traditionally associated with open habitats (Sweeney et al. 2010, Wilson et al. 2012b). In recent times, the majority of hen harriers in Ireland have also been documented nesting in young, low-lying pre-thicket conifer plantations.

A national survey in 2015 reported 108–157 breeding hen harrier pairs in Ireland (Ruddock et al. 2016), which represents a significant decline compared with the 2010 national survey (128–172 breeding pairs) (Ruddock et al. 2012). This may be because breeding areas for hen harriers are undergoing increasing levels of habitat changes (Burfield and Van Bommel 2004, Wilson et al. 2017). Afforestation is one of the principal causes of habitat change in Ireland, with approximately 11% of the country afforested over the twentieth century (Wilson et al. 2012b, DAFM 2018). The addition of forestry patches into previously contiguous habitats of conservation importance (such as peatlands or unimproved grasslands (Wilson et al. 2012b)) causes habitat fragmentation and increases forest edge (Reino et al. 2009). The resulting increase in habitat edge from forestry may affect breeding hen harriers, e.g. as a result of increased nest predation (Reino et al. 2009, Douglas et al. 2014).

The aim of this study was to determine how habitat edge influences hen harrier nest site selection, breeding success and productivity in the Slieve Bloom Mountains Special Protection Area (SPA) in central Ireland from 2010 to 2017. Additionally, a population matrix model was designed to simulate the consequences of increasing habitat edge for breeding hen harrier. The Slieve Bloom Mountains SPA was chosen for this study due to the stable breeding population of hen harriers in a highly afforested area (i.e. an area with high fragmentation and edge). Hen harriers exhibit reproductive site fidelity (Balfour and Cadbury 1979, Strandberg et al. 2008, Geary et al. 2018), meaning that they return to the same area to breed each year. This may raise challenges for conservation and management of the species, if they continue to return to suboptimal breeding sites. This study was designed to account for this site fidelity in order to determine the best approach for conservation. By accounting for breeding site fidelity, this study takes into consideration that hen harrier nest site selection may be influenced by their site faithfulness rather than their attraction towards certain habitats. Furthermore, it accounts for possible pseudoreplication in data collection. Research has shown that some site faithful birds (such as seabirds) also consider the success of previous breeding attempts when choosing to return to breeding sites (Öst et al. 2011), however, to our knowledge, it is not yet known if hen harriers also consider previous attempts when choosing nesting location. The results of this study will improve our knowledge of the effect of habitat fragmentation on breeding hen harrier and inform the management and conservation of upland breeding habitats for this species and other ground nesting birds which face similar challenges, such as the Eurasian curlew *Numenius arquata* (Douglas et al. 2014).

Material and methods

Study area

The Slieve Bloom Mountains are found in central Ireland. An EU SPA of 21774 ha was designated for hen harriers in the Slieve Bloom Mountains in March 2007 (NPWS 2015a). The top of these mountain plateaux are covered with intact blanket bog (Fossitt 2000) which are unsuitable for nesting hen harrier due to the flat topography and wet substrate. The majority of the mountain slopes comprise forestry plantations of non-native sitka spruce *Picea sitchensis* and lodgepole pine *Pinus contorta* interspersed with narrow bands of remnant dry heath. The dry heath is not regularly burned under current management practices (Fossitt 2000, Monaghan 2010–2016, NPWS 2015a). The forestry plantations comprise 60% of the SPA (NPWS 2015a) and planting mostly occurred prior to its designation. There were no changes to the habitat composition of this SPA during the course of this study. In order to demonstrate the habitat configuration of open and closed (forest) habitats found in the Slieve Bloom Mountains SPA, a classification map was created manually using ArcGIS satellite imagery (at a scale of 1:30 000) (Fig. 1). The classifications comprise 'Open' (peatland habitats, heath/bog mosaics, rough grassland), 'Forest' (any forest plantations at pre-thicket or thicket stage) and 'IAG' (improved agricultural grassland). In situations where it was unclear if a habitat was rough or improved agricultural grassland, this was included in the 'Open' category.

Hen harrier data

Data on breeding success, productivity and nest site selection were sourced from the hen harrier Slieve Bloom Mountains Breeding Reports 2010–2017 (Monaghan 2010–2016, unpublished records 2017). Breeding success was a binary response variable measured by whether nests were unsuccessful (no chicks fledged) or successful (at least one chick fledged). Productivity was measured as the number of fledglings produced in the nest. Nest site selection was the dominant habitat within 10 m^2 of the nest site location selected by hen harriers.

For nest site selection data, locations of confirmed nest sites were plotted on satellite imagery using ArcGIS (ver. 10.4, 2017). The linear distance of each nest to the nearest forestry edge, improved agricultural grassland edge, track edge (i.e. roads, dirt tracks, walking paths) and bog edge was measured using the ArcGIS measuring tool at the end of the eight year study period (November 2019) and interpreted from 1:2000 colour satellite imagery dating between three to five years in age. Also, the total area of contiguous habitat and habitat edge surrounding nest locations was measured to provide an edge/area ratio (i.e. the measured edge of a habitat patch, divided by the measured area of that patch). An edge/area ratio represents how fragmented a patch is (i.e. higher edge/area ratios indicate more fragmented habitat patches), and is used in similar studies on edge effect (Reino et al. 2009, McMahon et al. 2010). For nests found in areas of open, contiguous habitats (blanket bog, heath or grassland), habitat edge was defined as the boundary where the open area met surrounding forest or track edge. These open patches

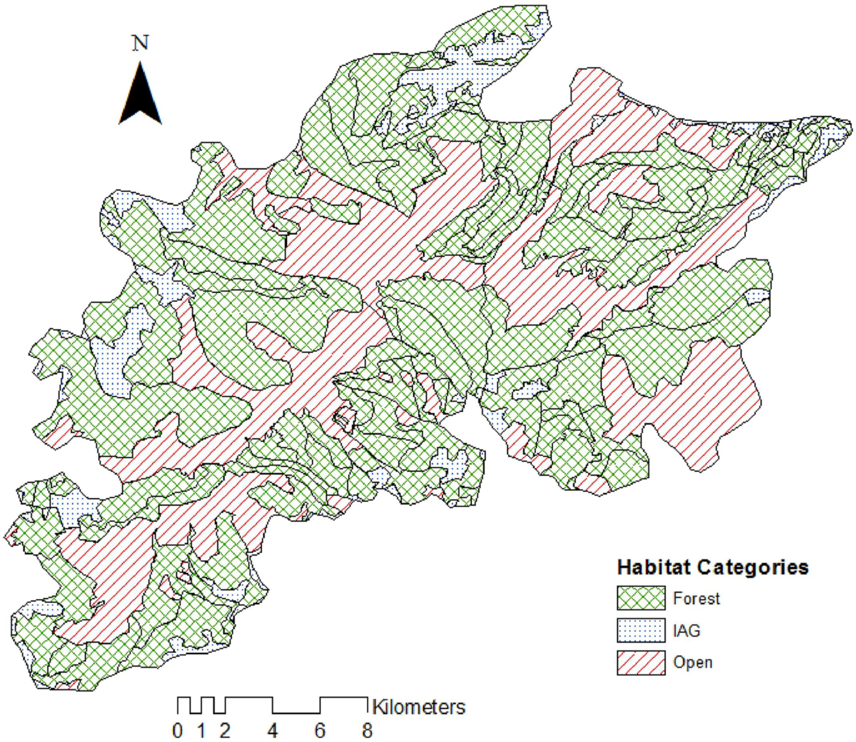

Figure 1. A classification map of the Slieve Bloom Mountains SPA with habitats assigned manually to three categories: 'Open' (peatland habitats, heath/bog mosaics, rough grassland), 'Forest' (any forest plantations at pre-thicket or thicket stage) and 'IAG' (improved agricultural grassland).

were often large, with less edge, resulting in smaller edge/area ratios. For nests found in forestry, habitat edge was defined as the boundary where the forest met open contiguous habitats or a track edge (roads, dirt tracks, walking paths). These forest patches were most often smaller, with more edge, resulting in higher edge/area ratios. These variables (distance to forestry edge, improved agricultural grassland edge, track edge, bog edge and total edge and area) were measured in kilometres. They were then standardised by subtracting the mean and dividing by the standard deviation because the values between variables had large ranges (distances from less than one to more than 5 km).

To account for non-random variation in the analysis of nest site selection, random points were generated using ArcGIS throughout the area of the Slieve Bloom Mountains SPA, with 30 random points allocated per year (240 random points in total). These random points were compared with the nest locations of hen harriers. A difference between nest locations and random points would indicate that nest locations are not chosen randomly by harriers in relation to the explanatory variables in this study, while no difference would indicate random choice, as in similar studies by Redpath et al. (1998) and Wilson et al. (2009). As with the analysis for confirmed nest locations, distance to forestry edge, improved agricultural grassland edge, track edge and bog edge and, total edge and area were also calculated for random points using ArcGIS.

Statistical modelling

Three response variables were investigated in this study: 1) nest site selection (selected or not selected); 2) breeding success (success or failure); and 3) productivity (number of fledglings). We investigated the effect of edge on the response variables using the R programming and language environment ver. 3.4.1 (<www.r-project.org>). The first two variables comprised binomial data and were tested with a generalized linear mixed model (lme4 package; Bates et al. 2015) with binomial errors. The productivity variable comprised ordinal categorical data and was tested with a cumulative link mixed model (ordinal package; Christensen 2019). The productivity variable was ranked from the lowest category of zero chicks to the highest category of four chicks. The cumulative link model evaluated the probability of observations in low or high categories. The randomly generated points described in the previous section were included in models analysing nest site selection only. To account for the difference in hen harrier breeding between open and forested habitats, these groups were analysed separately.

In each model, seven explanatory variables were: distance to forestry, distance to improved agricultural grassland, distance to human-made track, distance to bog, edge, area and edge/area ratio (Table 1). Two random effects were specified: block and year. Block was derived by investigating nest clusters across the eight years of the study. Nests fell into five clusters; it is likely that this clustering was caused by adults returning to the same area to breed in multiple years (reproductive site fidelity). This would lead to pseudoreplication if all breeding attempts were treated as independent events (Vergara et al. 2006, Burke et al. 2015). Therefore, five blocks were assigned; one to each cluster of nests (A1, A2, B1, C1 and C2) (Fig. 2). The distance within and between blocks was calculated to give an indication of the proximity

Table 1. Description of variables used in mixed models.

Variable	Variable type	Possible response	Description
Nest site selection	Response (binomial)	Yes:No	The site where adult pairs select to build their nest
Breeding success	Response (binomial)	0:1	The success (at least one chick fledged) or failure (no chicks fledged) of a nest
Productivity	Response (ordinal categorical)	0:1:2:3:4	The number of chicks to successfully fledge a nest
Nest habitat	Explanatory		Predominant habitat type where the nest is found within 10 m²
Edge	Explanatory		The perimeter surrounding a nest site (km), limited by habitat change
Area	Explanatory		The total area surrounding a nest site (km²) limited by habitat edge (max: 16 km²)
Edge/Area ratio	Explanatory		Ratio of edge (km) to area (km²) of nest habitat
Distance from forestry	Explanatory		Distance (m) to nearest patch of forest
Distance from peatland	Explanatory		Distance (m) to nearest peatland
Distance from agriculture	Explanatory		Distance (m) to nearest improved agricultural grassland
Distance from track	Explanatory		Distance (m) to nearest human made track
Year	Random effect		Year of nest recording (2010–2017)
Block	Random effect		Five geographical groupings based on clusters of nests recorded over eight years

between nest points within each block, and the proximity of one block to another (Table 2). The method of including block as a random effect was also used with this species in a previous study (Redpath et al. 2001).

A process of stepwise deletion followed by stepwise addition was undertaken for all models to remove non-significant variables from a maximal model. Non-significant variables were identified using likelihood ratio tests and removed until the minimal adequate model was reached (Crawley 2012, McMahon et al. 2013). The parameters included in the maximal model and final models are presented in Table 3.

Population matrix model

A deterministic population matrix model was used to simulate the growth rate of the hen harrier population according to productivity and survival rates (popbio package; Stubben and Milligan 2007; diagram package; Soetaert 2017) in R. Estimated survival, productivity and population sizes between 2010 and 2017 were calculated for three age classes: juveniles, subadults and adults (Whitfield and Fielding 2009) (Table 4). Survival rates for all three age classes were derived from literature (Etheridge et al. 1997, Whitfield and Fielding 2009, Ruddock et al. 2016) and this study: juvenile survival – 21%; subadult survival – 78%; adult survival – 78% (this assumes that survival rates are generally similar between males and females). As part of monitoring in the Slieve Bloom Mountains, four juveniles were tagged across two years (two in 2016 and two in 2017 (Monaghan 2010–2016), of which one bird survived to the age of one year. Although a small sample size, this value is lower than that recorded in a study of UK birds by Etheridge et al. (1997) (36%). It is possible that the survival value for Irish birds would be different to UK birds on moorlands managed for

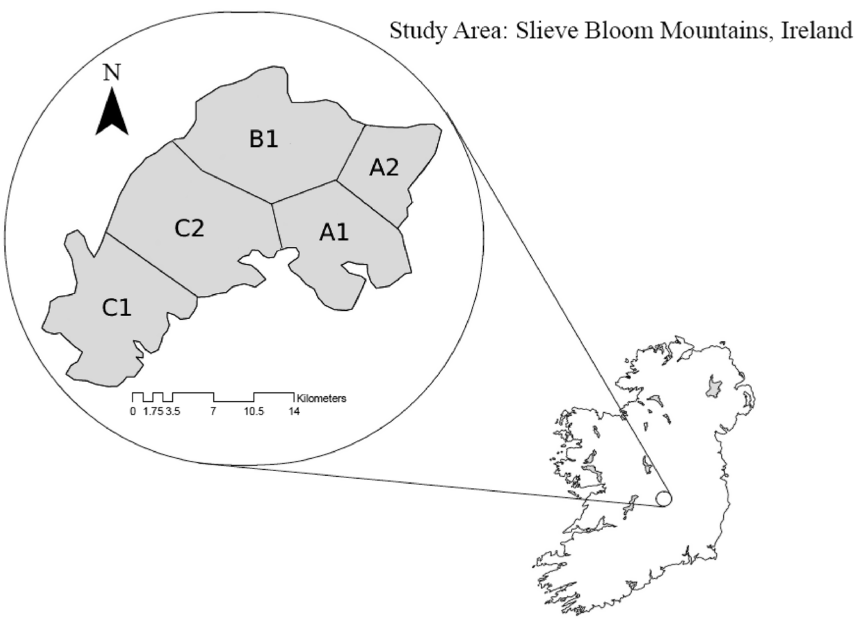

Figure 2. Location of the Slieve Bloom Mountains in Ireland with sub-sites (Blocks A1, A2, B1, C1 and C2) used in the analyses. Block selection was based on how clusters of previous nest sites fell.

Table 2. The average distance (km) within and between five nest blocks (A1, A2, B1, C1 and C2) in the Slieve Bloom Mountains. The 'Within' column shows the average distance between nests within each block as well as total average in the bottom row. The 'Between' column shows the average distance of each block to the other four blocks, as well as the total average in the bottom row. The symbol 'σ' refers to the standard deviation calculated for both 'Within' and 'Between' columns.

Block	Within	σ	Between	σ
A1	3.05	0.77	11.00	7.08
A2	3.09	0.66	17.19	10.49
B1	3.63	1.20	12.67	9.19
C1	3.61	0.71	22.95	7.62
C2	4.47	1.37	12.89	4.32
Total	3.57	0.57	15.34	2.33

game. Ruddock et al. (2016) reported juvenile survival rates at 16% in their study of Irish hen harriers. The average of these two survival rates for Irish juvenile hen harriers (25% and 16%) was taken to give a juvenile survival rate of 21%. For adult survival rates, a value of 78% reported by Ruddock et al. (2016), similar to that of a study on Welsh hen harrier (Whitfield and Fielding 2009), was incorporated into the model. Following methodology described by Whitfield and Fielding (2009), subadult survival rate was equal to adult survival rate (78%) as the authors proposed that birds aged Year 1 or more would have equal survival rates (Table 2). The age of first breeding for female hen harriers is Year 1 (Etheridge et al. 1997, Whitfield and Fielding 2009). As breeding age for female and male harriers can differ (Whitfield and Fielding 2009) and as males may also be polygamous (Whitfield and Fielding 2009), a female-only

Table 3. The final mixed models testing the effect of distance to forestry, distance to agriculture, distance to track, distance to bog, edge, area and edge/area ratio on nest site selection, breeding success and productivity (as seen in the maximal model in the top of the table). Nests in open habitats (bog, heath, acidic grassland) and pre-thicket forestry were tested separately. No significant variables were found in models for forest habitat nests, therefore the null models are presented below. A description of the variables is presented in Table 1.

Maximal model
Y ~ Edge/Area ratio + Edge + Area + Distance from forestry + Distance from peatland + Distance from track + Distance from agriculture + Nest habitat +(1|Year)+(1|Block)
Final models – open habitat nests (n = 68)
Nest site selection
glmer(Nest ~ Edge/Area + Edge + Distance from forestry + Distance from peatland + (1|Year) + (1|Block), binomial)
Breeding success
glmer(Success ~ Edge/Area + (1|Year) + (1|Block), binomial)
Productivity
clmm(Productivity ~ Edge/Area + (1|Year) + (1|Block), link = 'logit', threshold = 'symmetric', Hess = TRUE)
Final models – forest habitat nests (n = 10)
Nest site selection
glmer(Nest ~ 1 + (1|Year) + (1|Block), binomial)
Breeding success
glmer(Success ~ 1+(1|Year) + (1|Block), binomial)
Productivity
clmm(Productivity ~ 1 + (1|Year) + (1|Block), link = 'logit', threshold = 'symmetric', Hess = TRUE)

Table 4. The three age classes used in the population matrix model and their respective values. Population size and reproductive value refers to female harrier only, by dividing original values by two. The values for population size represent the starting values for a female hen harrier population in the Slieve Bloom Mountains in 2017.

Age class	Survival rate	Reproductive value	Population size (n)
Juvenile	0.21	0	7.5
Subadult	0.78	0	1.5
Adult	0.78	5.6	9.5

model was calculated. Female-only models are commonly used in population modelling as potential rates of population growth are typically limited by female reproduction rates (Whitfield and Fielding 2009, Monadjem et al. 2012).

Informed by the harriers' breeding biology, a stage-based, post-breeding census model was used to construct the population matrix model. This model assumes that only adults produce offspring, but also includes the probability that a subadult (year 1) will breed and be classed as an adult (calculated as 0.72; Whitfield and Fielding 2009). The values used in the design of this matrix model are based on the 2017 hen harrier breeding population but the reproductive values were calculated based on the average number of female chicks fledged over the eight years of this study (5.6 female chicks per year). The population sizes of juvenile (year 0), subadult (year 1) and adult birds (year 1+) were calculated using our own study data and divided by two to produce a female-only model (chicks, 7.5; subadults, 1.5; adults, 9.5). Fledgling sex ratio appears to vary over time in some populations, with a greater proportion of female fledglings observed in an Orkney population during the 1960s and 1970s, but a greater proportion of males observed during the 1970s and 1980s (Picozzi 1984). More recent studies suggest that sex ratio at birth may be closer to a 1:1 ratio (Whitfield and Fielding 2009). Without confirmation of the sex ratio of hen harriers at birth in the Slieve Bloom population, a 1:1 ratio was assumed for the population matrix model in this study. A juvenile population size of 15 was included, based on numbers of chicks (year 0 birds) fledged in 2017. The population sizes of subadult (year 1) birds was calculated by taking the number of chicks fledged (year 0) in 2016 multiplied by their probability of surviving to the next year. This resulted in a possible 3 subadults in 2017. There were 22 breeding adults observed in 2017 and, as previously estimated, there were 3 subadults, therefore a final total of 19 adults in 2017 was calculated.

The population matrix model provides a value for the growth rate of a population (λ). A population growth rate less than 1 indicates a population decrease and above 1 indicates population increase (Werner and Caswell 1977). As immigration and emigration rates were not recorded as part of this study, they were not included in the population model, therefore the growth rate of this model should not be regarded as a direct representation of the breeding population in the Slieve Bloom Mountains. Instead, this population model indicates possible drivers of change in population growth rate and can also be used to indicate how this growth rate might change in response to edge/area ratio.

An eigenanalysis was run to show the sensitivity and elasticity of each element of the population matrix model (Table 5).

Table 5. Sensitivities and elasticities of hen harrier survival and productivity rates at different age categories.

	Juvenile survival	Subadult survival	Adult survival	Adult productivity	Population growth rate (λ)
Sensitivity	1.14	0.24	0.56	0.05	
Elasticity	0.20	0.04	0.36	0.20	
					1.21

Sensitivity is a measure of absolute change of each element, while elasticity is used to standardise the sensitivity values by providing a proportional change of each element. As such, elasticity values are comparable and can indicate which components of the matrix model have the most influence on growth rate. Following this, the productivity and juvenile survival rates within the population model were randomly varied using values taken from previous empirical studies in order to estimate potential changes in the population in response to changing habitat configuration (Fig. 3). Population growth rate was calculated from these values to simulate different edge/area ratio scenarios. We varied juvenile success rate to investigate the effect of edge on breeding success, as an effect on breeding success would also impact the survival rate of juvenile birds.

Results

Hen harrier breeding numbers from 2010 to 2017 from the Slieve Bloom Hen harrier Breeding Seasons reports (Monaghan 2010–2016) and unpublished records (2017) are presented in Table 6. All 78 nest sites identified in these reports were located within the Slieve Bloom Mountains SPA during our study. The number of breeding hen harriers recorded each year remained broadly stable over the course of the study (Table 6). The average number of chicks fledged per pair was 1.19.

Nest site selection, breeding success and productivity

Of the 78 nests recorded, 87% were found in peatland habitats (n = 68). The remainder were recorded in pre-thicket forestry (13%, n = 10). Of the 240 randomly generated points, 33% were found in open peatland (n = 78), 59% were in forest (n = 142) and 8% were found in improved agricultural grassland (n = 20). Of nests found in peatland habitats, 47% were successful, while only 20% of nests found on forestry were successful. The majority of data points (nests and random points, n = 166) in the 'open habitat nests' model were found in peatland habitats (88%, n = 146), with 12% (n = 20) found in improved agricultural grass (random points only). Of nests recorded in pre-thicket forestry, our model detected no significant effects of distance to improved agricultural grassland, distance to human-made track, distance to bog, edge, area or edge/area ratio on nest site selection, breeding success or productivity. Note that the variable 'distance to forest edge' was not included in this model as the distance to these nests was zero. Of nests recorded in open habitats, our nest site selection model detected a significant positive effect of edge/area ratio on nest site selection: as edge/area increases by one standard deviation, the probability of hen harriers nesting in that site increases by a factor of 3.38 (95% CI 1.58–7.24). Similarly, a positive relationship with edge was observed: as edge increases by one standard deviation, the probability of hen harriers nesting in that site increases by a factor of 4.27 (95% CI 2.35–7.74). Furthermore, distance to forestry and distance to peatland had a significant negative effect on nest site selection. As distance from forestry increases by one standard deviation, probability of nesting decreases by a factor of 0.35 (95% CI 0.16–0.77) and as distance from peatland increases by one standard deviation, probability of nesting decreases by a factor 0.003 (95% CI 0.00–0.47). Our models also revealed that, edge/area ratio had a significant negative effect on both breeding success and productivity; as edge/area increases by one standard deviation, probability of breeding success decreases by a factor of 0.29 (95% CI 0.09–0.93) and probability of observations in high productivity categories (i.e. greater number of fledglings) decreases by a factor of 0.36 (95% CI 0.10–0.91).

Population matrix model

The initial population matrix model predicted an annual population growth rate of 1.21 (21%) (Table 5). The proportional change of each element (elasticity) indicates that variation in adult survival has the greatest proportional impact on population growth rate. This is followed by adult productivity and juvenile survival rates (Table 5). When we randomly varied the productivity and juvenile survival

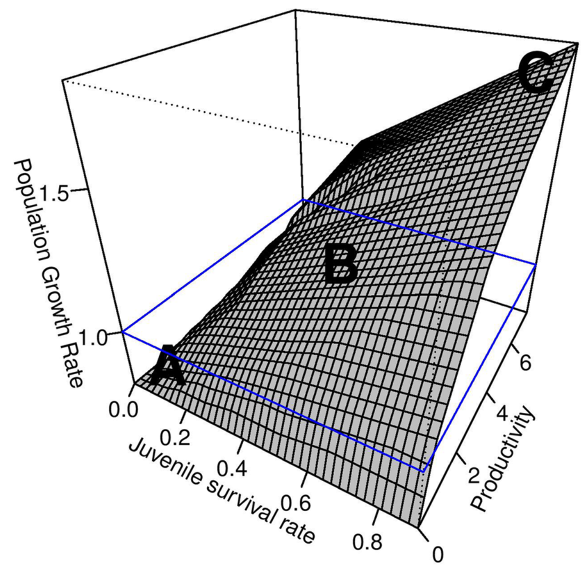

Figure 3. Juvenile survival rates and productivity were randomly varied and population growth rate calculated from these values in order to visualise how the Slieve Bloom hen harrier population might respond to changes in habitat configuration such as edge/area ratio. Three positions on the plot (A, B and C) represent areas of high, medium and low edge/area ratio respectively. The blue line on this graph indicates the point at which the population is stable (λ = 1).

Table 6. A summary of hen harrier breeding parameters recorded in the Slieve Bloom Mountains through 2010–2017 (data from Slieve Bloom Hen harrier Breeding Seasons Reports 2010–2016; Monaghan 2010–2016 and unpublished records 2017).

	2010	2011	2012	2013	2014	2015	2016	2017	Average
Breeding pairs	7	10	10	10	8	12	10	11	9.75
Successful nests	6	2	2	5	4	6	3	6	4.25
(%) Successful	86	20	20	50	50	50	30	55	45.13
Chicks fledged	15	6	4	15	14	14	6	15	11.13
Avg chick per pair	2.14	0.6	0.4	1.5	1.75	1.17	0.6	1.36	1.19

values, the population growth rate responded as expected: when juvenile survival rates are high, population growth rate increases, despite low productivity. But if juvenile survival rates are low, population growth rate will decrease even if productivity is high. Population growth rate was stable ($\lambda = 1$) when juvenile survival rate was above 0.21 and productivity was above 2 (i.e. 21% of the juvenile population in this SPA survived and an average of 2 female chicks per year were produced) (Fig. 3). If productivity in the Slieve Blooms SPA were to remain at the current level (5.6 female chicks per year), juvenile survival rate must stay above 0.075 for the population to remain stable. However, this would require a significant change to habitat configuration involving a reduction in juvenile survival rate of 13.5%. In theory, if a new 200 m by 200 m patch of forestry was added to pre-existing forestry in the Slieve Blooms SPA, this would result in a lower edge/area ratio for that modified patch (decreasing the average forest patch ratio by 0.9). Clearfelling a similar sized patch would have the opposite effect, increasing the edge/area ratio (increasing ratio by 2.7). In much of the Slieve Bloom Mountains, these forest patches are directly adjacent to patches of open contiguous landscape, so while the addition of a new patch of forest might reduce the edge/area ratio of the forest patch, it could also result in higher ratios and fragmentation for the open landscape patch (increasing the average open habitat patch ratio by 0.04).

Discussion

This study highlights the importance of habitat configuration in the management of breeding hen harriers. Although hen harriers in Ireland are associated with fragmented sites, their breeding success and productivity appear to respond negatively to habitat fragmentation and edge. This suggests that heterogeneous and mosaic forest-open landscapes could have negative implications for this species, especially if edge/area ratio in these landscapes continues to increase due to human activities such as agriculture and forestry. From a management perspective, it appears that hen harriers and other ground nesting birds of conservation concern, such as Eurasian curlew, would benefit from more homogenous blocks of suitable nesting and foraging habitat in the breeding grounds, with fewer isolated patches of high edge/area habitat, such as small forestry plantations (Fahrig et al. 2011, Douglas et al. 2014). The weaker relationship between nest site selection and distance to forestry suggest that habitat composition (i.e. the coverage and variety of habitats found around nests) may be of less importance to hen harrier compared to habitat configuration (i.e. the shape and pattern of habitat distribution) (Fahrig et al. 2011).

Our small sample size for nests found in forestry may explain the lack of significant relationships with our nest site selection, breeding success or productivity models. It is possible that further analysis of a larger sample size of hen harrier nests within forest habitats could yield significant relationships with the variables in this study. Nonetheless, our nest site selection model (Table 7) indicates a significant positive association between areas of high edge and edge/area ratio and hen harrier nest site choice, but a negative association with distance to forestry and distance to peatlands. This means that as edge and edge/area ratio increases, the likelihood of hen harriers nesting in that site increases, but as distance to forestry and distance to peatland habitats increase, the likelihood of hen harriers nesting in those site decreases. This suggests that hen harriers select for areas close to forest and peatland edge. While it is possible that hen harriers actively select nests close to forest edge, it could also be that available areas containing the most suitable nesting habitat are also near forest edge (Monaghan 2010–2016). In the Slieve Blooms SPA, the majority of suitable heather for nesting is found in narrow bands on the mountains' slopes adjacent to forestry edge. It is also important to consider the site fidelity element of hen harrier nesting, as hen harriers could continue to return to a breeding site even during land use or habitat configuration changes.

The possibility of a mismatch between hen harrier nest site selection and their relationship with some habitats was

Table 7. Results of mixed models testing the effect of distance to forestry, distance to agriculture, distance to track, distance to bog and edge/area ratio on nest site selection, breeding success and productivity including nests found in open habitats (bog, heath, acidic grassland) only. Only variables with $p < 0.05$ are presented. The variables presented in the table below include the total number of variables included in the final model for open habitat nests.

Response	Explanatory	Estimate	Standard error	χ^2	p
Nest site selection	Edge	1.451	0.304	25.60	<0.005
	Edge/Area ratio	1.218	0.388	7.59	<0.01
	Distance from forestry	−1.036	0.394	10.90	<0.001
	Distance from peatland	−5.751	2.549	10.90	<0.001
Success	Edge/Area	−1.246	0.599	9.06	<0.005
Productivity	Edge/Area	−1.208	0.566	10.19	<0.005

discussed in previous studies (Wilson et al. 2009, Wilson et al. 2012a). Wilson et al. (2009) discuss hen harrier preference for nesting in second rotation forestry despite higher predation pressure. In 2012, Wilson et al. also discussed a mismatch between breeding success and habitat preference. This study found a negative relationship towards forest habitat in one of the three study areas only. Both studies also discuss the possibility of hen harriers experiencing an ecological trap. An ecological trap occurs when a low quality habitat that is selected by organisms over a higher quality habitat (Dwernychuk and Boag 1972). Ecological traps have the potential to drive a population to extinction. They are primarily found in habitats modified by human activity (Battin 2004). The results of our study also support the possibility of an ecological trap for hen harriers nesting in open habitats in the Slieve Blooms SPA in relation to edge/area ratio. This trap could occur as a result of hen harrier site fidelity if the birds continue to return to habitats which become suboptimal for breeding. As such, breeding success and productivity may be more reliable indicators of habitat quality as these variables are not influenced by hen harrier site fidelity. However these variables may still be affected by other external factors, such as predation (Reino et al. 2009, Ludwig et al. 2017).

Edge estimates in the breeding success and productivity models had large confidence intervals. It is likely that other factors not included in this study (such as predation, prey abundance or adverse weather conditions) also affect breeding success and productivity and contribute to the variability in the effect of edge. In our study, we define habitat edge (for nests in open habitats) as where this open habitat meets either forest edge or track edge. One possible explanation for the negative relationship found between edge/area ratio and breeding success and productivity could be the particularly high levels of forest edge in these fragmented areas and its impact on predator–prey dynamics (Batary and Baldi 2004). Studies have shown that increased forestry edge can lead to an increase in generalist ground predators such as red fox *Vulpes vulpes* or pine marten *Martes martes* (Kurki et al. 1998, Douglas et al. 2014) as well as avian predators that perch in trees such as corvids (Andren 1992) and raptors (Newton et al. 1982). Douglas et al. (2014) found that changing habitat configuration (as a result of afforestation) could reduce breeding success in ground nesting birds, mainly due to higher rates of predation in adjacent open landscapes. Douglas et al. (2014) also concluded that an increase of woodland cover would require a significant increase of human predator control efforts to maintain a stable breeding population of ground nesting birds and that the removal of isolated forestry plantations (and subsequent removal of edge effects) would reduce predation pressure.

Our population matrix model indicates that adult survival rates have the greatest proportional impact on population growth rate. This model indicates a population increase in line with the Hen harrier Project 2018 and 2019 which report an increasing/stable population (10 confirmed breeding pairs for both years). The model also highlights the importance of preserving and improving the habitat quality of the extant breeding population of hen harrier in the Slieve Bloom Mountains. It indicates potential adverse impacts to this population should adult survival rates decrease (e.g. due to increased predation rates or limited prey availability). This model and Fig. 3 can be used to consider how sensitive this estimated population growth rate could be to variation in habitat configuration. The results of our study indicate that higher edge/area ratio (as a result of habitat fragmentation) may negatively affect productivity and breeding success which, in turn, may negatively impact population growth rate. We acknowledge that this study investigates the response of breeding hen harriers to habitat edge at a small scale (average patch size 7 km^2). A larger landscape scale could, for example, result in positive relationships with edge as a result of increased prey availability within harrier foraging ranges.

The pressures of increased habitat edge and fragmentation, afforestation and intensive agriculture faced by hen harrier in Ireland can be found elsewhere across Europe. However, the main pressures faced by hen harrier differ geographically. While predation levels appear to be a primary pressure on Ireland's breeding hen harrier, it is less significant in Britain, where predation levels are lower in managed moorland (Ludwig et al. 2017). Nonetheless, hen harrier on managed moorland in Britain face different pressures such as illegal persecution (Ludwig et al. 2017). Human–wildlife conflict and illegal persecution occur to a lesser extent in Ireland (Wilson et al. 2010, Bonsu et al. 2019), especially regarding the designation and management of Irelands' six hen harrier SPAs (Bonsu et al. 2019).

While our results indicate that hen harriers nest sites are associated with increasing proximity to forestry, an increase in forestry could have adverse implications for hen harriers due to increased habitat edge and fragmentation. Ireland has one of the highest rates of forest expansion in Europe (Kuemmerle et al. 2016) and forest cover grew from 6.8% of total land use in 1980 to 10.6% in 2014 (Central Statistics Office 2016). Across Europe, the situation is similar (Madsen 2002). Although planting on peatland habitats in Ireland is being phased out, the primary target habitat for afforestation is now rough grassland, another important hen harrier habitat for hunting (Amar and Redpath 2005). Furthermore, pre-thicket forest nesting habitats will decline in future years as existing forests within this SPA continue to mature (NPWS 2015b), meaning that a reduction in new plantations and protection (and restoration) of open, contiguous and intact peatland habitats will be of core importance for hen harriers in the future.

Conclusions

Habitat edge and edge/area ratio were positively associated with hen harrier nest site selection in our models. In contrast, edge/area ratio appears to have had a negative effect on breeding success and productivity. These results suggest a plausible ecological trap. We believe it is unlikely that these birds actively choose fragmented areas, but that the only nesting habitat available to them is found in high edge/area sites. Our results also suggest that habitat composition is less important to nesting harriers and that habitat configuration plays the more important role in breeding outcome. The population matrix model suggests that the Slieve Blooms hen harrier population is increasing, with variation in adult survival having the greatest proportional impact. However without immigration/emigration rates, this is not a direct representation of the true status of this population. Nonetheless, the matrix model does indicate that a negative impact of increased edge/area ratio on productivity and survival rates could cause the population to decline. The management implications of our findings are that sufficient areas of unfragmented, low edge/area ratio habitat need to be preserved and, where possible, enhanced for breeding hen harrier. Decreasing the edge/area ratio of open peatland/heath nesting resource via a managed retreat of the surrounding conifer plantations by way of a medium to long-term forestry plan could benefit hen harrier and other ground nesting birds of conservation concern.

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