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The impact of urban development and human disturbance on the numbers of nightjar *Caprimulgus europaeus* on heathlands in Dorset, England

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Abstract

The factors influencing the number of nightjars on 36 heathland sites (referred to as patches) in Dorset, England were examined using novel spatial integration of existing datasets. Surrogate measures of human density and settlement, including the amount of developed land at different distances from the heath (obtained from aerial photographs) and the actual number of buildings (obtained from Post Code databases) were all found to be highly correlated with each other and to show a strong negative relationship with the density of nightjars present on a patch, regardless of patch size. The amount of woodland (the preferred foraging habitat) surrounding each patch (within 500 m of the patch boundary) was also a significant predictor of nightjar numbers. When used together, the extent of woodland and developed land both gave significant improvements to predictions of nightjar density. The results indicate that the number of nightjars present on a heathland patch is influenced by the surrounding land-use and that the effect of urban development is more than just habitat loss. We suggest that trends identified are at least partly due to actual human presence on the heathlands and as such, human disturbance is potentially a problem for this species.

Keywords: Nightjar; Human disturbance; Urban development; Habitat loss; Heathland; Recreational access; Postcode

1. Introduction

Lowland Heathland is one of the priority habitats for conservation in England (HMSO, 1995). One of the key pressures associated with heathlands is urban development and the proximity of large human populations, because heathland occurs predominantly in southern England. Haskins (2000) highlights the variety of factors, associated with built development, which may compromise the conservation priorities of an adjoining heathland site. Of these factors, human disturbance is one of particular current interest. The passage of the Countryside and Rights of Way Act in November 2000, which will allow open access to heathlands, focused attention on the need for more research to address the relationship between access to the countryside and bird conservation (Liley, 2001). The effects of human disturbance on birds have been reviewed by several authors (see Sidaway, 1990; Hockin et al., 1992; Carney and Syderman, 1999; Nisbet, 2000) and disturbance has been shown to reduce population size in at least one species (Liley, 1999). However, very few studies have focused on heathland bird species and our knowledge of the impact of disturbance on these species is largely anecdotal. Liley (2001) recommended that this was one of the groups of species that should be targeted for future research.

The nightjar *Caprimulgus europaeus* is one of the key bird species associated with lowland heathland in the British Isles. It is identified as a species of European Conservation Concern (Annex 1 of the Birds Directive), is included on the 'Red List' of species of conservation concern (Anon, 1996; Gregory et al., 2002) and is a priority species under the UK Biodiversity Action Plan (HMSO, 1998). The species is a summer migrant to

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Britain, arriving in May, nesting on open heathland or open ground in conifer plantations. A feature of the nightjars' ecology is that they often forage away from their nesting areas, with studies in Dorset showing that radio-tagged birds travel an average of 3.1 km to feed (Alexander and Cresswell, 1990). Studies have shown that nightjars prefer to feed in semi-natural habitats (Alexander and Cresswell, 1990; Sierro et al., 2001), especially deciduous woodland (Cresswell, 1996). Nightjars are ground nesting species, with nest sites situated on open ground. One of the few studies of breeding nightjars (Berry, 1979) identified human disturbance as a possible cause of breeding failure. The species is therefore one where there is potentially cause for concern regarding human disturbance.

The Dorset Heathlands provide an ideal location for a study on the impacts of urban development on nightjar numbers. Dorset holds 7373 ha of heathland, split into 151 different fragments, referred to as heathland patches (Rose et al., 2000). These patches have been mapped, their areas measured and the composition of their heathland vegetation described (Chapman et al., 1989; Rose et al., 2000). Patches occur both adjacent to and within the large conurbations of Bournemouth and Poole, as well as to the west of Poole Harbour, where they are often far from any urban development.

This paper presents a novel approach to the examination of the different influences on the number of nightjars present on heathland patches in Dorset. The 1996 Heathland Survey of Dorset (see Rose et al., 2000 for details) defines the heathland patches and the amount of heathland present at each. Nightjar numbers on each patch were sourced from the 1992 national survey (BTO/RSPB). Aerial photographs from 1997 were used to determine the amount of urban development and the amount of woodland surrounding each heathland patch, and the Postcode Database was used to identify the actual number of buildings adjacent to each patch.

2. Methods

2.1. Heathland patch distribution and fragmentation

Heathland data were obtained from the survey of the Dorset heaths conducted in 1996 by the former Institute of Terrestrial Ecology (now the Centre of Ecology and Hydrology, CEH). This survey provided the baseline data on the distribution and vegetation changes which have occurred on the heathlands in Dorset (Webb and Haskins, 1980; Chapman et al., 1989; Webb and Vermaat, 1990; Rose et al., 2000) and which have been used to examine the distribution of Dartford Warblers within the Dorset Heaths (Van den Berg et al., 2001).

The 1996 heathland survey was based on a recording unit of a 200×200 m grid square based on the Ordnance Survey National Grid. All such squares containing heathland-associated vegetation within Dorset were surveyed. The total heathland vegetation area in each grid square was defined using the methods specified in Chapman et al. (1989), as subsequently used by Rose et al. (2000) and Van den Berg et al. (2001). This definition included all *Calluna* and *Erica*-dominated vegetation communities on dry and humid heath together with areas of wet heath and peatland, gorse and other scrub and recently burnt bare areas of known heathland. Contiguous squares were grouped as patches. Two squares were defined as being contiguous when they were in contact along their sides (laterally) or at any of their corners (diagonally) and the percentage cover of heathland vegetation in at least one of the two squares exceeded 75%. Thus the boundary of such patches were defined by the presence of heathland vegetation, rather than being determined by any site designations or land ownership. For further details of all the methods for field surveying, defining and estimating areas of heathland-associated vegetation and aggregating squares into heathland patches, see Chapman et al. (1989), Rose et al. (2000) and Van den Berg et al. (2001). The total heathland area of a patch was taken as the sum of the total heathland vegetation areas of all grid squares within the patch. Only patches with more than 10 ha of heathland-associated vegetation were included in our analyses. The individual patches were taken as the basic sampling unit for statistical analysis.

One potential impact of urban and other human developments on the totality of heathlands in a region is that the individual heathland patches can be isolated from other patches of heathland. Small patches may be more prone to local extinction of individual plant or animal species, and isolated patches may be less likely to be colonised by dispersal and migration from other patches. In particular, Van den Berg et al. (2001) found that Dartford Warblers were less likely to be present in places where the heathland was more isolated. This may be partly because Dartford Warblers are resident birds with low rates of dispersal. In contrast, nightjars are migratory and summer residents on the Dorset heaths, so their distribution is less likely to be affected by the effects of heathland fragmentation and isolation. However, such effects were still assessed. For each 200 m survey square i, we calculated its harmonic mean distance ($F_{(i)}$) to all other squares containing some heathland vegetation, as per Van den Berg et al. (2001). The 'fragmentation index' G_j for a patch j was then defined as the average values of $F_{(i)}$ for all the squares forming the patch.

2.2. Nightjar distribution data

The numbers of nightjars on each of 29 heathland patches were taken from the results of the national survey conducted by the RSPB/BTO in 1992 (Morris et al., 1994). None of the patches with less than 10 ha of heathland had been surveyed for nightjars. However, data from this survey were not available for all of the larger patches, due either to the patches not being surveyed or because the boundaries of the area surveyed did not necessarily match the boundary of the heathland patch. In such cases additional data were supplied by the RSPB Dorset Heathland Project (which has conducted bird surveys across Dorset since 1990), and from other local reserve managers. All additional bird records were from comparable Common Bird Census (CBC) type surveys (see Bibby et al., 1992 for details), conducted over the whole of a patch in a given calendar year. For five additional patches, the numbers present in 1991 were used and for two other patches, the numbers in 1996 and 2000, respectively, were used, giving a total sample of 36 patches. Although there may be inter-year differences in nightjar numbers, inspection of the data for those few patches surveyed in several years suggest that nightjar numbers tended to be stable during the 1990s. In addition, none of the seven patches based on nightjar numbers in years other than in 1992 produced unusual residuals in any of the fitted regression models or indicated any year effects.

2.3. Proportion of developed land and forestry surrounding each heathland patch

The boundaries for all 36 heathland patches were digitised using MapInfo (Version 6), at a zoom level of 3 km, and over a base map of the 1:50 000 Ordnance Survey. For each patch, three buffer zones were drawn around the outside of the digitised patch boundary at distances of 250, 500 and 750 m. Using ortho-rectified aerial photographs of Dorset (taken in 1997) as a base layer, the urban area within each buffer zone was then measured. This urban area was calculated by drawing polygons around all developed areas visible on the aerial photographs at a zoom level of 3 km. Developed areas included all buildings, warehouses and main roads.

Using the same aerial photographs, and the same zoom level, all blocks of woodland, excluding hedgerows, were identified, and the area of each calculated by drawing polygons around the edge, and then the areas summed within the 500 m buffer.

2.4. Postcode data on the number of houses surrounding each patch

The number of houses within 500 m of each patch was extracted from the Post Office Postcode Delivery Points Database, available in MapInfo. This database contains the names and geographical locations of the 1.7 million unique postcodes in the United Kingdom and also includes the number of residential and non-residential delivery points (addresses) within each postcode. One of the intended uses of this database is that it can identify the approximate number of households within any part of the United Kingdom. Each postcode is mapped by a central point. For each patch, we calculated the total number of residential and non-residential properties in all postcodes whose central point fell anywhere, inside or within 500 m of, the boundary of a patch.

2.5. Statistical analysis

Density of nightjars per patch was calculated as the estimated number of nightjar territories on the patch divided by the total heathland area of the patch. Initial exploratory analyses examined the correlations between nightjar density and the variables measuring patch characteristics. However, for patches with very low nightjar numbers, the relative precision of estimates of nightjar density will be lower (i.e. have a higher coefficient of variation) than for patches with relative large numbers of nightjars. Therefore using simple (i.e. unweighted) multiple regression to assess the relationship between nightjar density and the environmental factors is not appropriate, or at least not optimal. The relationship was therefore assessed using Generalised Linear Models (McCullagh and Nelder, 1989), treating the count of nightjar numbers on a site as having a Poisson distribution with mean equal to the model prediction for the site and assuming a multiple linear relationship between the logarithm of nightjar numbers and the environmental variables. More specifically, the variance of the residuals was assumed to be a multiple k of that expected for a Poisson distribution where k is estimated as the residual mean deviance (McCullagh and Nelder, 1989, pp. 199–200). Using this assumption to allow for the variability being greater than that expected for a Poisson error distribution, the standard errors of the regression model coefficients obtained by fitting a Poisson likelihood are automatically increased by the appropriate factor ($\sqrt{k}$).

These log-linear Poisson error models were thus of the form:

$$\log_e N_i = \alpha_0 + \alpha_1 \log_e A_i + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p \quad (1)$$

where N_i = number of nightjars on patch i, A_i = Heathland area of patch i, $X_{i1}, X_{i2}, \ldots, X_{ip}$ are the values of the p environmental predictor variables and α_0, α_1, β_1, β_2, $\ldots$, β_p are the estimates of the regression coefficients. Treating α_1 as a regression parameter to be estimated rather than fixed at a value of one (the latter being equivalent to treating $\log_e A_i$ as an ‘offset’ variable in

GENSTAT), allows for the possibility of nightjar density being dependent on the size of a patch. The overall fits of model (1) using different combinations of predictor variables were assessed by comparing their residual deviances (McCullagh and Nelder, 1989).

3. Results

The numbers of nightjars and other associated data for each patch are summarised in the Appendix. Nightjar presence was recorded on all except four of the 36 patches. Although over 30 nightjars were recorded on each of the six largest patches, seven or less nightjars were recorded on two-thirds (24) of the patches. The nightjar density on these 24 patches will be estimated with relatively less precision, hence the need to use a Poisson error model as explained in the methods.

Fig. 1 shows the geographic distribution of the Heathland patches in Dorset. The major urban conurbations of Poole and Bournemouth are in the central east part of the map region. The heathland patches near these conurbations will all tend to have a high percentage of developed land within the surrounding buffer zone (Fig. 1a). It is immediately apparent that the highest nightjar densities tend to occur on Heathland patches away from these highly developed areas (Fig. 1b). Although there is no overall simple correlation between nightjar density and either Easting (Pearson correlation coefficient $r=-0.16$, $P=0.35$) or Northing ($r=0.05$, $P=0.79$), there is a natural degree of local spatial autocorrelation to both the nightjar densities and the degree of urban development on and around heathland patches. The potential implications of this are investigated later.

The measures of percentage cover by urban development within the different distances of buffer zones (250, 500 and 750 m) and the two measures of the density of properties (residential and non-residential) based on postcode data were all highly correlated (Table 1). In particular, the density of residential properties was very closely related to the percentage cover of urban development with the 500 m buffer zone (Fig. 2), even though the two variables were obtained from completely different data sources (i.e. postcodes and aerial photographs). It is therefore not possible within this analysis to distinguish between possible effects of human impacts (e.g. disturbance) as represented by the density of dwellings and possible effects of habitat area loss due to cover by urban developments. There was a strong negative correlation between nightjar density per hectare of heathland per patch and all the measures of urban development or the local density of people (Table 1). As the percentage cover by urban development within the 500 m buffer zone had marginally the strongest correlation ($r=-0.59$) with nightjar density (Fig. 3), this single variable was used in all the subsequent analyses to represent all effects of urban development and/or human disturbance on the heathland patches. Although the number of nightjars on a patch increases, as expected, with patch size (Fig. 4), there is some tendency for nightjar density to decline with (log) patch size ($r=-0.38$, $P=0.024$). Moreover, Fig. 4 shows that for any given size of patch, the number of nightjar present tends to be less on patches surrounded by the greatest extent of developed land. Thus the effect of urban development occurs across the whole size range of heathland patches.

Nightjar density was positively correlated ($r=0.35$, $P=0.035$) with the percentage cover of woodland within 500 m of the patch boundary (Fig. 5), suggesting that the negative correlation with the amount of urban development could be at least partly due to a lack of woodland, which is one of the preferred foraging habitats of nightjars. There was only a weak negative correlation between the percentage cover of developed land and the percentage cover of woodland within the 500 m buffer zone ($r=-0.36$, $P=0.034$). This is largely because 15–85% (average 44%) of the 500 m buffer zone on the study patches was neither woodland nor

Table 1
Pearson's correlation coefficients between nightjar density and all the variables used to represent urban development and human impacts for each patch ($n=36$ patches)

		%URB250	%URB500	%URB750	RES	NONRES	TBUILD
% Urban within 250 m	%URB250						
% Urban within 500 m	%URB500	0.99					
% Urban within 750 m	%URB750	0.98	0.99				
Residential property density	RES	0.95	0.95	0.95			
Non residential property density	NONRES	0.72	0.67	0.65	0.66		
Residential + non-residential property total density	TBUILD	0.95	0.95	0.95	1.00	0.69	
Nightjar density	NDENS	−0.58	−0.59	−0.58	−0.55	−0.39*	−0.55

All other correlations significant at $P<0.001$.
* $=P<0.05$.

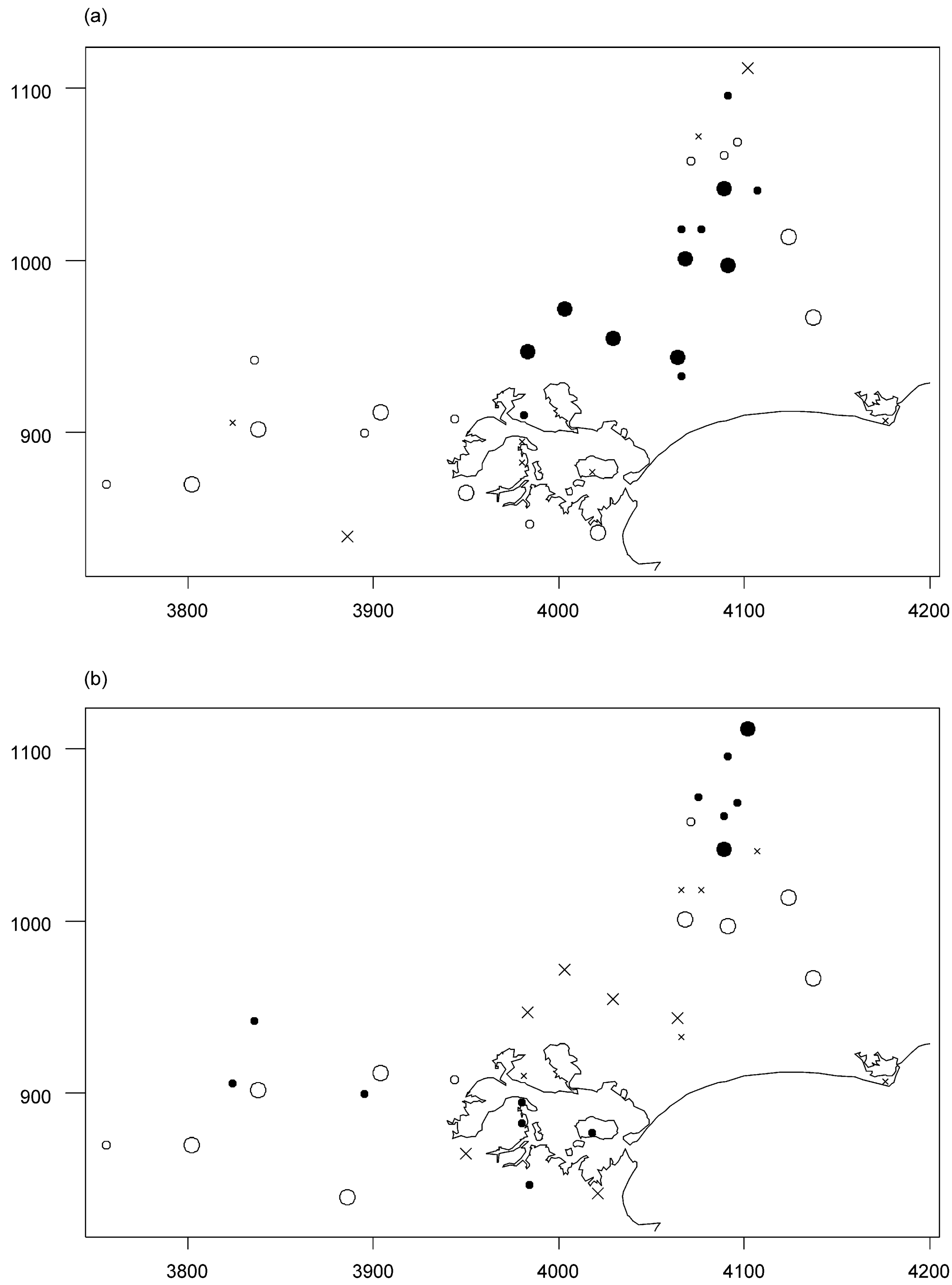

Fig. 1. (a) Map of sites showing the distribution of Heathland patches grouped into categories of % of developed land within the 500 m wide buffer zone (× = <1%, ○ = 1–20%, ● = >20%). (b) Map of sites showing the distribution of Heathland patches grouped into categories of nightjar density (ha^{-1}) (× = <0.06, ○ = 0.06–0.12, ● = >0.12). Small and large symbols denote patches with heathland areas ⩽50 and >50 ha, respectively. Axes indicate 10-km grid squares; the line shows the coastline and Poole Harbour.

urban development, so the two variables were not automatically negatively correlated and hence their effects were not confounded within this dataset; which is fortunate. Neither the percentage cover of urban development nor the percentage cover of woodland within 500 m of the patch boundary showed any overall correlation with heathland patch size ($r = -0.04$ and $r = 0.09$, respectively); although none of the five largest patches had a high percentage cover of developed land in the surrounding 500 m buffer zone (Fig. 4).

Including the percentage cover of both developed land (%URB500) and woodland (%WOOD500) in the log-linear Poisson error model (1) gave the fitted model (SE of regression coefficients in brackets):

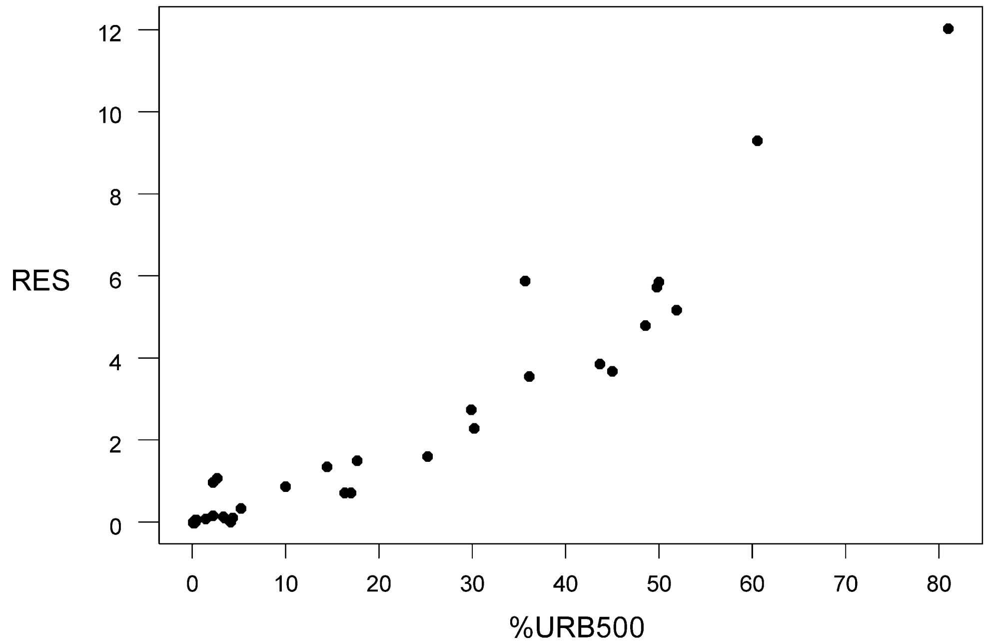

Fig. 2. Relationship between the density of residential property (RES, ha^{-1}) and the percentage cover of urban development within the 500 m buffer zone (%URB500). Correlation $r=0.95$; $n=36$ patches.

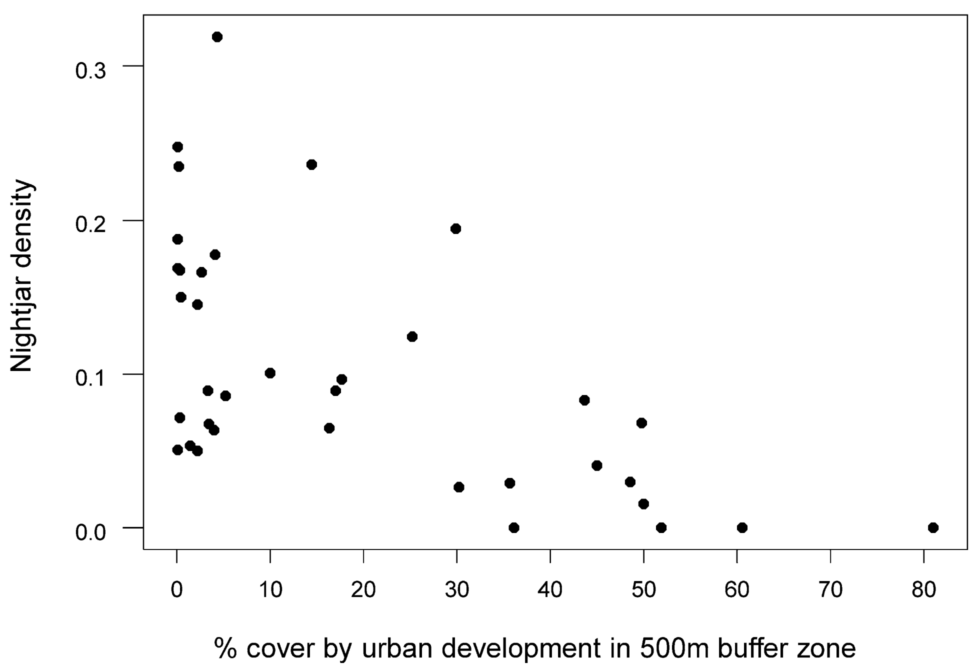

Fig. 3. Relationship between nightjar density per patch (ha^{-1}) and the percentage cover of developed land within the 500 m buffer zone (%URB500).

$$\underset{}{\log_e Ni} = \underset{(0.309)}{-1.268} + \underset{(0.045)}{0.733} \log_e Ai \underset{(0.0042)}{-0.0165} \ \%\text{URB500} \underset{(0.0039)}{+0.0121} \ \%\text{WOOD500} \quad (2)$$

The partial regression coefficients were statistically significant for both the percentage cover of developed land ($t=3.92$, $P<0.001$) and the percentage cover of woodland ($t=2.95$, $P=0.006$); indicating that nightjar density is related to the extent of cover of developed land and of woodland in the buffer zone surrounding a heathland patch.

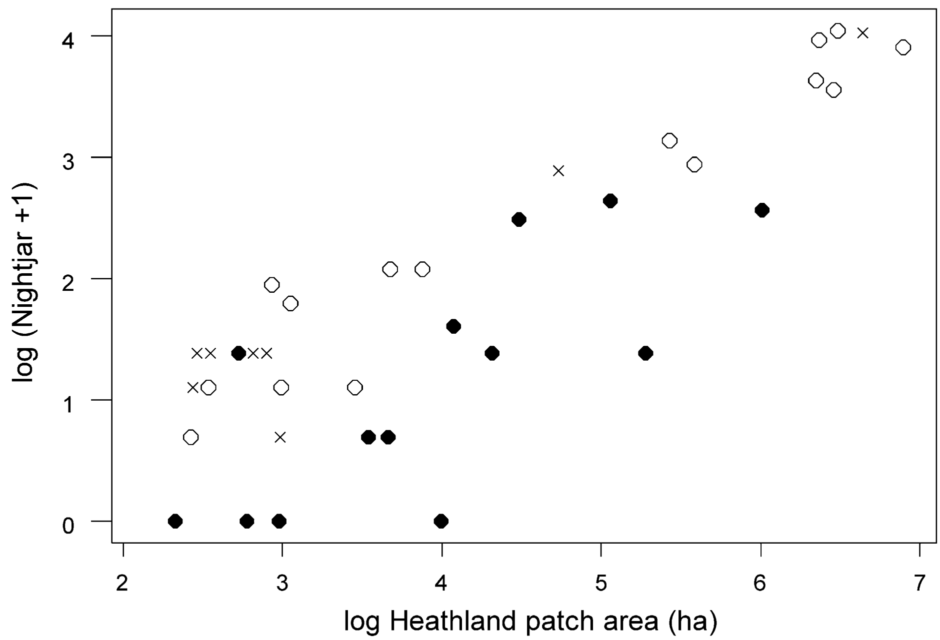

Fig. 4. Relationship between $\log_e$ number of nightjars and the $\log_e$ Heathland area of each patch, classified by classes of the percentage cover of developed land within the 500 m buffer zone (%URB500) (× = <2%, ○ = 2–20%, ● = >20%).

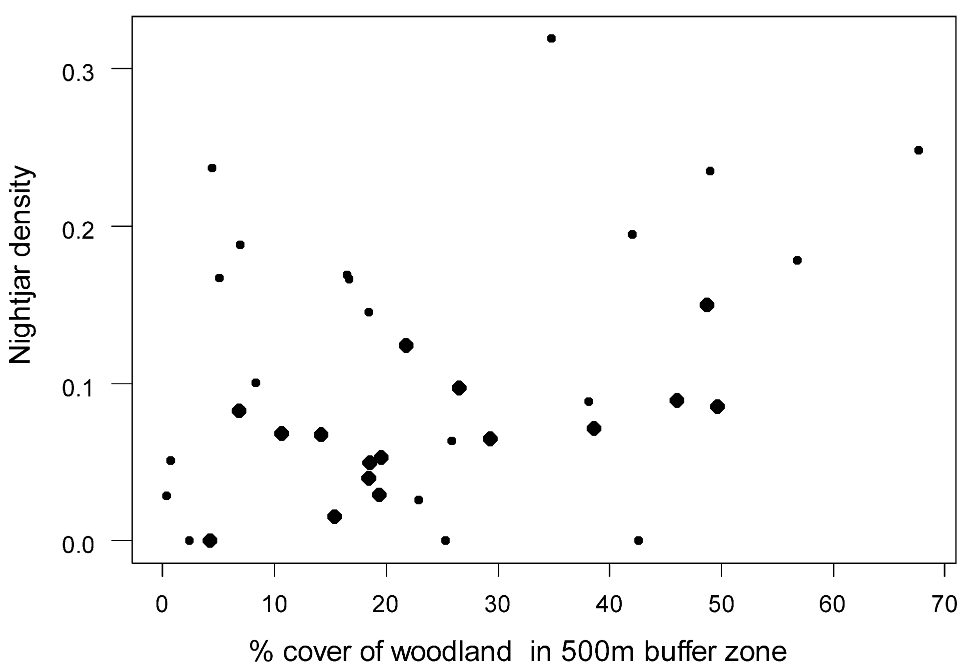

Fig. 5. Relationship between Nightjar density per patch (ha^{-1}) and the percentage cover of woodland within the 500 m buffer zone (%WOOD500). Small and large symbols denote patches with heathland areas ⩽50 and >50 ha respectively.

The relationship between nightjar numbers and percentage cover of developed land adjusted for patch size and the extent of woodland cover in the 500 m buffer zone is graphically well shown using a double residual plot. The standardised residuals for $\log_e$ nightjar numbers obtained by fitting model (1) using only heathland patch area and percentage cover of woodland as predictor variables are plotted against the residuals for the multiple linear regression of percentage cover of developed land on the same two predictor variables (Fig. 6). The correlation ($r = -0.70$, $P < 0.001$) between the two sets of residuals is the partial correlation between nightjar numbers and percentage of developed land adjusted for the regression effects of $\log_e$ patch heathland area and percentage cover of woodland in the surrounding 500 m buffer zone.

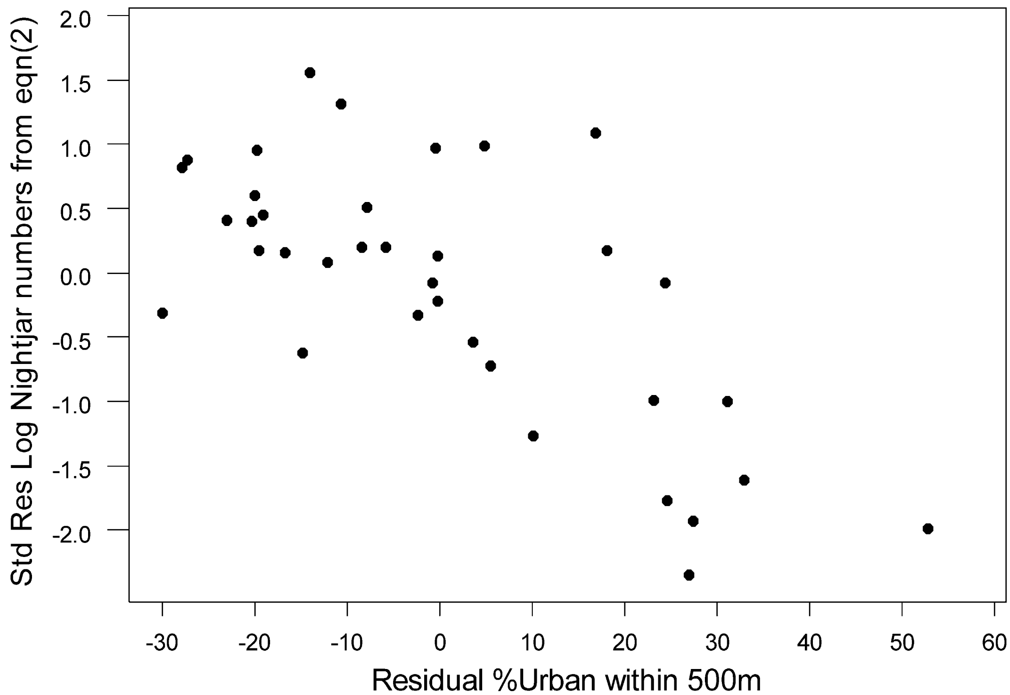

Fig. 6. Double residual plot showing residual $\log_e$ Nightjar numbers versus residual percentage cover of developed land both adjusted for the regression effects of $\log_e$ patch heathland area and percentage cover of woodland in the surrounding 500 m buffer zone. Correlation $r = -0.70$, $P < 0.001$.

The partial regression coefficient for ($\log_e$) heathland area (A_i) in (2) was significantly less than unity ($t = 5.93$, $P < 0.001$); this was the case for all the fitted models. This provides a valid test, which indicates that nightjar density is less on the larger heathland patches, including after allowing for the characteristics of the land surrounding each patch (i.e. the cover of woodland habitat and developed land).

An alternative model to (2) using the densities of residual and non-residual properties within the 500 m buffer zone boundary instead of the percentage cover of developed land did not give such a good fit [residual mean deviance = 1.36 compared to 1.25 for model (2)]. Adding the density of residential properties to model (2) did not improve the fit (partial $t = 0.76$, $P = 0.45$).

The heathland patch 'fragmentation index' G_j was not correlated with nightjar density and did not give a statistically significant improvement to any of the fitted models; for example, when added to model (2), its partial $t = 0.29$, $P = 0.77$.

As mentioned earlier, there is a natural degree of local spatial autocorrelation to both the nightjar densities on heathland patches and the degree of surrounding urban development. (Fig. 1a and b). This could cause subtle spurious correlations between nightjar densities and the extent of urban development if some (un-measured) environmental characteristics of the heaths near the main built-up regions made them less suitable for nightjars.

The CEH heathland vegetation surveys estimated the area of each type of heathland in each 200 m grid square and hence for each heathland patch. The types included dry heath, humid heath, wet heath, peatland and scrub (Rose et al., 2000). Adding the area of any of these types of heathland to model (2) did not give any statistically significant improvement in predicting nightjar numbers. Thus, at the patch scale, nightjar numbers do not seem to be closely dependent on the area of any one particular type of heathland vegetation.

The effect of the spatial autocorrelation on the nightjar–urban development relationship was assessed using a partial multiple Mantel test (Manly, 1997, pp. 179–181). The difference in nightjar densities between each pair of patches is regressed in a multiple regression against the geographic distance between the two patches and their difference in percentage cover of developed land. However, the statistical significance of the regression coefficients is assessed from a Mantel randomisation test whereby the pairwise differences in nightjar density are randomised by randomly permuting the order of the 36 patches (see Manly, 1997, for further details). The idea is that if all close-together patches have similar nightjar densities and similar degrees of urban surroundings, then this joint pattern can be explained by geographic distance. The partial Mantel test for the effect of percentage cover of urban surroundings, allowing for the geographic distance apart of patches, gave a randomisation test P value of 0.0001 based on 10 000 randomisations. Similar partial Mantel test results were obtained when geographic distances were log transformed in order to place greater emphasis on the short distances between patches which are close together. This suggests that the correlation between nightjar density and the extent of urban development is not just a consequence of some large-scale geographic distribution correlated with some un-measured factor. However, as Manly (1997) points out, this test does not eliminate the effect of small-scale geographic covariance.

Eq. (2) can be used to approximately predict the number of nightjars that might be present in the absence of any urban development. Using the value for the%-cover of woodland within 500 m as currently estimated, and assuming all sites to have no development within 500 m, Eq. (2) gives a total number of nightjar territories, for all 36 patches, of 525, an increase of 20% on the observed totals used in the analysis (438).

4. Discussion and interpretation

The analysis presented here has integrated several sources of data to examine trends in nightjar numbers across the Dorset heathlands. The results clearly demonstrate that the number of nightjars present on a heathland site is linked to a measure of urban development around the periphery of the site, with sites surrounded by more development supporting lower densities of nightjars. As the measures of housing density or urban development within distances of up to 750 m were all highly correlated, it was not possible to separate these in order to identify either the distance at which the effect may occur or whether actual human population size rather than urban area is the more significant.

The measures of urban area and housing density that have been used are surrogate measures for a suite of factors associated with urbanisation. These factors, which include the levels of different human activities occurring on the site and changes in the land use and habitats surrounding the site (Haskins, 2000), may not be independent and, as such, the index provides a single measure for a number of inter-related variables. The variables that might be considered particularly relevant to nightjars include human disturbance, light pollution, predation from natural predators and domestic pets that could occur at higher densities in urban areas, and habitat change, through for example an increase in the incidence of fires (accidental and otherwise) on urban heaths.

It has been shown that people living close to heathland sites in Dorset do visit them on a regular basis (Atlantic Consultants, 1996) and the high levels of access and recreational use, such as dog walking, on some Dorset heaths are shown by a variety of authors (Molenaar, 1998; Norrington, 1998; Haskins, 2000). Sites with a given level of surrounding development may well vary in the levels of access because, for example, the position of access points onto the heath in relation to the location of housing may vary or because the measure of developed area does not take into account the density of housing. However, given the strong correlation between the density of houses and the percentage of surrounding land which is developed (Table 1, Fig. 2), the measures used are believed to be a good indicator of the degree of access occurring at each site. Ground nesting species, such as nightjars, have been shown to be vulnerable to a range of disturbance effects, such as predation of eggs or chicks by dogs (Nol and Brooks, 1982; Pienkowski, 1984), and accidental trampling of nests by people (Liley, 1999). Studies of other species have shown that birds will, during the breeding season, avoid areas with a high level of human activity (Schulz and Stock, 1993; Liley, 1999), or occur at lower densities in disturbed areas (Van der Zande et al., 1984). We would therefore tentatively suggest that levels of human access onto the heaths are causing the identified trend and that the effects of human disturbance to nightjars warrants further investigation.

The extent and consequences of human disturbance on populations of vertebrates is a contentious issue (Gill et al., 1996, 2001). In order to assess the impact of disturbance on population size it is necessary to address how behavioural changes in response to disturbance affect demographic parameters such as survival and reproductive success. An understanding of the strength of density-dependence within a system is also required (Gill et al., 2001). For a nocturnal species, whose nests are difficult to find, such an understanding would be difficult and time consuming to achieve. However, the results presented here suggest that such work is merited, and are sufficient to indicate that 'urban effects' such as disturbance are responsible for a reduction in the number of nightjars currently present within the Dorset Heaths.

There are some other factors which could also cause a reduction in nightjar density on more urban heaths. For example, in a separate study, using a similar approach of calculating the area of developed land surrounding heathland sites, Kirby and Tantram (1999) showed that fires are more common on urban heaths. As heather is a key feature of nightjar nest sites (Berry, 1979), fire may well reduce site quality and therefore possibly nightjar density on urban heaths.

The results of our study are independent of patch size in that, for any size of patch, nightjar density tends to be lower on patches adjacent to developed land. A number of predators are known to occur at high densities in urban environments, for example domestic cats (Clarke and Pacin, 2002), foxes *Vulpes vulpes* (Wilkinson and Smith, 2001), hedgehogs *Erinaceus europaeus* (Doncaster, 1994) and magpies *Pica pica* (Sachteleben et al., 1992; Groom, 1993). Their overall effect therefore might not be expected to be as great on very large heaths whose centres are several hundred metres from any surrounding urban developments. However, the results of our study do not suggest any such edge effects because nightjar density tended to be lower rather than higher on large heathland patches.

The loss of foraging habitat outside the breeding area is an additional possible cause of reduction in nightjar densities. In the best fitting model [Eq. (2)] involving the percentage cover of woodland and the percentage cover of urban development within 500 m, both variables had significant effects. This indicates that the loss of foraging habitat in the area surrounding the heaths is one factor affecting nightjar numbers. In addition, the analysis also indicates that nightjar density is less on larger heathland patches, after allowing for the amount of development and area of woodland surrounding the patch. Heathland is avoided as a foraging habitat (Alexander and Cresswell, 1990), so where it is in large continuous patches within a landscape, suitable foraging areas for nightjars, in relation to the area of potential breeding sites, may be lacking.

The available foraging habitat within 500 m was determined by calculating simply the area of woodland, and therefore could not take into account any differences in the quality of the habitat. Radio-tracking studies have shown that nightjars will often avoid some areas and instead travel to superficially similar habitat further away, suggesting that they exploit a few particularly rich feeding sites (Alexander and Cresswell, 1990). While the lack of any measure of foraging habitat quality imposes some caution in interpreting the results, the fact that the measure of woodland area was only mildly correlated with urban area does suggest that loss of (woodland) foraging habitat has an additional effect.

The results of this study demonstrate that it is patches adjacent to urban areas, and hence those surrounded by a high human population, that support fewer nightjars. Although most of the heathland patches within Dorset do already have open or de facto public access, the Countryside and Rights of Way Act (2000) will give open access to practically all heathlands. Consequently, we suggest that heathland sites adjacent to areas with a high human population, that will be granted open access, require consideration of access management measures to avoid deleterious impacts on nightjars. Access patterns can be manipulated through the location of gates, footpaths, car-parks, etc. and at some sites restricting types of access (such as dogs off leads) or zoning areas to provide areas with no public access during the breeding season may be possible. The actual effects of different access on nightjar breeding success and behaviour, and the effectiveness of access management techniques are both areas that would warrant further study. As a species that has shown some recovery from historical decline, it is essential that access provision is compatible with the conservation of this priority species.

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(*Appendix begins on next page*)

Appendix. Details of patches and associated information used in the analysis

Patch name	Patch area (ha)	Area of heathland within the patch (ha)	Number of nightjars	Area of developed land within 500 m	Area of woodland within 500 m	total land area within 500 m of patch
Warmwell	48	31.64	2	9.33	62.46	289.53
Winfrith Heath	392	267.23	18	20.77	86.85	1003.81
Bovington	968	585.68	52	44.08	628.97	2333.84
Clouds Hill	24	12.13	3	0.00	120.70	202.29
Blackhill, BR	80	48.23	7	6.22	54.19	373.46
Povington and Grange	1076	768.46	55	2.55	457.29	2260.05
Morden/Great Ovens/Bloxworth	1280	655.23	56	73.38	702.77	2696.77
Trigon/Cold Harbour	32	18.81	6	9.65	80.08	262.16
Arne/Hartland/Stoborough	1396	989.98	49	36.71	319.72	3122.02
Sandford Heath/Black Hill	36	11.27	1	39.04	87.68	265.95
Upton Heath	296	196.48	3	260.90	79.95	817.43
Rempstone Heath	116	39.40	7	14.26	199.00	466.09
Rockley Sands	72	35.01	1	102.94	0.82	361.33
Shipstal, Arne	28	11.87	2	0.00	31.46	218.57
Gold Point, Arne	28	16.00	3	0.00	13.06	217.41
Corfe Hills	172	74.88	3	167.55	68.69	544.50
Studland/Godlingston	876	639.39	34	14.86	214.32	1971.05
Canford	572	407.17	12	369.01	147.42	1332.22
Brownsea	24	12.78	3	0.29	91.08	210.06
Turbary	120	54.43	0	334.27	17.41	532.43
Bourne Valley	24	10.26	0	123.66	4.79	228.38
Ferndown	100	58.97	4	161.61	34.61	424.72
Uddens	44	16.05	0	82.07	97.01	271.69
Horton	44	19.94	2	24.06	20.33	287.91
Slop Bog	36	19.67	0	111.26	54.24	250.27
Horton II	32	17.97	3	0.40	10.60	242.90
Parley Common	288	157.47	13	260.68	40.81	884.78
West Moors Petroleum Dump	196	88.84	11	101.57	87.92	599.99
Lower Common, Three Legged Cross	56	21.15	5	37.52	11.38	317.68
Stephen's Castle	32	15.43	3	65.79	92.76	252.87
Cranbourne Common	276	113.60	17	2.20	267.07	824.20
nr Three legged Cross	32	12.04	2	5.42	34.27	238.17
Avon CP/Barnsfield & Hurn	1004	571.28	37	241.84	434.51	2486.83
Lions Hill	92	38.38	1	105.05	79.78	440.77
Town/Sopley/St. Catherines	380	227.54	22	127.86	192.96	1108.68
Hengistbury Head	32	19.72	1	0.00	1.39	242.73

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