The effect of urban development and recreational access on the distribution and abundance of nightjars on the Thames Basin and Dorset Heaths

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D R A F T

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Summary

We explore the links between housing levels, recreational access and nightjar abundance and distribution across approximately 18,000 ha of heathland and associated habitats in Dorset and the Thames Basin Heaths. We have identified 81 distinct sites ('patches') (58 in Dorset and 23 in Thames Basin Heaths) which are, at least in part, designated as Special Protection Areas (SPA), have public access and for which there is nightjar survey data from the national survey conducted in 2004. These 81 patches support some 740 nightjar territories, approximately 1/6th of the UK nightjar population.

Using aerial photography we have also mapped principal habitat types within each patch. Nightjar densities are highest in the more open habitats: young conifer, heathland and clearfell and lowest in woodland (deciduous and conifer). Nightjar density was higher in Dorset, but there was considerable variation in densities between patches and there was no significant difference in average densities between the Thames Basin Heaths and Dorset Heaths.

We have conducted a similar analysis to that done by Liley & Clarke (2003) which used nightjar survey data from 1992. This previous study was based on a sample of Dorset sites only. We have shown that the negative correlation between the density of nightjars on a site and the amount of housing in the vicinity of the site is still present, and furthermore occurs on both the Thames Basin Heaths and the Dorset Heaths. The negative correlations between nightjar numbers and housing were present at distances up to at least 5km away from the patch boundary. As the amount of housing in different bands is highly correlated it is impossible to attribute the effect to a specific distance band. We tested the relationship between housing and nightjar numbers in a variety of ways and show that the relationship is significant across both the Dorset Heaths and the Thames Basin Heaths.

Nightjar numbers have increased markedly between the two most recent national surveys (in 1992 and 2004). For Dorset patches we compared the densities between the two surveys, and it would appear that the increase has occurred particularly on large patches and patches surrounded by higher levels of housing. These results would be consistent with a shrinking in territory size (allowing more birds to settle on larger sites) and settlement of poorer quality sites (heaths surrounded by housing), which might be expected as population size increases.

Using actual visitor data we have also produced a model that allows the spatial distribution of visitors to be predicted across some 18,000 ha of heathland and forestry. The model predicts visitor numbers for individual access points. We show that the number of people arriving at a given access point is dependent on the amount of housing surrounding the access point and the amount of parking available. People arriving on foot can be predicted from the amount of housing in the surrounding area. For those arriving by car, parking capacity was the best single predictor of visitor numbers. It would appear that parking capacity is not limiting visitor numbers but rather that, to some extent, the distribution of current parking reflects patterns of access and the locations that people prefer to visit. Sites surrounded by high densities of housing do not necessarily also have the most parking, and therefore high visitor pressure is sometimes not associated with housing. We derive two means of predicting visitor numbers arriving by car, one method purely uses car-park size, the second method also includes the amount of housing surrounding each car-park, and is based on the statistically-supported assumption that larger car-parks attract people from a wider geographical area.

There are 531 access points onto the patches in Dorset and 729 access points onto the patches in the Thames Basin area. By applying our predictive model to each access point on all patches we can estimate total visitor numbers. The model estimates for the Dorset patches range from 4.8 – 5.5 million visits per year, and for the Thames Basin Heaths they range from 4.9 – 10.3 million visits per year. On most Dorset Heaths the visitor pressure (per ha) is low compared to the Thames Basin Heaths, but some Dorset sites (the urban heaths in Poole and Bournemouth and

the coastal sites such as Studland and Hengistbury) have very high levels of visitor pressure, higher than anywhere in the Thames Basin Heaths. The Thames Basin Heaths tend to have higher visitor pressure across their area, but do not have some of the very high, localised visitor pressure found in Dorset.

We distribute the predicted number of visitors within patches using existing survey data on visitor routes and the distance people ‘penetrate’ onto the heath from access points. This allows us to map visitor pressure (in 50m cells) across each patch. These maps highlight areas where visitor pressure is likely to be highest and allow relative comparisons to be made between sites and between SPAs.

Using predictions of visitor pressure within sites, we show that nightjar territories, compared to areas outside territories, are located in areas of low visitor pressure and that nightjars therefore appear to avoid areas of high disturbance within sites.

We tested this preference of nightjars for areas of low visitor pressure by running our visitor pressure model assuming that the number of people entering from each access point was the same. This essentially provided us with a hypothetical map of visitor pressure which removes the effect of large car-parks or nearby high housing levels. The visitor levels, using this null model, were also significantly lower within nightjar territories when compared to the area outside territories. This indicates there is some tendency for nightjars to be further from access points than random points on the patch. The nightjar preference for places away from access points (i.e. the null model) was less strong than the preference for areas with relatively low ‘best’ predicted visitor pressure especially for the TBH. We suggest that visitor pressure is sufficiently high on parts of the majority of the Thames Basin heaths that nightjars show some preference for the relative low areas of visitor pressure over and above their general preference for areas away from heath access points.

We also explored the extent to which nightjars avoid the edges of sites and found that nightjars are distributed away from patch edges. This was particularly apparent on the Thames Basin Heaths, where for 19 of 20 patches, the nightjars showed a preference for areas of relatively low visitor pressure, but these areas are also further away from the patch edge (than random points on the patch).

When we plot nightjar density against (predicted) visitor pressure there is a clear trend for nightjar density to decline with increasing visitor pressure. This decline is gradual, and there is not a clear cut-off point at which a marked change in nightjar density occurs. The trend is much less clear across the Dorset Heaths.

The results we present here have important consequences for access management and future housing development in both areas. For the first time we show a link between housing levels, disturbance and bird numbers. However, further research and analysis is needed to assess the more subtly potentially co-related effects of specific habitat types on nightjar distribution.

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The visitor model is developed from initial work Ralph and Durwyn did with English Nature (Thames & Chilterns Team) in March 2006 and then subsequently for Dorset County Council in the autumn of 2006. We are grateful to Doug Kite (Natural England), Sam King (Natural England), Keith Payne (Natural England), Nick Squirrell (Natural England) and Phil Sterling (Dorset County Council) for comments and ideas. Brian Crumbley (Natural England) provided copies of the OS and UKP aerial photography coverage under copyright from Natural England. Bryan Edwards (DERC) provided the data on the distribution of valley mires in Dorset, and Sophie Lake helped with the mapping of the mire boundaries data for Purbeck. Neil Gartshore collected much of the access point data for Dorset and we are also very grateful to Sue Moore and all the urban heath wardens in Dorset who provided access point data for the urban heath sites. The access point data for Thames Basin Heaths is based on that collated for English Nature by Exergesis. Katie Cruickshanks collected some supplementary data. James Peat helped with some of the analysis.

Introduction

Development close to heathlands has become a high profile, and contentious issue for conservationists. Housing and other development around the outside of heathland sites can impact on the conservation interest of those sites. These 'urban' impacts (see Underhill-Day, 2005 for a review) are varied, including, for example an increased incidence of fire, disturbance, trampling and increased predation rates. Given the conservation importance of heathlands in southern England, and the high degree of protection afforded to heathland sites, there is a clear need to determine the scale of the current problem and to ensure future development does not have a further impact.

One of the principal areas of concern is disturbance to birds, from local residents visiting the heaths for recreation. The impacts of disturbance to birds have been widely documented (Hill *et al.*, 1997 ; Hockin *et al.*, 1992; Kirby *et al.*, 2004; Liley, 2001; Sutherland, 2007, in press; Woodfield & Langston, 2004) but the extent to which disturbance may influence population size has been rarely shown (but see Liley & Sutherland, in press; Mallord et al., in press,). For heathland species there have been detailed studies on each of the three breeding Annex 1 bird species. For both woodlark (*Lullula arborea*) and nightjar (*Caprimulgus europaeus*) the numbers of birds on a site have been shown to negatively correlate with the amount of housing surrounding the site (Liley & Clarke, 2003; Mallord, 2005). Within sites, woodlark density has been shown to be negatively related to counts of people (Mallord, 2005; Mallord et al., in press,). Studies of nightjar breeding success (Langston et al., 2005; Murison, 2002) have shown that a greater proportion of nests fail on more urban heaths and that nests closer to footpaths are more likely to fail. Studies of Dartford warblers (*Sylvia undulata*) have shown that breeding success is negatively related to the number of people walking through a pair's territory for territories dominated by heather, rather than by gorse (Murison et al., in press,). There is also evidence that young Dartford warblers may be particularly vulnerable to predation from cats associated with houses adjacent to the heaths. These impacts must be considered within the context of the other urban effects which include a higher incidence of fires on urban heaths; changes to hydrology; pollution; dog fouling; trampling; vandalism and public opposition to conservation management such as tree felling and grazing.

Alongside the studies of disturbance effects to birds, a number of detailed studies of visitor access patterns have been conducted (see Clarke *et al.*, 2006; Liley *et al.*, 2006a; Liley & Underhill-Day, 2006; MORI, 2004; Rose & Clarke, 2005; Underhill-Day & Liley, 2005; Underhill-Day & Liley, in press) and have shown that visitors are typically local, with a high proportion travelling (by car or on foot) less than 5km to reach the heaths. Sites with more car-parking capacity typically receive more visitors. People visit for a wide variety of reasons but dog-walking is the principal reason.

The various studies of heathland bird species and people provide a useful resource for those in charge of managing access on heathland sites or those involved in planning decisions. However few studies have directly linked access levels to bird numbers in a way that it is possible to determine the levels of recreational activity at which impacts may occur and the extent to which housing in a given location will affect the integrity of protected sites. There is a need to separate the effects of land-take (for example fragmentation, habitat loss outside the heaths) with the impacts of recreational pressure (generated by new housing) in order to understand the importance that access management and provision of alternative sites may play in mitigating the effects of future development.

In order to address these issues we focus on two areas of heathland some 80km apart: the Dorset Heaths Special Protection Area (SPA) and the Thames Basin Heaths SPA. These have been the subject of high profile public inquiries and planning issues in recent years. Both SPAs contain heathland and associated habitats and are designated for their populations of breeding Dartford warblers, woodlarks and nightjars.

The Thames Basin Heaths are adjacent to settlements such as Guildford, Bracknell and Fleet and, with good transport links, are easily accessible from London. The SPA (8,294 ha) is made up of 13 SSSIs, spread across 11 local planning authorities and three counties. Pressure for new development in the area is high, with at least 35,170 houses planned to be built around the Thames Basin Heaths based on the current housing allocation to 2016 (Land Use Consultants, 2005). The Dorset Heaths SPA is comprised of 40 different SSSIs, and covers an area of 8,169ha. The component sites within the SPA stretch from the Hampshire border in the east nearly to Dorchester in the west, a distance of some 43km. The SPA spans six different planning authorities, and while some of the sites are very rural in character, some sites are within the urban conurbations of Poole and Bournemouth and surrounded by very high densities of housing. As with the Thames Basin Heaths area, the Poole – Bournemouth area has been identified as a key area for housing development (SWRA, 2006). Map 1 shows the two SPAs in relation to each other and key settlements within the region.

We focus on nightjars, as this species was recently comprehensively surveyed across the two SPAs. The national survey data is collected in a standard fashion and covers both SPAs. The 2004 national survey estimated a total of 4606 churring males (Conway et al., (in prep)). This was an increase of 36% since the previous national survey in 1992 (on which the analysis of Liley and Clarke (2003) was based), and there was a range increase of 2.6% in terms of occupied 10km squares. Increases were particularly high in Dorset, Hampshire and other southern counties.

Using existing visitor data and nightjar data we aim to:

1) Use standard visitor data from samples of access points to model visitor numbers and visitor distribution and make predictions for all access points
2) Use these models to explore the spatial distribution of visitors within sites
3) Determine the extent to which housing levels outside sites and visitor pressure within sites determines the distribution and numbers of nightjars
4) Use these results to make sensible recommendations for the management of access and control of further housing development within the two areas.

Methods

Defining “patches”

The designated boundaries of the European Sites do not necessarily follow boundaries that match where people might visit and the two SPAs are designated in a different fashion. Many of the component SSSI sites within the Thames Basin Heaths SPA contain extensive blocks of conifer plantation, with the SPA and SSSI boundaries following the boundary of the forestry. The SPA boundary in Dorset does not always entirely follow the SSSI boundary. There are also large areas of conifer plantation (such as Ringwood Forest and Wareham Forest) that are not designated in their entirety, instead only some specific parts (usually patches of open heath) are designated. In such cases there is extensive public access through the forests, and different SSSIs exist within what is essentially a single site. In order to allow similar analysis across both SPAs it was therefore necessary to define patches of SPA and associated land in a consistent manner. We adopted the following approach to define “patches” within a GIS (MapInfo vs7.5):

- The SPA boundary files were provided in digital format by Natural England, and used as the basis to define patches.
- We then created a second file within the GIS in which we modified the SPA boundaries to reflect areas of open access, as defined by the CRoW Act (2000) and detailed on the web[1]. At some locations this meant that areas of the SPA were removed and in other locations the boundary was extended to encompass land outside the SPA.
- Additional areas of visitable countryside were also added, for example areas of land adjacent to heaths such as forestry or on nature reserves where public access is permitted (and can provide access to heaths). This approach meant that small isolated parts of the Dorset Heaths SPA that occurred within larger blocks of forestry were joined into a single patch. Farmland criss-crossed with rights of way was not included.
- Where SSSIs were split by a main road such as a busy A road or a motorway (for example Chobham Common), or a railway (for example Whitmoor Common) such that people cannot cross easily between the blocks, we define each block as a separate patch. Therefore we treated Chobham Common SSSI as two patches, north and south of the M3, and the single underpass that joins the two patches we treat as an access point onto each patch.
- Areas with no public access (for example Holton Heath, West Moors Depot, Lulworth and Bovington in Dorset, Colony Bog and Eelmoor Marsh in the Thames Basin Heaths) were removed. Areas such as Ash Ranges (Thames Basin Heaths), where access is allowed when no military training takes place and according to MOD byelaws were included.

The final map therefore contained a series of polygons representing areas, referred to as ‘patches’, where relatively unrestricted access occurs to the SPA and surrounding land. Each patch was given a name and a unique code, allowing cross-reference with other files. Map 1 shows the Dorset and Thames Basin Heaths patches in relation to each other and key settlements. The patches for each respective area are shown in Maps 2 and 3. Maps 4 and 5 illustrate the patch boundaries we have used in relation to the SPA

[1] http://www.countrysideaccess.gov.uk/

boundaries. Map 6 shows the Thames Basin Heaths patches and highlights some of the areas where our boundaries differ from the SSSI boundaries.

Mapping of access points

All access points onto each patch were mapped onto the GIS as point data. For the Thames Basin Heaths SPA these data were provided by Natural England (the data originally being collected in part by Exergesis and in part by Footprint Ecology as part of previous contracts for English Nature). For the Dorset Heaths the access point data was already held by Footprint Ecology (having been collected by Footprint Ecology and staff from the Urban Heaths Partnership). The data were all collected in a standardised fashion, through site visits, the use of GIS to identify all boundary points crossed by a public right of way, and site knowledge. Only access points with a public right of access or de facto access were mapped; access directly from private gardens or similar were not included. For each access point the following were collected:

Access point type	Either 0: no parking possible in the immediate vicinity 1: Official car park with designated off-road parking 2: Unofficial parking, such as lay-by, verge, street parking or similar
Car-park spaces	An estimate of the number of parking spaces available. This was simple to collect for official car-parks, but where there was street parking or similar an attempt was made to quantify how many cars could be parked adjacent to the access point (nearby parking not immediately adjacent to the access point was not included).
Patch number	The patch to which the access point is associated, allowing cross reference with the other files
Name	If present (most car-parks tend to have a name)
Organisation	Organisation responsible for managing the access point, where clear
Notes	Recording the presence of any features which may attract or deter visitors using the access point, for example the presence of a café, visitor facilities or the fact that parking might be difficult or dangerous.

Each point was also given a unique code to allow cross reference with other data files.

Visitor Pressure

Two separate broad studies of visitor behaviour and access patterns to heathlands in southern England have been undertaken Clarke *et al* (2005) and Liley et al (2006). These two studies used similar methods, with the amount of survey time spent at each access point and the interviewing protocol identical, allowing the two datasets to be merged.

The survey data are based on interviewing people as they leave a heath and describe the distances people travel to visit heathlands, the number of people in their visiting group, why they visit, where they went on the heath and thus the length of their route, etc. Each access point was sampled for a total of 16 hours between August and early October, within the following time periods: 0700 – 0900; 1000-1200; 1300-1500; 1700-1900. Each time period was sampled once on a week day and once on a weekend day.

The combined data were used to develop predictive models of visitor numbers and distribution within the heaths. The aim was to produce a relatively simple measure of the likely visitor pressure at any particular location. The model outputs would provide a single layer within the GIS that showed the relative spatial distribution and abundance of people within the two SPAs.

Our approach to the modelling has three stages/components:

(i) A statistical method to predict visitor numbers to a specific access point from visitor survey data at a selected sample of access points, separately for visitors arriving on foot and by car

(ii) The application of (i) to all access points to predict the total numbers of visitors to each access point, and when summed, to each heath patch and to the whole SPA

(iii) Using visitor survey data on the distances people travel and penetrate once on the heath to plot the predicted spatial distribution of visitor pressure within each heath patch.

The model outputs were predictions for the total number of people per 16 hours in August, matching the actual data. It is difficult to reliably extrapolate these predictions to give an annual figure as we have little evidence on how visitor patterns may change throughout the year. Where an annual total is given it is calculated by converting the 16 hours to an hourly figure (by dividing by 16) and then multiplying by 12 to give a estimated daily rate and then by 365 to give an annual rate:

$$\text{Annual rate} = (\text{predicted 16 hour rate} / 16) * 12 * 365$$

The spatial distribution of visitors within each patch was calculated on the basis of a 50x50m grid, which covered all patches. Visitor pressure (the number of people per 16 hours) was estimated for each grid cell.

We present the development of the visitor pressure model within our analysis in the results section of the main report. We present the data used to develop the visitor pressure models in Appendix 1.

Habitat Data for Patches

A single habitat layer of non-overlapping polygons was plotted within the GIS. The intention was to create a simple base layer of key habitat types that would relate to the Annex 1 bird species. The habitats were mapped primarily through the use of aerial photographs (by UKPerspectives.com) provided under copyright by Natural England. The most recent aerial photography available was used, this was 2005 for much of the Thames Basin Heaths and for the Dorset Heaths much of the coverage was from 2002. All digitising was conducted by John Mallord, who has extensive knowledge of many of the sites. The aerial photography was supplemented by the use of NVC data (supplied by Natural England) and forestry data giving date of planting and clearance. Where forestry maps indicated clearance or planting that was not evident from the aerial photographs, the maps were drawn to reflect the habitat present in 2004, when the bird data were collected. All digitising was done at a standard zoom setting of 0.6225km on the screen (a resolution of 1cm = 0.01885km).

The following habitats were plotted:

Habitat	Definition
Clearfell	Rows visible on the aerial photographs
Coniferous	Woodland with >50% cover conifer (dark green)

Deciduous	Woodland with >50% cover deciduous (paler green and rounder tree canopy)
Dry heath	Open, purple / dark brown, including areas of bracken and occasional scattered trees
Scrub	Discrete patches of deciduous scrub
Farmland	Pasture with field boundaries clearly visible
Grassland	Acid grassland and other grassland habitats
Mix Heath	Heath with continuous cover of scattered trees
Other	Houses, water bodies, car-parks, sand pits etc
Young plantation	Newly planted pine plantation (with trees less than 6 years old)
Sand Heath	Dry heath with sandy patches and disturbed ground
Wet Heath	Areas of mire and / or humid / and or wet heath, usually appearing paler where *Molinia* flushes etc. were present. Occasional scattered trees.

The choice of habitats was made after some initial trials, using aerial photographs from different sites, to ensure that the habitat types were clearly recognisable and repeatedly identifiable.

Nightjar distribution data

Nightjar data from the national survey, conducted in 2004, were used (see Conway et al., (in prep); Lake, 2004; Lake, 2005; Sharkey, 2005). These data were collected by professional and volunteer surveyors, and are based on a minimum of two visits to all suitable habitat surrounding the two SPAs. All registrations (sightings of birds or birds heard) of nightjars during survey work were mapped using a standard methodology and then the map data summarised with each territory being mapped as a single point. A full description of methods is provided by (Conway et al., (in prep)).

Analysis of nightjar distribution and abundance

Densities of nightjars per patch were calculated as the estimated number of nightjar territories on the patch divided by the area of the patch. We also calculated nightjar density for particular habitats or groups of habitiats, and this was done by dividing the number of nightjars within that habitat or habitat(s) by the area of the habitat(s).

Initial analyses examined the correlation 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 & 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 & Nelder 1989, p199-200). 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:

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

where N_i = number of nightjars on patch i, A_i = Heathland area of patch i, X_{i1}, X_{i2},..., X_{ip} are the values of the p environmental predictor variables and α_0, α_1, β_1, β_2, …, 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 such models using different combinations of predictor variables were assessed by comparing their residual deviances (McCullagh & Nelder, 1989).

Within site analysis

Within site analysis was focused on determining the extent to which the distribution of nightjars within sites was determined by the predicted visitor pressure based on our models (C3 or C5 – see later) for predicting the number of visitors to each access points and spatial models for predicting their penetration distances onto the heaths. We compared areas within 150m of nightjar territory centres with the area outside this distance. The radius of 150m was chosen as this represents a typical nightjar territory: male nightjars typically sing ("chur") from a number of different locations around the edge of the territory, and these territories can encompass an area of 5 to 6 ha (equivalent to circles of radii 126m and 138m) (Berry, 1979). Other studies suggest territories considerably larger than this (see Morris et al., 1994) and therefore 150m would seem a sensible boundary.

As one method of assessing whether nightjar tend to avoid areas of relatively high pressure within a patch, we determined all 50m cells which were within 150m of a recorded nightjar, and then, for each patch, we calculated the mean visitor pressure (MVP_{150}) of cells within 150m and mean pressure (MVP_{other}) for all other cells. If the ratio RMVP (= MVP_{150} / $MVP_{other,}$) is less than unity, this may suggest that nightjar are more likely to occur where (predicted) visitor pressure is relatively low.

In order to separate the effect of visitor pressure from simply an avoidance of access points we ran a further version of our spatial model to predict visitor pressure per 50m cell. This null version ("model C0") of the model assumed an equal number of visitors at each access point on each heath, regardless of car park spaces or local housing density (10 visitors per access point was used but the number is irrelevant because we are only interested in relative pressure close to and away from nightjars). By comparing the relative effectiveness of our visitor pressure model and this null model in predicting nightjars we are essentially determining whether nightjars avoid areas with high visitor pressure or whether they simply avoid access points.

We also calculated the distance of every 50m cell from the nearest edge of the patch (in 50m classes), and then calculated the ratio RDIST of the mean distance to the patch edge ($MDIST_{150}$) of cells within 150m of a nightjar to the mean distance to the patch edge ($MDIST_{other}$) for other cells on the same patch. This ratio allowed us to determine whether there was an 'edge effect' (i.e. nightjars simply avoiding the area around the edge of sites), and whether this explained nightjar distribution better than our actual model of visitor pressure.

Wilcoxon signed rank tests were used to test whether the median of the ratios we calculated for each patch was significantly different from unity.

The extent to which any preference for relatively low visitor pressure under our standard visitor model was greater than the preference under null model C0 was assessed by calculating the “ratio of ratios”. This was done by dividing the ratio RMVP for our visitor model (C3 or C5) by RMVP for model C0 for each patch. If this ratio of ratios is less than one for significantly more than half of all patches, this suggests that nightjar distribution is related to (predicted) visitor pressure rather than just distance from access points.

In order to focus future visitor management within sites it is important to understand the levels of visitor pressure at which any affect on nightjar numbers might occur. We therefore grouped cells according to their predicted visitor density, allowing us to plot nightjar density by visitor pressure.

Box plots are used within the text. The boxes represent 25% - 75% of the data, with the horizontal line showing the median. The vertical lines (‘whiskers’) mark the limits within which 90% of the data lie (i.e. 5% - 95%) and the asterisks show outliers.

Asterisks are used within tables to indicate statistical significance of tests of no effect or no difference: * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Results

Summary of geography of the two SPAs

We generated patches to develop the visitor model, with each patch representing a discrete, visitable unit of forestry / heath associated with the respective SPAs. For the Dorset Heaths area there were 61 of these patches and for the Thames Basin Heaths there were 23 patches. The size, geography and area of key habitats for these are summarised in Table 1. The 61 patches for Dorset cover nearly 11,000 ha, of which approximately half is designated as SPA (plus some of the SPA was excluded as there was no public access, see maps 4 & 5). For the Thames Basin Heaths the majority of the patches (96% of their combined area) are part of the SPA, and the 23 patches total c.7000 ha. The patches in Dorset are mostly smaller (Figure 1), although the largest patch (Wareham Forest) and three of the five largest patches are in Dorset. The patches for both areas have broadly similar total areas of heathland and conifer, the two principal habitat types (Table 1).

Table 1: Comparison of the size and general features of the Dorset and Thames Basin Heath patches. The patch boundaries do not entirely match the SPA boundaries.

	Dorset Heaths	Thames Basin Heaths
Number of patches	61	23
Total area of patches (ha)	10,718	7,348
Median patch size (and range) (ha)	44 (4 – 1808)	132 (8 – 1543)
Total perimeter (km)	441	253
Number of access points	531	729
Number of access points with parking	277	158
Total number parking spaces	5,215	1,998
Number of houses within 5km of patches	229,410	287,903
Land area (ha) within 5km of patches (including the patches themselves)	101,031	76,335
Number of houses (within 5km) per ha of heathland	21.4	39.2
% of patch area designated as SPA	51	96
% of patch area dry heath	21	24
% of patch area mature conifer plantation	43	57
% of patch area clearfell	7	6

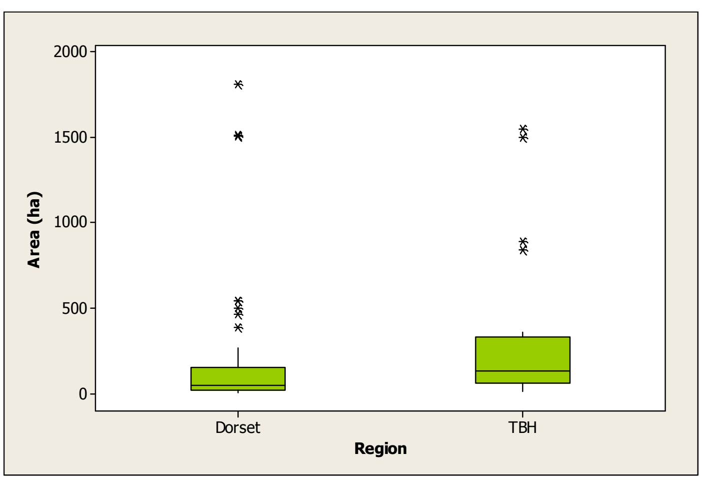


Figure 1: Area of patches in Dorset and the Thames Basin Heaths. The Dorset data includes all patches. For a description of how to interpret the box plots see methods.

The amount of housing around patches was calculated from postcode data for different distance bands from the patch boundary. The numbers of houses in each band was, as might be expected, highly correlated (Table 2). For example, the average housing density within 400m of a patch boundary has a correlation of 0.983 with the average housing density with 800m of a patch boundary over all patches

Table 2: Pearson correlation coefficients between housing densities within different distance bands away from the patch boundary. In all cases p<0.001; n = 81 patches surveyed for nightjars.

	<200m	<400m	<600m	<800m	<1000m	<1200m	<1600m	<2000m	<3000m
<400m	0.961								
<600m	0.960	0.989							
<800m	0.939	0.983	0.994						
<1000m	0.938	0.970	0.989	0.996					
<1200m	0.920	0.961	0.981	0.993	0.998				
<1600m	0.899	0.940	0.964	0.978	0.987	0.994			
<2000m	0.878	0.916	0.941	0.956	0.969	0.978	0.995		
<3000m	0.853	0.893	0.915	0.931	0.944	0.956	0.980	0.994	
<5000m	0.816	0.851	0.875	0.891	0.907	0.920	0.949	0.968	0.985

Most of the Dorset patches are less ‘urban’ than the Thames Basin ones. The median housing density for Dorset patches, within 1km of the patch boundary, is 0.36 per ha, which compares to 1.70 per ha in the Thames Basin Heaths. However, there is much less variation between the Thames Basin Heaths sites, and while most of the Dorset Heaths are more rural, there are also some sites surrounded with very high housing densities, much higher than the Thames Basin Heaths (Figure 2).

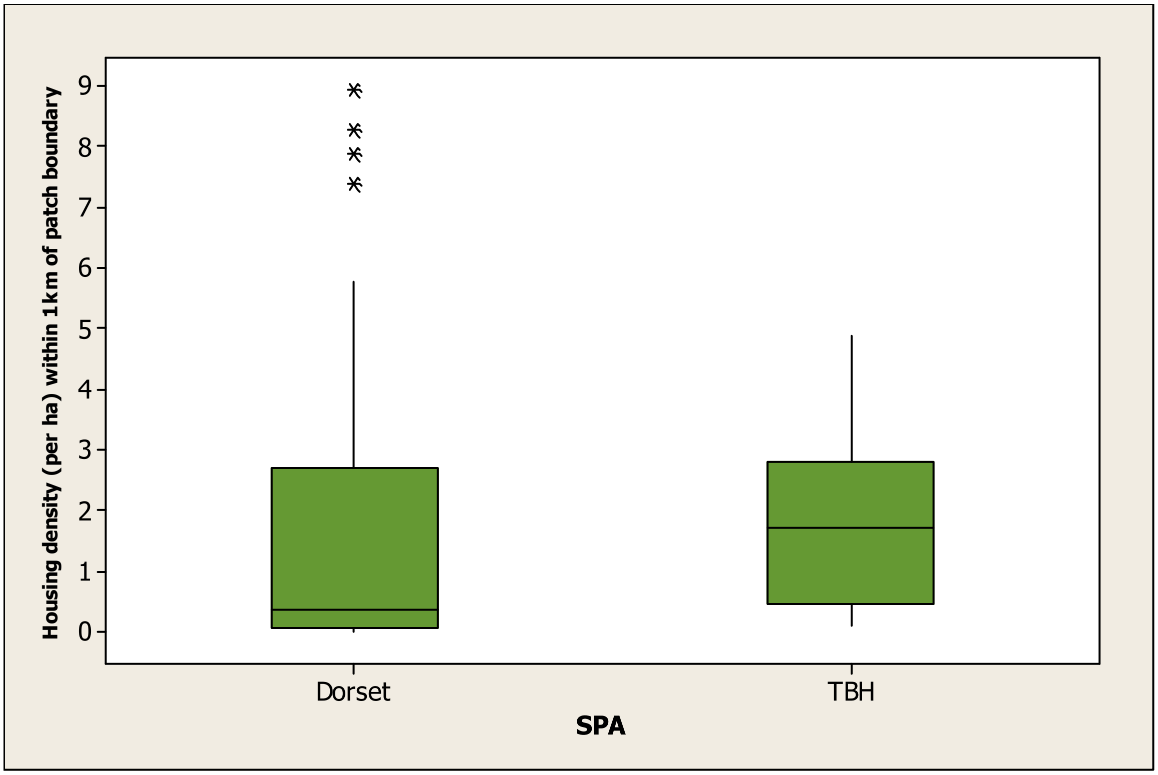


Figure 2: Boxplot showing housing density in the surrounding 1km of the Dorset and Thames Basin Heaths patches. The four outliers for Dorset (marked *) are Turbary Common, Bourne Valley, Talbot Heath and Alder Hills.

Models of Visitor Pressure

Factors which may influence visitor numbers at a specific access point are discussed in Liley *et al.* (2006) and include: the size of the human population living near the access point, the ease of access (e.g. a river or motorway may make reaching the site difficult), ease of parking / number of parking spaces, the number of other visitors (busy sites may be avoided by some people), facilities (toilets, cafes etc), the inherent quality of the site (e.g. the presence of viewpoints and wildlife) and the presence of alternative sites nearby. Many of these features are difficult to measure for all access points and not appropriate to a simple model of visitor numbers.

Using the combined visitor surveys data from the Dorset and Thames Basin Heaths, observed visitor numbers for 46 different access points were available. These data are presented in Appendix 1, which provides descriptions of each access point and presents the raw data from the visitor survey work. Our first approach was to extract, using a GIS with spatially-referenced postcode data, the total number of people[2] living at different distance bands extending away from each access point. In the questionnaire, visitors

[2] The postcode data provides details of the number of houses (residential properties) associated with each postcode, with each postcode stored within the GIS as point data spatially referenced by the centre of gravity of the postcode's map area. We extracted the postcodes within a given distance of each access point, and we convert these data to actual people by multiplying the number of houses by 2.36, the average number of occupants per UK residential property.

were asked for the postcode from where they had travelled (usually their home). From this we can derive the statistical distribution of the distances people travel to visit heaths; this varies depending on whether they arrived on foot or by car (Table 3, Figure 3). In Dorset, 85% of interviewed people arriving on foot ('foot visitors') came from within 1000m; in contrast, only 8% arriving by car ('car visitors') lived within 1000m. On the Thames Basin Heaths, 7% of car drivers came from within 1000m, and 80% of foot visitors came from within 500m. From this we concluded that the number of foot visitors and car visitors needed to be modelled and predicted separately.

Table 3: Percentage of people (adults only) travelling different distances to reach the heaths, from the respective visitor surveys (see Clarke *et al.*, 2006; Liley *et al.*, 2006a)

	Distance (m)						
	400	1000	2000	3000	4000	5000	10,000
TBH car visitors	1	7	28	39	51	62	80
TBH foot visitors	42	80	97	98	99	100	100
Dorset car visitors	2	8	26	39	52	72	98
Dorset foot visitors	1	85	88	92	93	94	98

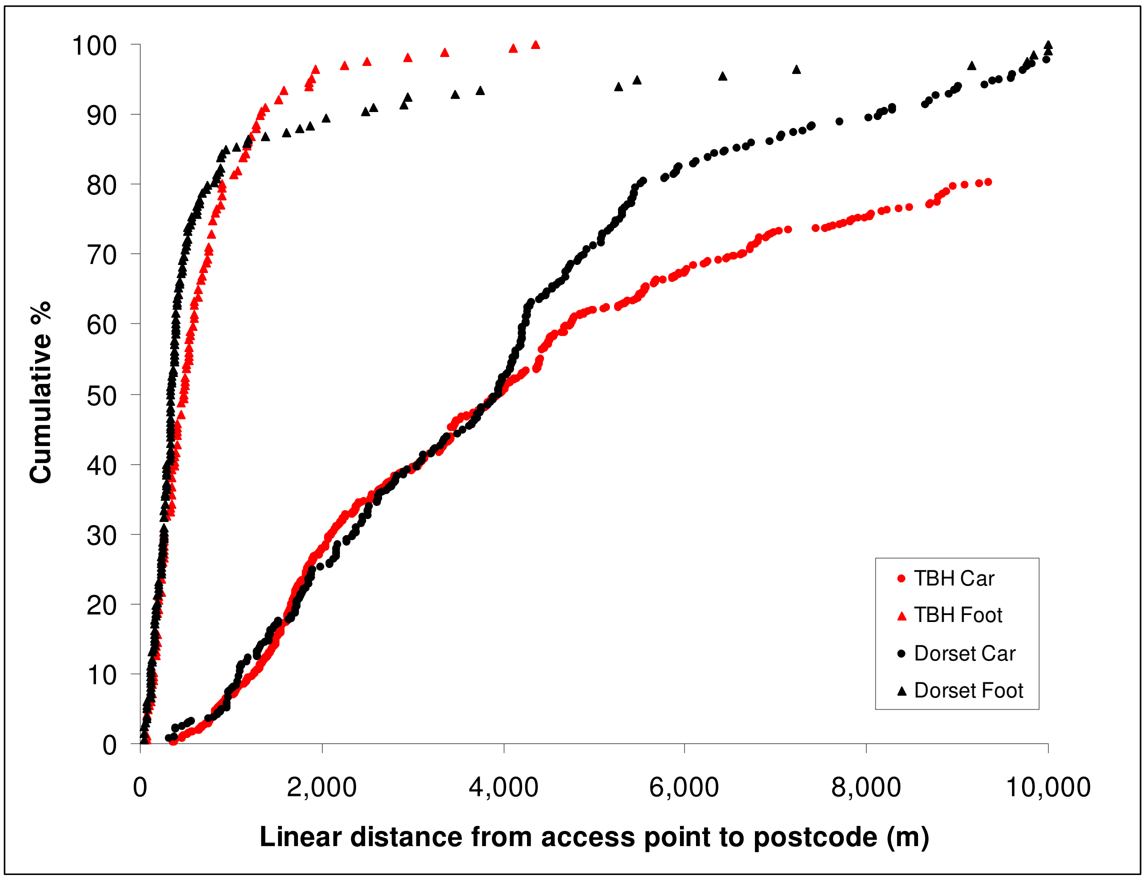


Figure 3: Distribution of the distances travelled to heath access points by car/van (circles) and on foot (triangles). Data accounts for group size (number of adults) in each party interviewed. Data are from the two visitor surveys on the respective SPAs (see Clarke *et al.*, 2006; Liley *et al.*, 2006a)

Models based on visitor rates within distance bands

We calculated the number of visitors coming from successive distance bands away from the access points. The number of visitors to an access point from each distance band could then be expressed as the proportion of residents within the distance band that visit the access point (and heath within a 16hr period). This can be calculated separately for each access point but due to the small numbers of visitors involved these proportions are usually subject to high levels of sampling variability. Moreover, individual characteristics and attractiveness of each access point (and patch) and its 'catchment' lead to large real variability in visitor rates between access points and patches. As an example of an outlier high visitor rate, 20 interviewed people visited Stoborough heath on foot from the 47 houses whose postcode was within 200-400m of the New Road access point. Based on the national average of 2.36 people per house, this equates to a visitor rate of 0.1803 (20/110.92), whereas the overall average visitor rate from this distance on foot across all surveyed access points in Dorset was only 0.0149 (see below).

However, we need estimates of such visitor rates to apply to the vast majority of other non-surveyed access points within the SPAs. Therefore, as a simple first step, more robust estimates of 'average' visitor rates (P_k) with any distance band k were obtained by dividing the total number of visitors within the distance band (summed over access points) by the total number of residents within the distance band (summed over access points) (Table 4, Table 5, Figure 4).

The foot visitor rates to the Dorset and Thames Basin heaths show similar patterns, rates are not consistently higher in one SPA; foot visitor rates for the TBH were slightly higher from distances of <200m but lower from distances of 200-400m. Car visitor rates for people living up to 3km tend to be higher for the TBH, although in the shortest distance band of 0-400m, rates were highest in Dorset.

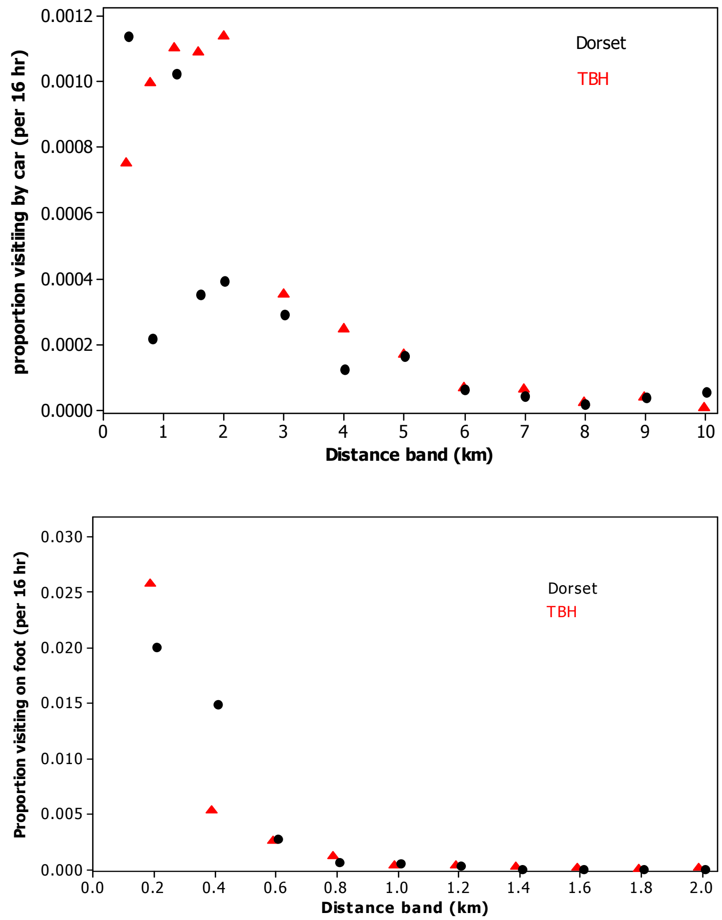


Figure 4: Proportion of residents visiting the site during the 16 hour survey period by car (top) and on foot (bottom), in relation to distance from the access point. These graphs are plotted by dividing the number of visitors interviewed that came from a distance band by the total number of people living within that distance band. Each point is calculated from the total residents and total visitors within that distance band summed over all access points within each SPA (Dorset (●), TBH (▲)).

Table 4: Overall numbers and proportions (P_k) of residents in distance bands from surveyed access points on the Dorset and Thames basin Heaths (TBH) SPAs who visited on foot (per 16 hr period).

Distance (km)	Total visitors on foot		Total residents		Proportion visiting (P_k)		
	Dorset	TBH	Dorset	TBH	Dorset	TBH	Overall
<0.2	43	34	2145	1317	0.020044	0.025819	0.022241
0.2-0.4	86	35	5763	6662	0.014923	0.005254	0.009738
0.4-0.6	27	33	9676	13126	0.002790	0.002514	0.002631
0.6-0.8	9	22	13355	17969	0.000674	0.001224	0.000990
0.8-1.0	10	9	17473	25686	0.000572	0.000350	0.000440
1.0-1.2	8	10	21547	28818	0.000371	0.000347	0.000357
1.2-1.4	1	8	29085	33694	0.000034	0.000237	0.000143
1.4-1.6	0	4	33604	38874	0.000000	0.000103	0.000055
1.6-1.8	2	0	40236	44727	0.000050	0.000000	0.000024
1.8-2.0	1	5	46350	51148	0.000022	0.000098	0.000062
2.0-2.2	2	0	47691	54905	0.000042	0.000000	0.000019
2.2-2.4	0	1	51453	61546	0.000000	0.000016	0.000009
2.4-2.6	3	1	57140	66271	0.000053	0.000015	0.000032
2.6-2.8	0	0	60064	69894	0.000000	0.000000	0.000000
2.8-3.0	3	1	62568	74989	0.000048	0.000013	0.000029
3-4	2	1	398210	472614	0.000005	0.000002	0.000003
4-5	0	2	467153	701371	0.000000	0.000003	0.000002
5-6	4	0	522605	814863	0.000008	0.000000	0.000003
6-7	1	0	457507	910974	0.000002	0.000000	0.000001
7-8	3	0	524892	989583	0.000006	0.000000	0.000002
8-9	0	0	635659	1176517	0.000000	0.000000	0.000000
9-10	4	0	699339	1263051	0.000006	0.000000	0.000002
>3km	14	3	3705365	6328973	0.000004	0.000000	0.000002

Table 5: Overall numbers and proportions (P_k) of residents in distance bands from surveyed access points on the Dorset and Thames basin Heaths (TBH) SPAs who visited by car (per 16 hr period).

Distance (km)	Total visitors by car		Total residents		Proportion visiting (P_k)		
	Dorset	TBH	Dorset	TBH	Dorset	TBH	Overall
<0.4	9	6	7908	7979	0.001138	0.000752	0.000944
0.4 - 0.8	5	31	23031	31095	0.000217	0.000997	0.000665
0.8 - 1.2	40	60	39020	54504	0.001025	0.001101	0.001069
1.2 - 1.6	22	79	62689	72568	0.000351	0.001089	0.000747
1.6 – 2.0	34	109	86586	95875	0.000393	0.001137	0.000784
2 - 3	81	116	278917	327606	0.000290	0.000354	0.000325
3 - 4	50	117	398210	472614	0.000126	0.000248	0.000192
4 - 5	78	118	467153	701371	0.000167	0.000168	0.000168
5 - 6	33	54	522605	814863	0.000063	0.000066	0.000065
6 - 7	19	59	457507	910974	0.000042	0.000065	0.000057
7 - 8	9	22	524892	989583	0.000017	0.000022	0.000020
8 - 9	24	46	635659	1176517	0.000038	0.000039	0.000039
9 - 10	39	6	699339	1263051	0.000056	0.000005	0.000023

Overall, given the large variability in visitor rates between individual access points, we concluded that it was best to combine the survey data for the two SPAs and use a single model of visitor rate with distance for both SPAs, but with separate models for visitors arriving by car and on foot.

These relationships between visitor rates and distance provide a potential method for predicting visitor numbers. For any particular access point in the SPA (not just those involved in the visitor survey questionnaire), we can use the GIS postcode database to determine the total number of people living within each distance band from the access point, multiply this by the estimated proportion predicted to visit from that distance and then sum across all distance bands to predict the expected number of visitors passing through that access point (within a similar 16 hour period). This predictive 'model', denoted model F1 and C1 for foot and car visitors respectively, can be expressed mathematically by:

Predicted numbers = sum over all distance bands k of (P_k x Res_k) (F1 and C1)

where P_k = visitor rate from distance band k (right-hand column of Table 4)
and Res_k = number of residents in distance band k from the access point

We tested the effectiveness of this approach by comparing the predicted number of visitors at each of the 46 surveyed access points with the actual number recorded at each access point during the survey questionnaire (Figure 5).

The predictions were not accurate. The amount of variation (R^2) in observed numbers explained (R^2 = 1 – (residual sum of squares) / (total sum of squares of observed values about their mean)) was 22% for foot visitors and less than zero for car visitors. There is so much variation between access points in visiting rates amongst those that come by car, that this simple, but intuitive, approach is not effective for predicting car visitor numbers. While the overall rates shown in Figure 4 provide an indication of the likelihood of visitors at different distance bands to visit sites, many sites do not seem to fit this pattern. There are probably a range of other unmeasured (or un-measurable) factors influencing how many people visit a particular heath via particular access points.

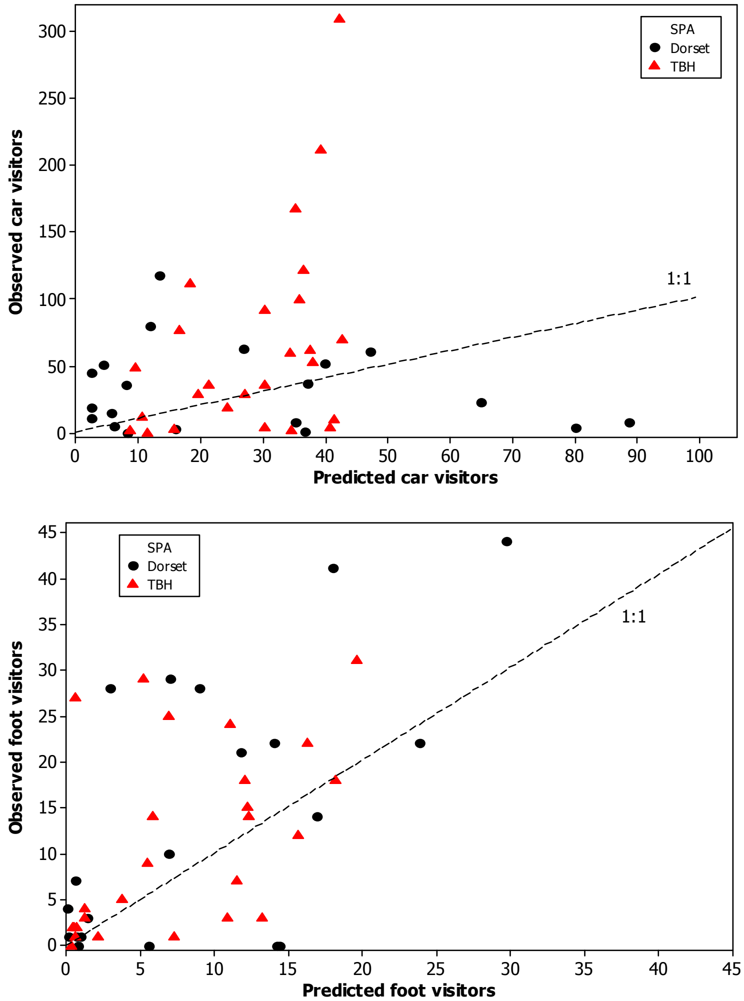


Figure 5: Observed (from the visitor surveys) versus predicted number of visitors (based on the overall visitor rate by distance data in Table 4) arriving by car (top) and on foot (bottom) for each site surveyed (20 sites in Dorset and 26 sites in the Thames Basin Heaths).

Regression-based predictive models

As an alternative to this intuitive modelling approach, we used multiple regression statistical models to predict visitor numbers using variables characterising the access point (e.g. parking space capacity, the number of residents living at specific distance bands and the number of alternative car-parks within 1km. The relationship between visitors numbers and predictor variables may also be non-linear. To overcome these problems, the regression relationships were fitted using Generalised Linear Models (GLM) (McCullagh and Nelder, 1989) with extra- Poisson distribution of model residuals, as used by Liley and Clarke (2003) (see Methods section for further details).

These statistical modeling approaches were conducted separately for visitors arriving on foot and for those arriving by car as they are influenced by different factors. The observed counts used in the analyses were the total number of visitors recorded over the 16 hour survey period at each access point (These can be converted to estimated daily rates later).

Predicting number of visitors arriving on foot

It was found that the number of foot visitors was related to the number of people living within a range of relatively short distance bands, especially 0-400m (R^2 = 37%), 400-800m (R^2 = 34%) and maximally for 0-800 (R^2 = 40%) (all test $p < 0.001$); moreover the percentage of variance explained (R^2) was less than 12% for all combinations of distance bands within the range 800m to 10km.

Although splitting the residents within 800m into two variables - the number of people residing with 0-400m and the number living between 400 and 800m (denoted 'NRes0-400' and 'NRes400-800' respectively) did not give a statistically significant improvement in model fit (least squares regression R^2 = 41%), the resulting model had more intuitive sense as the predictive Poisson GLM equation was (standard errors (S.E.) of regression coefficients given in brackets):

$$\text{Foot visitors(per 16hr)} = \underset{(1.43)}{4.09} + \underset{(0.00783)}{0.00631}\ \text{'NRes0-400'} + \underset{(0.00206)}{0.00394}\ \text{'NRes400-800'} \quad \text{(F2)}$$

The intercept term of 4.09 was statically significant and represents the base average number of visitors on foot which cannot be attributed to the density of nearby housing. It was initially tempting to interpret the coefficients as implying that, on average, an additional 0.631% of people living within 400m and a smaller 0.394% of people living 400-800m away will visit a heath on foot within a typical 16 hour visiting period. However, these rates differ from the observed foot visitor rates from these distance bands of 1.246% ((43+34+86+35) / (2145+1317+5763+6662)) and 0.168% (91/54126) respectively (Table 4). Although over 80% of foot visitors do live within 800m, using model equation (F2) to predict foot visitor numbers for other access points would imply no effect of increased housing beyond 800m on foot visitor numbers, which is not true.

Therefore, our recommended model for predicting number of visitors arriving on foot is model F1 based on the observed overall visitor rates by distance band approach, given by equation (F1) and the observed overall foot visitors rates in Table 4.

Predicting number of visitors arriving by car

For people arriving by car ('car visitors'), the number of car-park spaces at each access point was a highly significant predictor of visitor numbers (Figure 6, test $p < 0.001$), and in no model could the simple regression prediction be improved through the inclusion of the number of residents at any particular distance bands, or the number of alternative car parking spaces within 500m or 1000m. Due to the inherent considerable variability between access points, there is no definitive method to determine the optimum form of the statistical relationship between car visitor numbers and the number of car parking spaces. We (see also Liley et al., 2006, in press) derived a predictive Poisson GLM equation, whereby the numbers visiting by car was related to the square root of the number of car parking spaces (denoted '√CarParkSpaces') at the heath access point, as follows (standard errors (S.E.) of regression coefficients given in brackets):

$$\text{Car visitors (per 16hr)} = \underset{(1.61)}{15.31}\ \sqrt{\text{CarParkSpaces}} \qquad \text{(C2)}$$

Various other forms of the relationship between these two variables were also assessed. However, the form of equation eventually selected for use in predicting car visitors to other access points in the Dorset and TBH SPAs was the following simple log-log relationship (R^2=41%):

$$\text{Log}_e(\text{Car visitors} + 1) = \underset{(0.338)}{1.551} + \underset{(0.1397)}{0.7703}\ \text{Log}_e(\text{CarParkSpaces} + 1) \qquad \text{(C3a)}$$

The relationship on these log-log transformed scales appear to be approximately linear, although there is now some suggestion that the (proportional) residual variance in visitor numbers is slightly greater when there are relatively few car park spaces (Figure 6).

Equation C3a can be re-written as:

$$\text{Car visitors (per 16hr)} = 4.716\ (\text{CarParkSpaces})^{0.7703} - 1 \qquad \text{(C3b)}$$

This implies that the number of car visitors increases with the number of car park spaces raised to the power of 0.77, rather than to the power 0.5 implied in model C2; a power coefficient of 1 would imply visitor numbers are directly proportional to the number of car park spaces; model C3 implies a moderate tendency for increases in visitors numbers with increases in car parking spaces to be less for larger car parks. Because this predictive equation was derived by back-transforming a regression relationship derived on the log-log scale, the estimates for a given number of car park spaces will for the geometric mean number of car visitors, rather than the higher arithmetic mean numbers (which can be strongly influenced by one or more observations of unusually high visitor numbers). For this study, the geometric mean, which should also approximate the median for a given level of parking space, is considered to be most appropriate for the majority of access points.

Table 6 shows the practical effect of predictive equation (C3) for a range of car parking spaces; one space implies on average 7 visitors arriving by car, two spaces give a predicted average visitor rate of 10 people, while a large car park with 50 spaces is predicted to lead to, on average, nearly 100 (96) visitors per 16 hour visiting period.

Access points with no immediately adjacent parking spaces are still predicted to attract, on average, 4 visitors per 16 hr period who drove from home by car; this is not unreasonable as there are often places to park short distances away from some access points, such as on residential roads in nearby housing estates. As an extreme example, 52 people interviewed at the St Catherine's access point north of Christchurch said they drove from home to visit the SPA and parked away from the access point which has no space to park directly adjacent to the access point itself. This also highlights the problem of characterising the features and facilities of access points. The prediction from model C3 was always within the observed range of car visitors to the surveyed access points with the same or similar level of car park spaces, apart from for the two access points with no spaces for which the observed visitors by car (11 and 52) was greater than the 4 predicted (Table 6).

Table 6: Observed and predicted number of visitors arriving by car (per 16hour visiting period) in relation to the number of car parking spaces at a heath access point; predictions based on log-log model equation C3. Observed visitor numbers based on the 46 Dorset and TBH access points.

Car park spaces		0	1	2	4	6	10	20	50	100	200	400	800
Predicted visitors arriving by car based on model C3		4	7	10	15	20	29	48	96	164	279	476	812
Observed car visitors	spaces	0	1	2	3-4	5-8	10-15	16-25	35-65	120	200		
	n	2	4	7	7	7	6	7	4	1	1		
	mean	31	19	11	7	37	47	85	125	92	309		
	min	11	2	0	1	4	3	10	77				
	max	52	53	29	19	60	70	167	211				

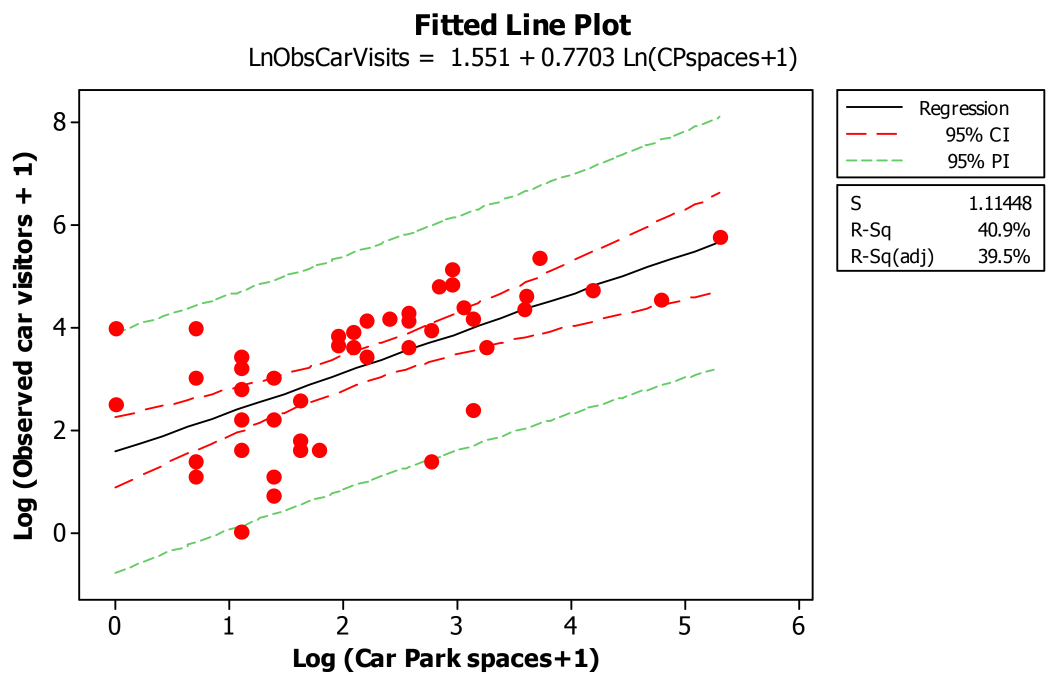


Figure 6: Linear regression relationship (model equation C3) between the logarithm (to base e) of the observed number of visitors arriving by car ($\log_e(y+1)$) and the logarithm of the number of car parking spaces at each access point ($\log_e(x+1)$) for the 46 Dorset and THB access points.

There was no statistically significant difference (i.e. p>0.05) in the estimated model C3 log-log relationship between the Dorset and Thames Basin Heath SPAs (Figure 7). Therefore this single model based on the combined survey data was assumed to be valid for both SPAs.

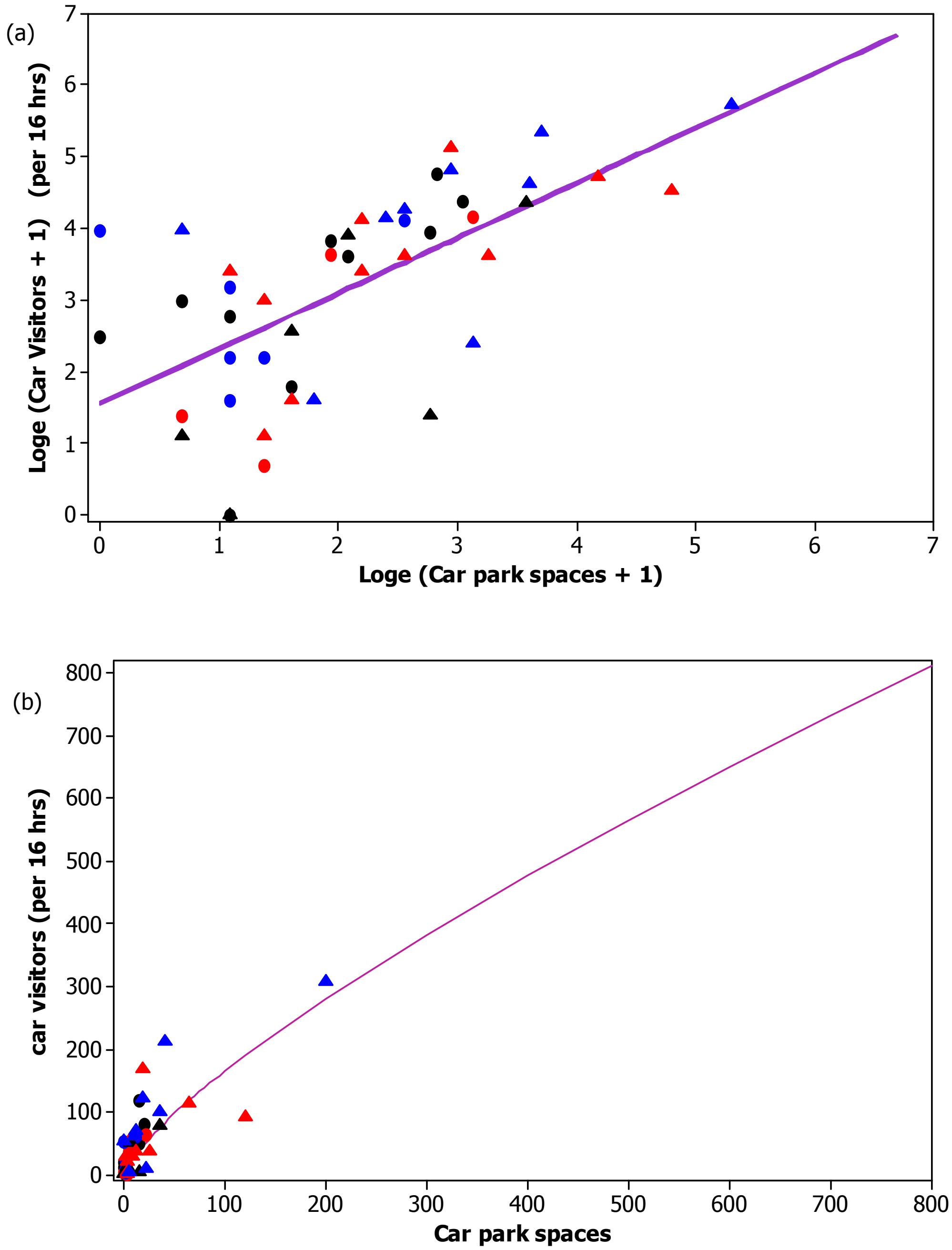


Figure 7: Observed and model C3 fitted relationship between number of visitors arriving by car and the number of car parking spaces at each access point (Dorset (circle), TBH (triangle); residents within 5km (black = <45000, red = 45000-150000, blue = >150000); (a) log-log model C3a, (b) back transformed model C3b plotted up to the maximum of 800 car park spaces estimated for any access point in either SPA.

Models based on visitor rates in relation to distance and car park spaces

Having established that car visitor rates vary and generally decline with distance from the access point and that the overall number of visitors by car is related to the number of car park spaces available at the access point, we then tried to combine these two features into the following model which assumes the car visitor rate versus distance curve is dependent on the amount of car parking spaces.

The 46 surveyed access points were divided into three roughly equal-sized groups based on their number of car park spaces (13 (28%) with 0-2 spaces, 20 (44%) with 3-15 spaces, and 13 (28%) with 16-200 spaces and the observed rates of visiting by car from each distance band calculated independently for each of the three groups (Table 7, Figure 8).

Table 7: Observed overall car visitor rates from distance bands, separately for access points with 0-2, 3-15 and 16-200car parking spaces; these rates form the basis of model C4.

Distance (km)	Total visitors by car			Total residents			Proportion visiting		
	0-2	3-15	15-200	0-2	3-15	15-200	0-2	3-15	15-200
<0.4	4	9	2	6936	6898	2053	0.000577	0.001305	0.000974
0.4 - 0.8	2	20	14	15283	25861	12982	0.000131	0.000773	0.001078
0.8 - 1.2	20	41	39	24747	41925	26852	0.000808	0.000978	0.001452
1.2 - 1.6	14	44	43	31931	69004	34321	0.000438	0.000638	0.001253
1.6 – 2.0	18	46	79	45149	86772	50539	0.000399	0.000530	0.001563
2 - 3	34	71	92	176908	240840	188774	0.000192	0.000295	0.000487
3 - 4	11	25	131	253511	337815	279497	0.000043	0.000074	0.000469
4 - 5	17	56	123	312551	476482	379490	0.000054	0.000118	0.000324
5 - 6	4	37	46	343087	580678	413703	0.000012	0.000064	0.000111
6 - 7	2	32	44	291840	655804	420838	0.000007	0.000049	0.000105
7 - 8	2	7	22	290950	781408	442118	0.000007	0.000009	0.000050
8 - 9	6	9	55	408131	889430	514615	0.000015	0.000010	0.000107
9 - 10	0	15	30	434754	921504	606131	0.000000	0.000016	0.000050

The overall car visitor rate to access points with 3-15 car parking spaces is higher than to access points with two or fewer car park spaces at all distances (except 8-9km). Moreover, at all distances, the visitor rate to access points with the largest class of car park spaces (16-200 spaces) is at least twice as high as, and up to six times higher than, the rate for access points with fewer spaces (the only exception is for within 400m of the access points for which car visitor rates were slightly higher at intermediate levels of car park spaces (Table 7, Figure 8).

For any specific access point, the appropriate group's car visitor rate curve for the number of car park spaces at the access point can be used to derive a prediction of the expected number of visitors by car to that point (termed model C4), as follows:

Predicted car visitors at an access point with car park spaces in group *i* (C4)
= sum over all bands *k* of (P_{jk} x Res_k)
where P_k = visitor rate from band *k* amongst access points in car park group *j*

and Res_k = number of residents in distance band k from the access point

This model is an improvement of the single car visitor rate curve of model C1 and the amount of variation (R^2) in observed car visitor numbers explained (R^2 = 1 – (residual sum of squares) / (total sum of squares of observed values about their mean)) by model C4 was 18% (Figure 9).

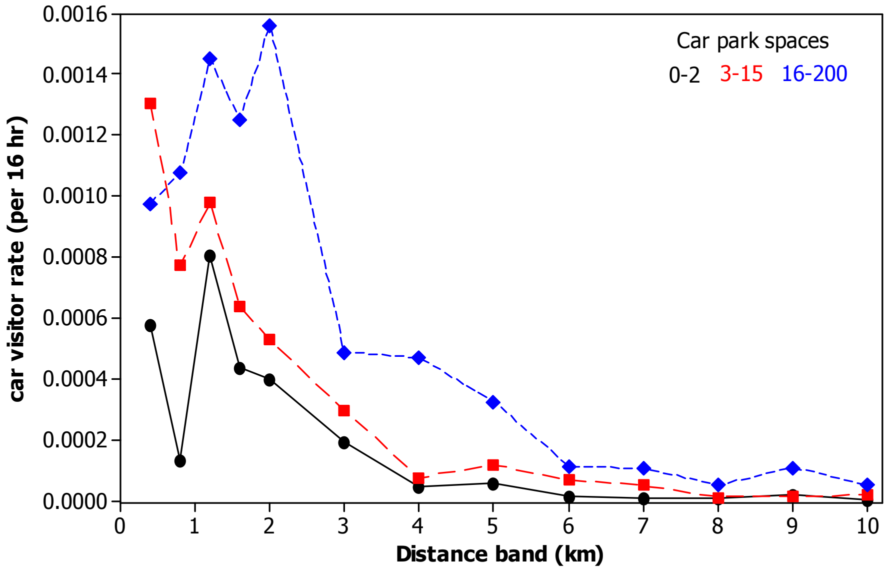


Figure 8: Observed overall car visitor rates from distance bands, separately for access points with 0-2 (●), 3-15 (■) and 16-200 (♦)car parking spaces; these curves form the basis of model C4.

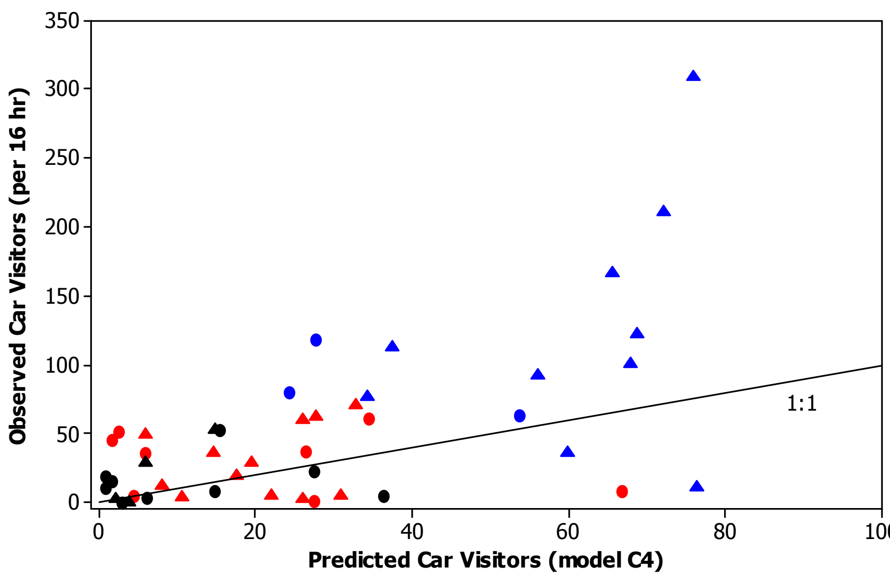


Figure 9: Observed and predicted number of visitors arriving by car to each access point (Dorset (circle), TBH (triangle); car park spaces (black = 0-2, red = 3-15, blue = 16-200); prediction is based on model equation C4.

Although model C4 is an improvement in fit over the single visitor rate versus distance curve of model C1, it still tends to under-predict car visitor numbers at access points with high numbers of car parking spaces. We could have tried to sub-divide the surveyed access points into more groups based on their car park spaces, but instead chose to try to fit models which related the visitor rate from any distance band to any particular access point to continuous mathematical functions of both distance and the number of car park spaces at the access point.

The relationships was fitted using Generalised Linear Models (GLM) (McCullagh and Nelder, 1989), treating the observed car visitor rate from a distance band to any particular access point as having a binomial distribution (i.e. r visitors out of n residents) and log-link model. To allow for the residual variability being greater than that expected for a simple Binomial error distribution, the standard errors of the regression model coefficients obtained by fitting a Binomial likelihood were automatically increased by the appropriate factor ($\sqrt{k}$), where k is the fitted model residual mean deviance (McCullagh & Nelder 1989, p199-200).

Several forms of model were assessed but the best overall model (C5), with all coefficients highly significant ($p < 0.001$) was (standard errors (S.E.) of regression coefficients given in brackets):

$$\text{Log}_e(\text{Car visitor rate}) = \underset{(0.130)}{-6.293} - \underset{(0.0458)}{0.7780}\ \text{Distance}_k + \underset{(0.00965)}{0.10125}\ \text{Distance}_k.\text{Log}_e(\text{CarParkSpaces}) \qquad \text{(C5a)}$$

where Distance_k = distance band k from the access point. As observed car visitor rates from distances up to 1km or even 2 km show no consistent trends (Figure 8), and some rates were based on low numbers of visitors, the data were combined prior to model fitting so that all distances up to 1.2 km were treated as 1.2km and all distances of 1.2-2.0 km were treated as 2.0km.

Table 8 and Figure 10 show the predicted car visitor rates based on model C5 for a range of distance bands and number of car park spaces. Under model C5, for a given number of car park spaces, the visitor rate is assumed to be constant for distances up to 1.2km, as suggested by the observed survey data, and thereafter declines exponentially by a constant proportion per kilometre.

Equation (C5a) can be re-expressed as:

$$\text{Log}_e(\text{Car visitor rate}) = -6.293 - (0.7780 - 0.10125\ \text{Log}_e(\text{CarParkSpaces}))\text{Distance}_k \qquad \text{(C5b)}$$

which indicates how the exponential rate of decline in visiting rate with distance decreases with the number of car park spaces. This suggests that people may tend to drive further to an access point which they know has lots of spaces to park a car.

Model C5 gives an improvement in fit over model C4 with the amount of variation (R^2) in observed car visitor numbers explained (R^2 = 1 – (residual sum of squares) / (total sum of squares of observed values about their mean)) increasing from18% to 29% (Figure 11).

Table 8: Predicted car visitor rates based on model C5 in relation to distance band from access point and number of car parking spaces at the access point

Distance (km)	Number of car parking spaces								
	0	2	5	10	20	50	100	200	800
0.0 - 1.2	0.0007270	0.0008308	0.0009038	0.0009729	0.0010524	0.0011722	0.0012737	0.0013847	0.0016380
1.2 – 2.0	0.0003901	0.0004873	0.0005608	0.0006340	0.0007227	0.0008650	0.0009933	0.0011419	0.0015108
2 - 3	0.0001792	0.0002502	0.0003088	0.0003712	0.0004518	0.0005916	0.0007280	0.0008973	0.0013656
3 - 4	0.0000823	0.0001284	0.0001701	0.0002174	0.0002825	0.0004046	0.0005336	0.0007051	0.0012343
4 - 5	0.0000378	0.0000659	0.0000937	0.0001273	0.0001766	0.0002767	0.0003911	0.0005541	0.0011157
5 - 6	0.0000174	0.0000338	0.0000516	0.0000745	0.0001104	0.0001893	0.0002866	0.0004354	0.0010085
6 - 7	0.0000080	0.0000174	0.0000284	0.0000436	0.0000690	0.0001294	0.0002101	0.0003421	0.0009115
7 - 8	0.0000037	0.0000089	0.0000156	0.0000256	0.0000431	0.0000885	0.0001540	0.0002689	0.0008239
8 - 9	0.0000017	0.0000046	0.0000086	0.0000150	0.0000270	0.0000605	0.0001128	0.0002113	0.0007447
9 - 10	0.0000008	0.0000024	0.0000047	0.0000088	0.0000169	0.0000414	0.0000827	0.0001660	0.0006731

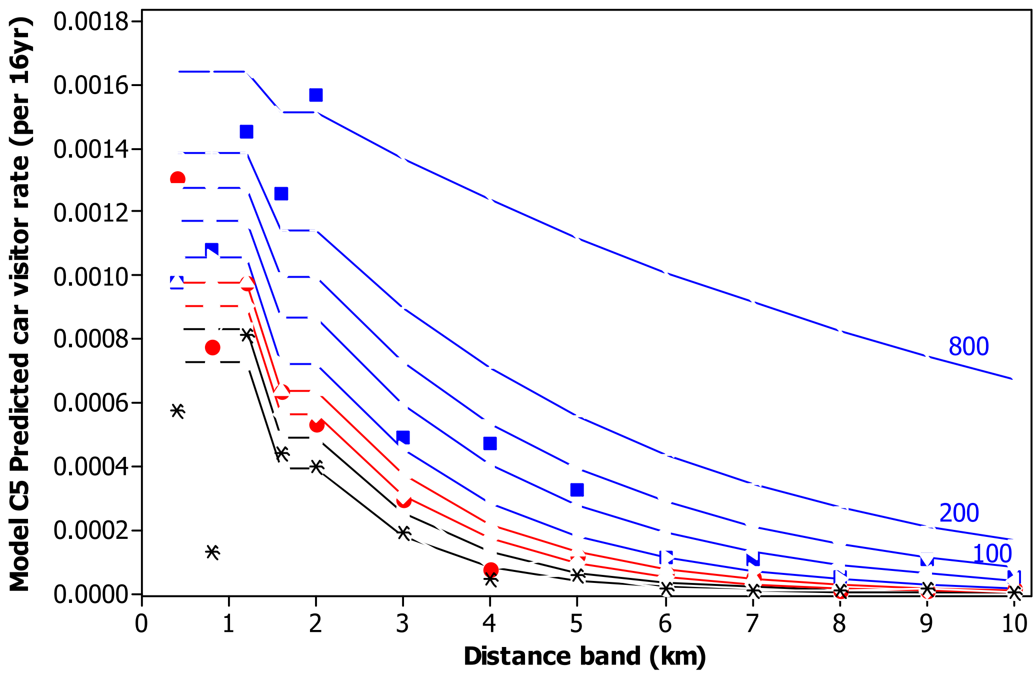


Figure 10: Car visitor rates predicted from model C5 in relation to distance bands and car park spaces (0, 2, 5, 10, 20, 50, 100, 200, 800), together with overall observed car visitor rates (as in Figure A2.7) for access points with 0-2 (●), 3-15 (■) and 16-200 (♦)car parking spaces.

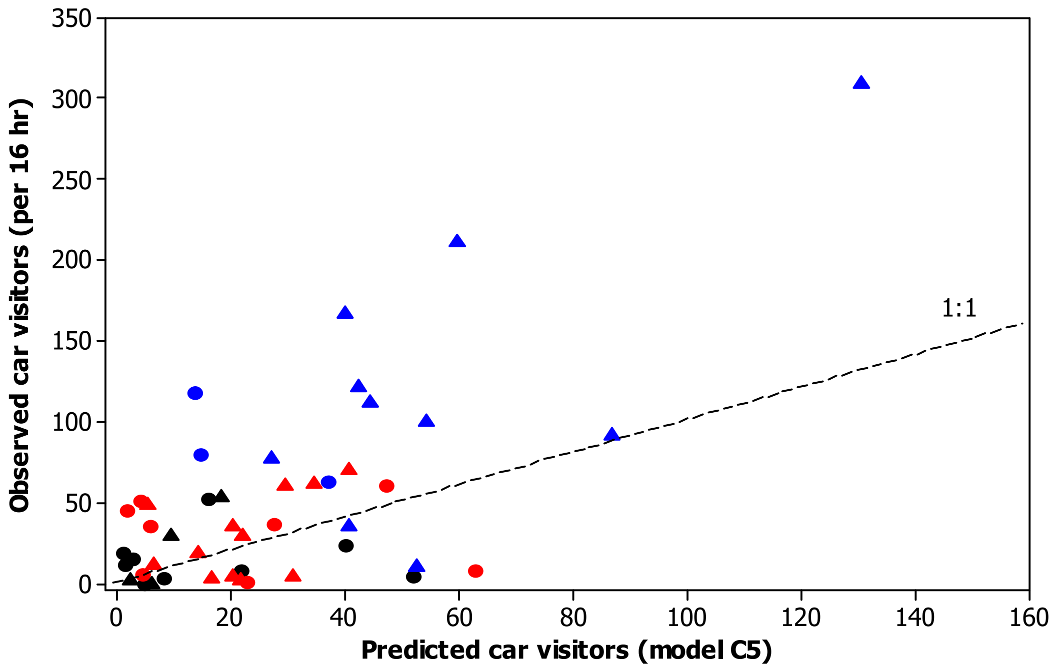


Figure 11: Observed and predicted number of visitors arriving by car to each access point (Dorset (circle), TBH (triangle); car park spaces (black = 0-2, red = 3-15, blue = 16-200); prediction is based on model equation C5.

Predicting total numbers of visitors

Model F1 is the recommended equation for predicting the number of visitors who walk to an access point. The number of visitors who travel by car can be predicted from either model equation C3 (based on the number of car park spaces only) or model equation C5 (whereby visitor rates of surrounding residents depend on both their distance away and the number of car park spaces at the access point).

The combination of the two predictions, namely for foot visitors (PREDFOOT) and for car visitors (PREDCAR), provides a means of determining the total number of visitors arriving at an access point by car or by foot. A small number of people also arrived by other means (e.g. bike, horse, public transport). To incorporate these additional people, we then assumed their numbers would be related to the total numbers arriving by car and foot and so we calculated the observed number of 'Others' as a percentage of those arriving by foot and car combined for each access point. We took the median percentage value of 3% across all access points as our adjustment factor.

A further adjustment was required as the equations above have been derived using the data on the number of people interviewed. Not all people leaving the site were interviewed – for example some declined, and therefore the count of people actually leaving (and thus visiting) the site was higher. Specifically, the relationship between the number interviewed and the total number of visitors was accurately described (r^2 = 95%) by the simple regression (Figure 12):

Total numbers of visitors leaving = 1.423 * Number of people interviewed

Combining these two factors (i.e. for 'Others' and non-interviewees) gives a correction factor of approximately 1.45 to apply to the predicted overall numbers of interviewees arriving by car and by foot.

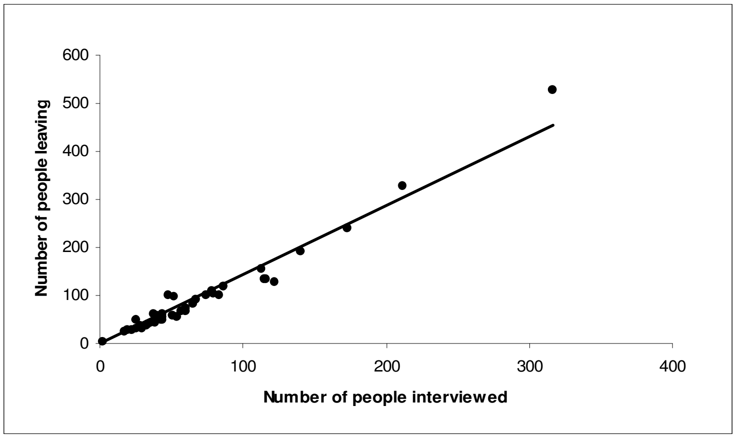


Figure 12: Relationship between the number of people interviewed at each site and the number of people leaving. Regression equation: y = 1.423x, r2 = 0.95.

The predicted total number of visitors at a given access point was therefore calculated as follows:

Predicted total visitors (PREDTVISIT) = 1.45 * (PREDFOOT + PREDCAR) (T1)

These overall estimates (PREDTVISIT) are for the total of the number of people predicted to visit over 16 hours of surveying, during a weekend and week-day in the summer.

Plotting the spatial distribution of visitors

Having derived predictions of the expected number of visitors to each access point, the next step was to derive estimates of the expected spatial distribution of visitors within each heathland patch on the Dorset Heaths SPA. This was done as follows.

<u>50m grid of pixels within the SPA, grouped in heathland access patches</u>

(i) A grid of 50m x 50m cells was drawn to cover the land area of the Dorset Heaths SPA. Any grid squares not within the SPA boundary were deleted.
(ii) Each column on the grid was identified with a letter and each row with a number, allowing each cell within the grid to have a unique identifier. They were also identified by their National Grid Reference (NGR) Easting and Northing in metres.
(iii) Visitors passing through an access point are assumed to only visit cells on the same patch.
(iv) Cells covering areas where visitors either cannot or obviously do not walk (e.g. valley mires) were identified and excluded ("exclusion cells") from the statistical prediction of the spatial distribution of visitor pressure within the patches.

Heathland patch penetration distance

(v) It was not possible to obtain or derive the precise distance that an interviewed person had travelled into the heath. However, Clarke *et al* (2005) and Liley *et al* (2005) both recorded the route that each visitor claimed they had followed. After inputting all of the routes into a GIS, the distance from the access point to the mid-point of a route was taken as the penetration distance. The frequency distribution of distances that visitors travelled on the Dorset and Thames Basin heaths were generally similar (although penetration distance was naturally less on some of the smaller Dorset heath patch). The data from the two visitor surveys were combined to give a single overall probability distribution of penetration distances (Figure 13). This distribution was intentionally based on 50m intervals of penetration distances. Using this single distribution for all patches, regardless of size, is not unreasonable, as most people will walk around most of a very small patch and this will be predicted in the spatial model using the overall distribution based on penetration distances onto all patches (For example, on a patch only 300m wide most people will tend to walk all across and around it and using the overall penetration distribution in Figure 13 predicts that about 90% of people will walk 300m from an access point)

Visitor pressure in each 50m cell

(vi) Given the predicted number of visitors (V_i) passing through an access point *i*, we can use this cumulative penetration distribution to estimate the proportion (Pi_d) of visitors who penetrate at least *d* metres onto the heath from this access point.

(vii) In terms of mapping visitor pressure in this study, we assume that all parts (i.e. cells) on a patch can potentially be reached and/or impacted by visitors, apart from those already identified as "exclusion cells". (Obviously this is not strictly true as, for example, stands of dense scrub are much less easily accessed.)

(viii) Each visitor who penetrated a distance *d* on the heath is assumed to travel over *K* cells at each of the 50m distance classes up to a distance *d* from the access point. In our estimates we set *K* equal to 2 (but 3 might also be a reasonable number if a circular route is assumed !)

(ix) For each access point *i* we determine the number of pixels (M_{id}) on the same patch within each distance class *d* from the access point.

(x) Then the estimated number of people N_{id} travelling from a particular access point *i* across a particular cell at a distance class *d* from the access point is estimated by:

$$N_{id} = V_i * P_{id} * K / M_{id}$$

(xi) The total number of people visiting a particular cell from all access points on the same patch is estimated by summing the estimates of the number of visitors to the cell from the individual access points.

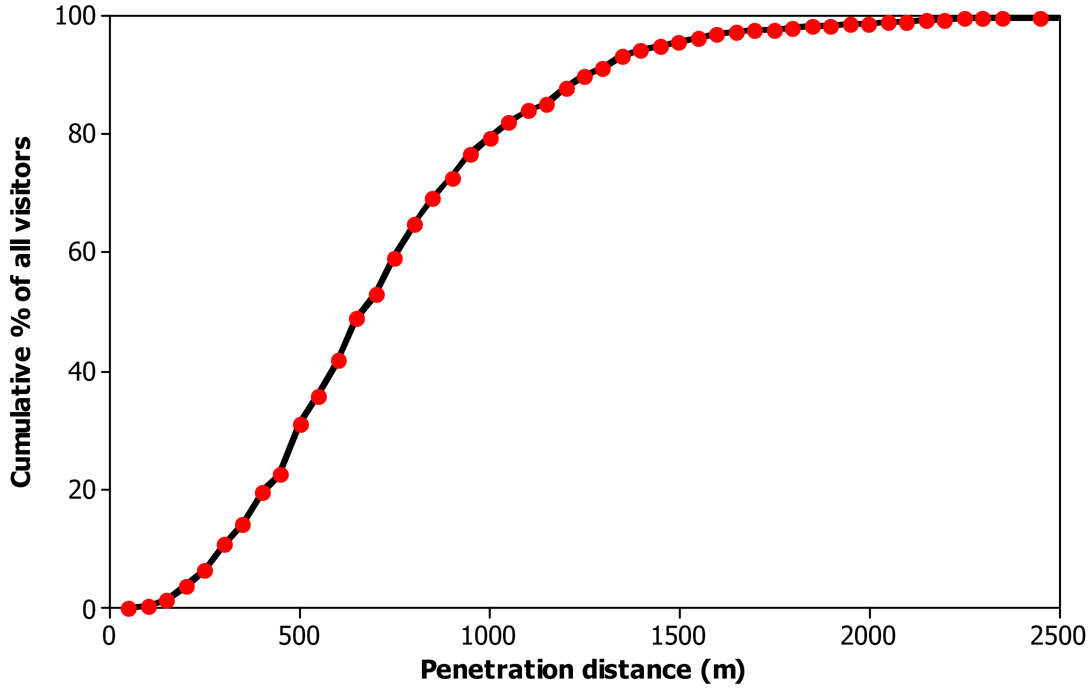


Figure 13: Cumulative frequency distribution of the penetration distance onto heaths by all visitors combined.

Places (i.e. pixels) on the heath which are either not near any access points or only near access points with very low expected numbers of visitors will, as might be expected, have low predicted visitor pressure. However, our detailed modelling, predictions and spatial analysis has allowed us to derive quantitative estimates of the absolute and relative density of visitors throughout each part of each SPA heathland patch

Summary of model predictions

The predicted visitor totals, by patch, are summarised in Appendix 2. The predictions for both model C3 and C5 are given for each patch. It can be seen that the two models do give different estimates of visitor levels. Model C3 predicts car visitors entirely on the basis of car-park size. Model C5 predicts car-visitors based both on housing levels surrounding the access point and on car-park size. The discrepancies between the two models will therefore be most acute where small car-parks occur surrounded by high densities of housing (model C5 will predict higher visitor levels than model C3), or where large car-parks occur in areas with little or no housing (model C3 will predict many more visitors than model C5). The differences between the two models highlight the differences between the two areas. For Dorset both models predict in the region of 20,000 people per 16 hours in August, a figure which roughly equates to 5 million visits per annum (Table 9). Model C3 predicts the higher total for Dorset, yet it can be seen that a large proportion of this prediction (one quarter) of the visitors are predicted to visit Studland and Hengistbury, the two sites with very large car-parks adjacent to sandy beaches. Model C5 predicts far fewer visitors to these sites than C3, and C5 predicts the higher numbers of visitors to the more urban heaths – those surrounded with high densities of housing.

In the Thames Basin Heaths there is a huge difference between the two models, with C5 predicting over double the number of visitors predicted by C3. This is because model C5 predicts higher totals for sites with more housing surrounding them, and as Figure 2 shows, the Thames Basin Heaths are typically surrounded by more housing than the Dorset Heaths. The differences between the two models are informative in themselves, and highlight the difficulty in extrapolating from a small data set (only 4% of the access points to which the model predictions were applied were sampled and surveyed). However, the models are also based on standardised data and the analyses do show significant trends. The two models in essence provide a maximum and a minimum for the site concerned, and crucially, provide relative values across the sites which can be used to identify areas with high and low visitor pressure.

It is clear that visitor pressure levels are, on average, higher on the Thames Basin Heaths. The median visitor pressure in Dorset is considerably lower in both models. While the visitor levels are typically low across much of the Dorset Heaths, certain parts of the Dorset Heaths patches receive very high visitor pressure, much higher than any of the sites in the Thames Basin Heaths, where the visitor pressure is more evenly spread. This high pressure is associated with the more urban heaths (such as Bourne Valley, Alder Hills and Canford). The highest visitor pressures predicted by the model are at the two coastal patches Studland / Rempstone and Hengistbury, where there are very large car-parks.

Table 9: Comparison of predictions of visitor pressure or the Thames Basin and Dorset Heaths (using Model C3). The annual total is an approximation, calculated by converting the 16 hour total to an hourly rate by dividing by 16, then multiplying this value by 12 (to give a daily rate) and then by 365 to give an annual rate.

	TBH		*Dorset*		*Dorset, excluding Hengistbury & Studland*	
Total no. grid squares	29,498		42,969		36,666	
Total area of covered by grid (ha)	7374. 5		10,742.25		9,166	
	Model C3	Model C5	Model C3	Model C5	Model C3	Model C5
Median value of visitor pressure per 50x50m pixel	9.6	10.6	4.3	1.3	4.5	1.5
Total predicted visitors per 16 hours in Aug.	17,954	37,796	20,211	17,450	14,895	16,047
Estimate of annual visitor totals	4,914,907	10,346,645	5,532,761	4,776,963	4,077,566	4,392,866

Maps 7 and 8 show the spatial distribution of visitor pressure within the two SPAs at the same scale for both models. The higher visitor pressure on the Thames Basin Heaths is clear, and in addition the variation in the spatial distribution of visitor pressure is clear. The impact of the large car-parks (for example Studland, Hengistbury and the north of Broadmoor and Bagshot SSSI) is evident. Site size and shape can also be seen to influence visitor numbers. On long thin sites, such as Bourne Valley in Dorset or Horsell Common in the Thames Basin Heaths, visitors penetrate to the middle of the site and therefore visitor pressure is fairly uniform across the site. On very large, circular sites, such as Broadmoor and Bagshot SSSI (Crowthorne Wood), the middle of the site has much fewer visitors through it than the edges of the site.

Site/Patch level analysis

Comparison of nightjar numbers and densities between Dorset and Thames Basic Heaths

In total there were 523 nightjars recorded for the Dorset Heaths patches and just over half that total on the Thames Basin Heaths patches (276 nightjars). For three of the Dorset patches however the nightjar survey data was incomplete; either the whole patch (Town Common & St. Catherine's and West Moors Plantation) was not surveyed, or part of the patch (Ringwood Forest and Moors Valley) was not surveyed. These three sites were therefore excluded from our analysis, and with these three patches excluded there were a total 464 nightjars in 8,906 ha across 58 Dorset patches. These 58 patches are used in subsequent analyses.

The nightjar density overall was higher on the Dorset Heaths and even the areas of Dorset patches outside the SPA had a higher nightjar density than those areas within the Thames Basin Heaths SPA (Table 10).

Table 10: Area of patches and number of nightjars within and outside the SPA in each area. The patches are the visitable patches we have defined to encompass heath and forestry associated with the SPA (see methods).

	Thames Basin Heaths Patches			***Dorset Heaths Patches***		
	SPA	Non-SPA	Total	SPA	Non-SPA	Total
Area of patches (ha)	7,033	315	7,348	5,113	3793	8,906
Number of nightjars	275	1	276	431	155	464
Nightjar density	0.039	0.003	0.038	0.084	0.041	0.052

The total of 464 nightjars in the 2004 survey on 58 Dorset patches compared to 276 on 23 Thames Basin sites (Table 11). This total of 729 nightjars accounts for approximately 16% of the UK nightjar population (see Conway et al., (in prep)). Although the total area of the 58 Dorset patches (8906 ha) is 21% greater than the total area of the 23 TBH patches (7348 ha), the overall average density of nightjar across each region was still higher in Dorset (0.052 nightjar ha^{-1}) than for the TBH (0.038 ha^{-1}). However, because of the considerable variability in mean nightjar density per patch within each region, the differences between the Dorset patch densities and the TBH patch densities were not statistically significant when assessed by either a Student's two-sample t-test (t=1.81, d.f.=79, p =0.073) or a Mann-Whitney test based on the ranked densities (test p = 0.117 adjusted for ties) (Table 11).

Table 11: Comparison of nightjar numbers and densities (per ha) on the (a) total area and (b) 'heathland' area of the Dorset and Thames Basin Heaths patches.

	(a) Total area of patch			Heathland area of patch		
	Dorset	TBH	Both	Dorset	TBH	Both
Patches	58	23	81	58	23	81
Total nightjars over all patches	464	276	740	329	204	533
Total area over all patches(ha)	8906	7348	16254	4578	2897	7475
Overall nightjar density (ha^{-1})	0.052	0.038	0.046	0.072	0.070	0.071
Mean of patch densities (ha^{-1})	0.055	0.036	0.049	0.083	0.068	0.079
St.Dev. of patch densities (ha^{-1})	0.046	0.028	0.042	0.075	0.053	0.069
Median of patch densities (ha^{-1})	0.049	0.027	0.041	0.073	0.066	0.070
Maximum of patch densities (ha^{-1})	0.204	0.098	0.204	0.275	0.180	0.275
Patches with no birds	13	3	16	15	5	20
Patches with 1 bird	13	4	17	11	4	15
Patches with 2 birds	6	3	9	8	2	10
% of patches with ≤ 2 birds	55%	43%	52%	59%	48%	56%
% of patches with ≤ 4 birds	64%	52%	60%	67%	57%	64%
Max nightjars on a single patch	103	63	103	67	48	67
Student's t test for SPA differences in mean Nightjar density	t = 1.81, p = 0.073			t = 0.91, p = 0.368		
Mann-Whitney test for SPA differences in median density	p = 0.117 (adjusted for ties)			p = 0.567 (adjusted for ties)		

Conifer plantations covered 37% of total area over all mapped patches in Dorset and a massive 57% of the total area of mapped patches in the Thames Basin heaths. Although numerous nightjar territories were recorded in conifer plantations during the 2004 survey (118 in Dorset and 68 in TBH), the density of nightjars in conifer plantation (0.036 ha^{-1} in Dorset and 0.016 ha^{-1} in TBH) is much lower than the average in the patches (Figure 14). Analysis of nightjar numbers and densities was therefore also calculated for those habitats and parts of the patches which were more open habitat and which, for simplicity, we label as 'heathland' (* in Table 12).

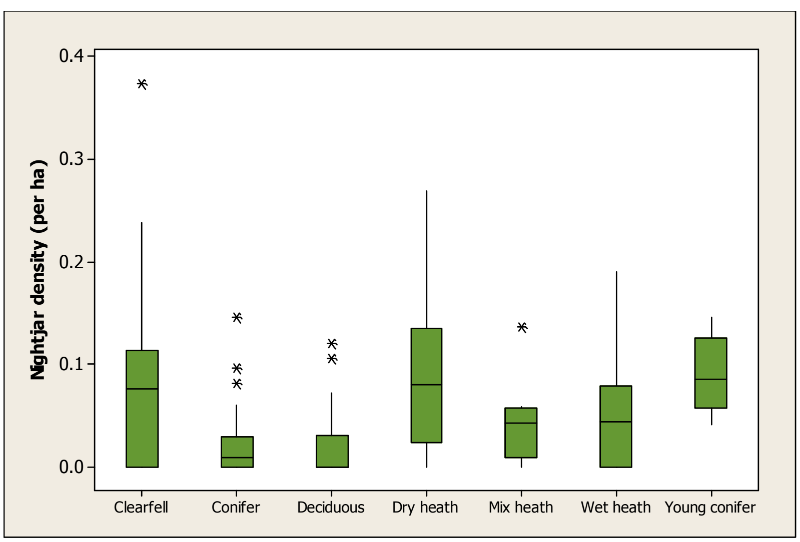


Figure 14: Nightjar density per site, by habitat. Density is calculated as the number of birds divided by the area (ha) at each site. Densities were calculated for each patch, but only when at least 5ha of the habitat was present.

When restricted to ‘heathland’ habitats, the mean density of nightjars per patch was higher, for Dorset (0.083 ha^{-1}) and especially for the TBH (0.068 ha^{-1}). There were no statistically significant differences between the two SPAs in mean nightjar density on ‘heathland’ per patch (Table 11).

Table 12: Total area, total number of nightjar and overall nightjar density for each habitat type across the Dorset patches, TBH patches and all patches combined. * indicates ‘heathland’ habitats.

Habitat		Total area (ha)			Total Nightjar			Overall Nightjar density		
		Dorset	TBH	Both	Dorset	TBH	Both	Dorset	TBH	Both
Clearfell	*	585	430	1015	59	30	89	0.101	0.070	0.088
Conifer		3271	4166	7437	118	68	186	0.036	0.016	0.025
Deciduous		446	17	463	10	1	11	0.022	0.059	0.024
Dry heath	*	2204	1749	3954	180	133	313	0.082	0.076	0.079
Farmland		2	17	19	0	0	0	0.000	0.000	0.000
Grassland		452	115	567	6	1	7	0.013	0.009	0.012
Mix heath	*	9	307	316	0	16	16	0.000	0.052	0.051
Other		166	135	301	1	2	3	0.006	0.015	0.010
Sand heath	*	25	96	121	0	3	3	0.000	0.031	0.025
Scrub	*	11	0	11	0	0	0	0.000	-	0.000
Wet heath	*	1608	171	1779	76	15	91	0.047	0.088	0.051
Young conifer	*	136	143	279	14	7	21	0.103	0.049	0.075

Correlations between nightjar density and surrounding housing density

Liley & Clarke (2003) found statistically significant negative correlations (r) for the Dorset heathlands between nightjar density (per ha) on a patch and the percentage cover of developed land (as derived from aerial photographs) within the surrounding buffer zones of 250m (r = -0.58), 500m (r = -0.59) and 750m (r = -0.58). They also found that percentage cover of developed land was very highly correlated (r = 0.95) with the density of residential properties (i.e. houses) in the same 500m buffer zone (Figure 2 in Liley & Clarke 2003), and consequently nightjar density was also negatively correlated with housing density within the 500m buffer zone (r = -0.55).

In our current study, we calculated the correlation between nightjar density on a patch (based on the 2004 nightjar survey) and the housing density within a range of distances from the edge of each patch, separately for the Dorset and Thames Basin Heaths (TBH) patches and for the two SPA datasets combined (Table 13). The correlations were calculated for nightjar density based on the whole patch area and also based on the 'heathland' area only. These simple negative correlations of whole patch nightjar density with housing density for Dorset were similar (- 0.373 to -0.417) and statistically significant (all p<0.01) for each distance range up to the assessed maximum of 5km; although correlations marginally peaked at distance limits of between 800 and 2000m (Table 13).

For the Thames Basin Heaths, the negative correlations of whole patch nightjar density with housing density were slightly stronger (-0.425 to -0.481) than those for Dorset for housing distance limits up to 800m. However, because the TBH comprise and/or were divided into far fewer patches, the statistical degrees of freedom are much less and the correlations were therefore statistically significant (p<0.05) only for distances up to 800m; correlations thereafter decrease in strength with distance (Table 13(a)).

Table 13: Correlations between nightjar density (per ha) (based on (a) whole patch area and (b) 'heathland' habitat area) and the density of houses (per ha) within each of a range of distance limits from the heath patch edge; separately for the 58 Dorset patches, 23 TBH patches and combined SPA data. *, **, * denote correlation is statistically significant at the 0.05, 0.01 and 0.001 probability level respectively.**

Distance band	(a) based on whole patch area			(b) based on 'heathland' area only		
	Both	Dorset	TBH	Both	Dorset	TBH
<200m	-0.377 ***	-0.383 **	-0.463 *	-0.371 ***	-0.354 **	-0.535 **
<400m	-0.377 ***	-0.373 **	-0.481 *	-0.367 ***	-0.346 **	-0.522 *
<600m	-0.389 ***	-0.387 **	-0.454 *	-0.376 ***	-0.358 **	-0.495 *
<800m	-0.396 ***	-0.398 **	-0.425 *	-0.380 ***	-0.369 **	-0.456 *
<1000m	-0.401 ***	-0.408 **	-0.385	-0.380 ***	-0.376 **	-0.412
<1.2km	-0.403 ***	-0.413 **	-0.347	-0.376 ***	-0.378 **	-0.365
<1.6km	-0.404 ***	-0.417 **	-0.292	-0.370 ***	-0.379 **	-0.298
<2.0km	-0.400 ***	-0.416 **	-0.254	-0.364 ***	-0.379 **	-0.250
<3km	-0.388 ***	-0.404 **	-0.209	-0.356 **	-0.378 **	-0.175
<5km	-0.371 ***	-0.383 **	-0.102	-0.351 **	-0.382 **	-0.054

Very similar patterns of correlations between nightjar density and housing density were found when nightjar density was restricted to the 'heathland' habitats area; although correlations with housing density were generally slightly higher than before for the TBH and slightly lower than before for Dorset (Table 13 (b)). For the Thames Basin Heaths the correlation between nightjar density on 'heathland' patches and housing density was statistically significant up to housing distance limits of 200m, 400, 600m and 800m, but peaking at 200m (r = -0.535, p =0.009).

Figure 15 (a) shows the relationship between whole patch nightjar density and housing density within 400m (Zone A in the Thames Basin Delivery Plan). For both the Dorset and TBH regions, there is a tendency for nightjar density to be relatively low when housing density within 400m is relatively high, in agreement with the simple (Pearson) correlation analysis (Table 13). The Spearman rank correlations (r_s) between these two variables are slightly stronger for Dorset (r_s=-0.401, p=0.002), slightly weaker for TBH (r_s=-0.368, p=0.084) and slightly stronger for the combined region data (r_s= -0.418, p<0.001). Figure 15(b) shows the corresponding relationships with housing density within 400m when nightjar density is restricted to the area of open 'heathland' habitats.

There are statistically significant correlations between nightjar density and housing density within each SPA region when based on any distance (200m, 400m 600m) up to 800m from the patch edges (Table 13). Figure 16 and Figure 17 show the relationship between nightjar density and housing density within 200m and 600m of the patch edges respectively; the patterns of relationships are of broadly similar strength. Obviously, a subset of the housing within 600m of a patch is also within 400m and a further subset is within 200m, so housing densities within different limits will be partially correlated (Table 2).

Visually, the relationship between nightjar density and housing density within 400m is very similar for the Dorset and TBH regions (Figure 15). One difference between the datasets for the two SPAs is that the housing density within 400m currently reaches higher levels in Dorset than the TBH. Moreover, none of the five Dorset patches with housing densities within 400m above 5 houses per hectare have any nightjars present (the five patches (areas in brackets) are Turbary Common (40.4ha), Bourne Valley (37.6ha), Bourne Valley-Talbot Heath (35.9ha), Alder Hills (4.6ha) and 'Lytchett adjacent to sewage station' (7.2ha)). In contrast, none of the 23 patches defined for the TBH has a current housing density within 400m greater than 4.4 houses per hectare.

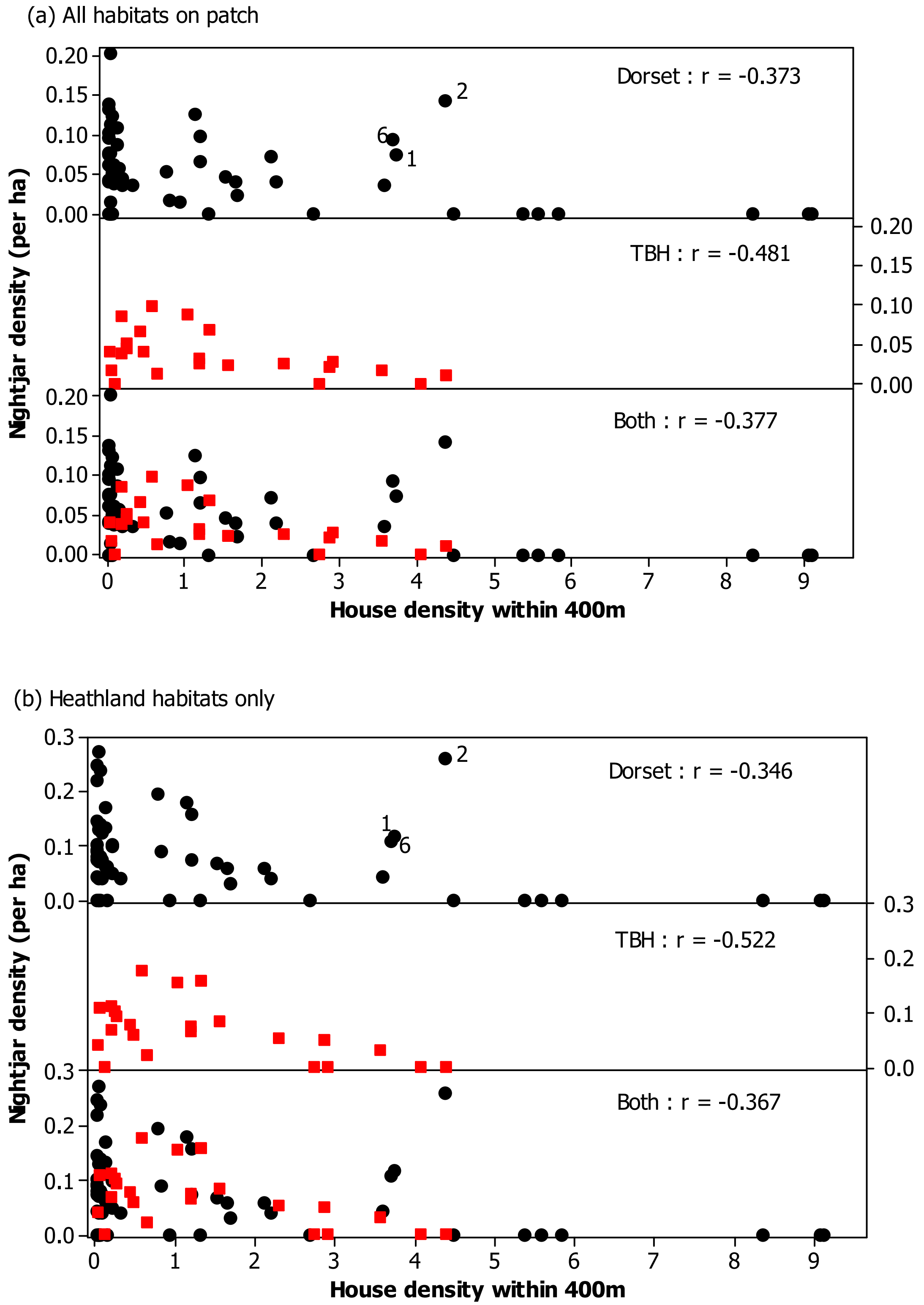
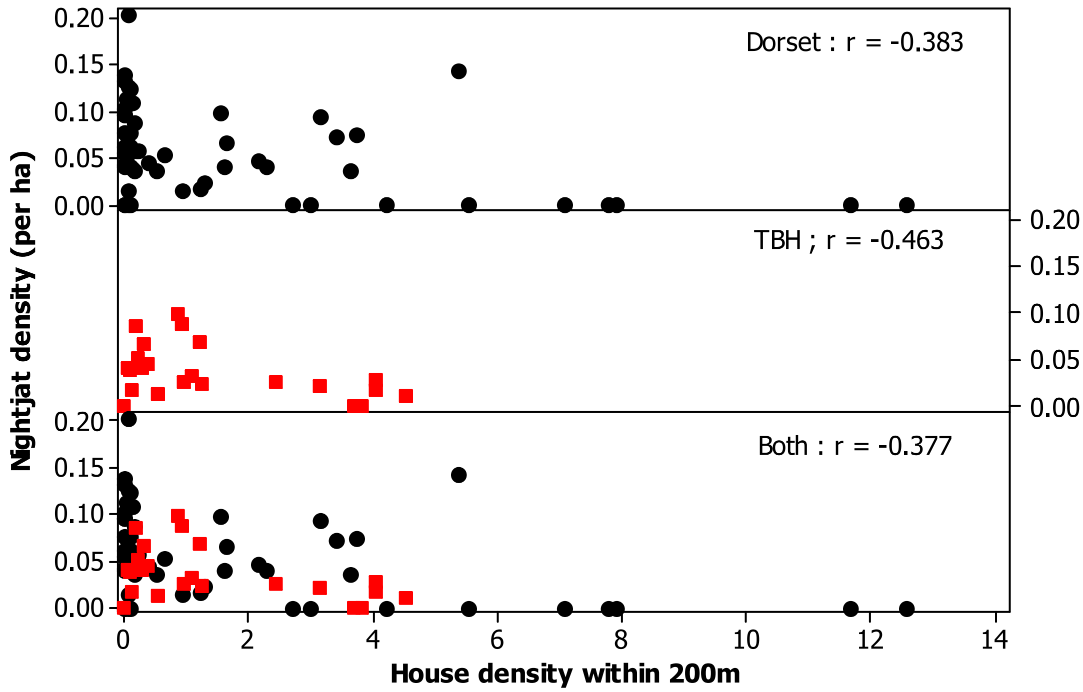


Figure 15: Relationship between nightjar density (ha^{-1}) and housing density (ha^{-1}) within the surrounding 400m, based on (a) all habitats on patch and (b) open heathland habitats only, for 58 Dorset patches (●), 23 Thames Basin Heath patches (■) and combined SPA data; numbers indicate nightjars present on three 'outlier' Dorset patches.

(a) All habitats on patch



(b) Heathland habitats only

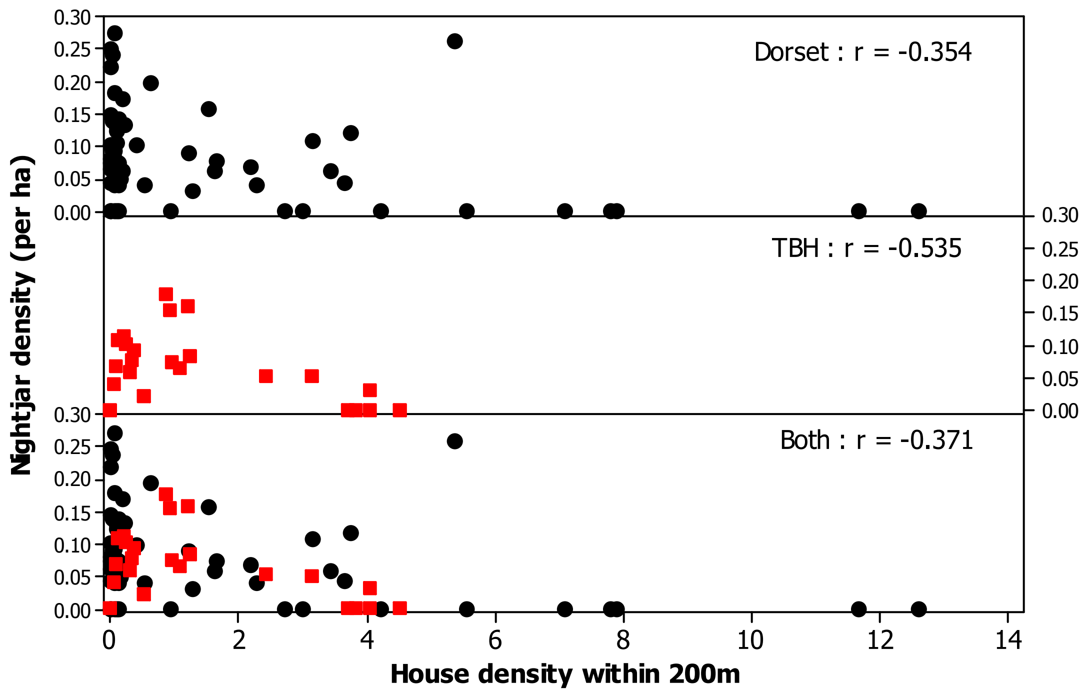
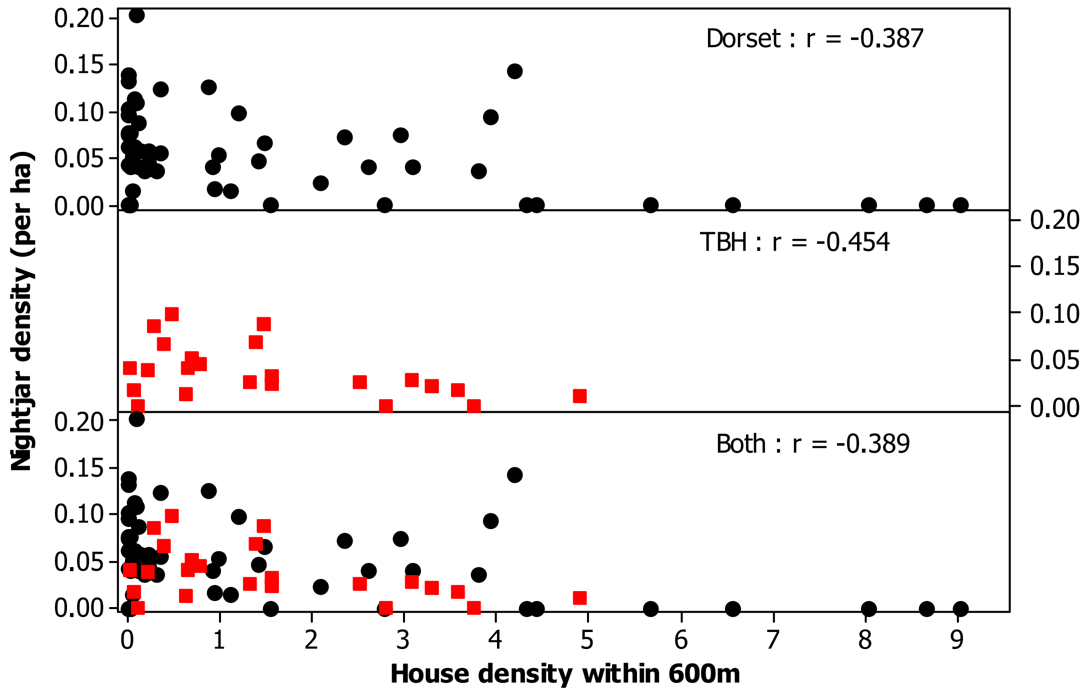


Figure 16: Relationship between nightjar density (ha^{-1}) and housing density (ha^{-1}) within the surrounding 200m, based on (a) all habitats on patch and (b) open heathland habitats only, for 58 Dorset patches (●), 23 Thames Basin Heath patches (■) and combined SPA data.

(a) All habitats on patch



(b) Heathland habitats only

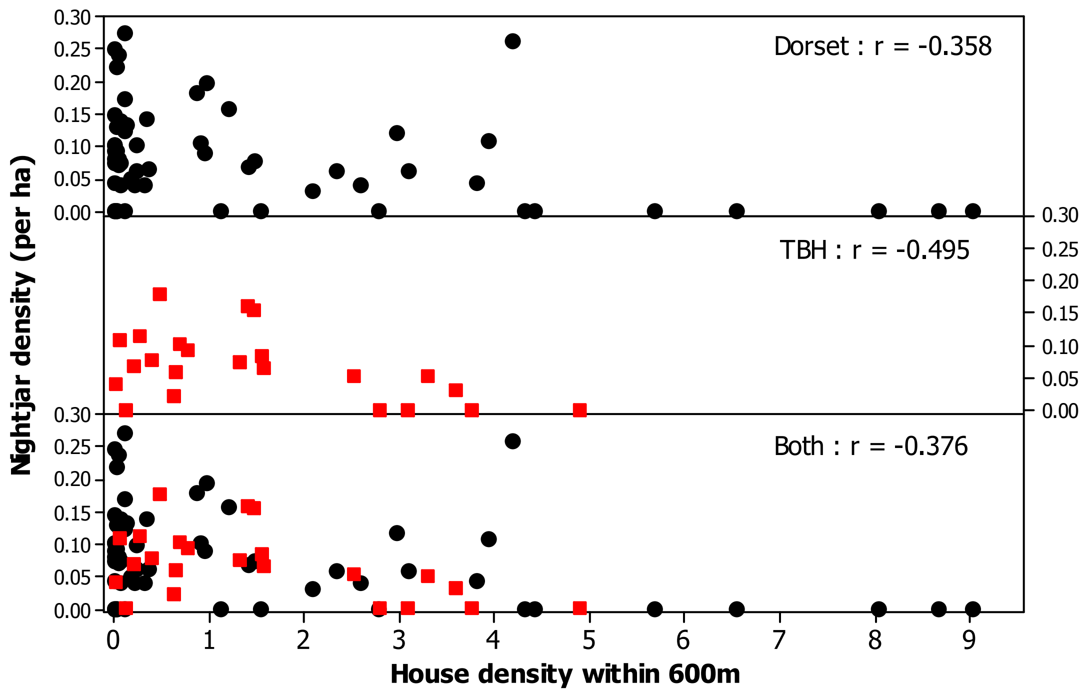


Figure 17: Relationship between nightjar density (ha^{-1}) and housing density (ha^{-1}) within the surrounding 600m, based on (a) all habitats on patch and (b) open heathland habitats only, for 58 Dorset patches (●), 23 Thames Basin Heath patches (■) and combined SPA data.

Regression relationships between log nightjar numbers, log patch area and housing density

The main outliers from the general relationship between nightjar density and housing density in Figure 15 are three Dorset patches, but these only had one, two or six nightjar present (highlighted in Figure 15). This highlights the statistical estimation problem that densities based on very few birds will be subject to very high levels of sampling variability (one detected bird more or less could sometimes double or half the estimated density); therefore at least two of the three outliers in Figure 15 should not be given much weight.

Because nightjars are a relatively rare species, only very low numbers are found on many patches. Fifty-five percent of the 58 patches in Dorset and 43% of the 23 patches in the Thames Basin heaths had two or less nightjars (Table 11).

More generally, as noted by Liley and Clarke (2003), 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. Following the same approach as Liley and Clarke (2003), the relationship was therefore assessed using Generalised Linear Models (GLM) (McCullagh & 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 (e.g. housing density). The following form of relationship was fitted as:

$$\text{Nightjar numbers on patch} = \exp(\ a + b \log_e(\text{Patch area}) + c\ (\text{Housing density})) \qquad (\text{E1})$$

where 'exp' denotes the exponential function. Model (E1) was fitted separately for the Dorset patches, the Thames Basin Heaths patches and all patches combined, and using the housing density within a distance of 200m, 400m, 600m, 800m, 1200m, 1600, 2km, 3km or 5km from the patch boundary.

The relationship was also fitted to the data based on the area and numbers of nightjars within the 'heathland' habitats only, namely:

$$\text{Nightjars on heathland} = \exp(a + b \log_e(\text{Heathland area}) + c\ (\text{Housing density})) \qquad (\text{E1H})$$

The results of the various model fits are summarised in Table 14. Based on these extra-Poisson GLM (equation E1), the partial relationship of nightjar numbers per patch with housing density (adjusted for whole patch area) was actually statistically significant (i.e. $p < 0.05$) for all distance limits up to 5km for the Dorset patches (and for regions combined), but significant only up to a limit of 800m when based solely on the 23 TBH patches.

When both nightjar numbers and patch area were restricted to the part of the patch composed of 'heathland' habitats, (equation E1H) the effect of housing density remained statistically significant up to distances of 5km for the Dorset patches and combined region data. However, amongst the heathland areas of the 23 TBH patches, housing density was only statistically significant (i.e. $p < 0.05$) for a distance of 200m, although it was almost significant for distances of 400m (p = 0.055) and 600m (p = 0.067) (Table 14).

Table 14: Generalised Linear Model relationship (with extra-Poisson residual distribution) between nightjar numbers ($log_e(X+1)$) and the combined effect of (log_e) patch area and housing density within a distance of 200m, 400m, 600m, 800m and 1000m; test probability *p* values <0.05 highlighted in bold; residual mean deviance for model likelihood fits ranged from 1.40-2.67 for whole patch models and 1.24-2.02 for heathland only models.

		regression coefficient (± S.E.)			
	distance (m)	constant	log_e(Area)	house density	house density test *p*
Whole patch area					
Combined	200	-2.418 ± 0.277	0.912 ± 0.042	-0.188 ± 0.057	**0.001**
	400	-2.431 ± 0.270	0.917 ± 0.041	-0.224 ± 0.061	**0.001**
	600	-2.440 ± 0.269	0.920 ± 0.041	-0.206 ± 0.055	**0.001**
	800	-2.451 ± 0.266	0.924 ± 0.041	-0.213 ± 0.054	**0.001**
	1000	-2.470 ± 0.264	0.928 ± 0.041	-0.203 ± 0.052	**0.001**
Dorset	200	-2.652 ± 0.287	0.961 ± 0.045	-0.113 ± 0.053	**0.039**
	400	-2.657 ± 0.291	0.961 ± 0.045	-0.126 ± 0.061	**0.045**
	600	-2.652 ± 0.289	0.961 ± 0.045	-0.123 ± 0.057	**0.036**
	800	-2.630 ± 0.289	0.959 ± 0.045	-0.131 ± 0.059	**0.029**
	1000	-2.628 ± 0.287	0.959 ± 0.044	-0.130 ± 0.056	**0.025**
TBH	200	-2.199 ± 0.641	0.865 ± 0.095	-0.280 ± 0.126	**0.038**
	400	-2.303 ± 0.621	0.889 ± 0.093	-0.317 ± 0.135	**0.029**
	600	-2.368 ± 0.630	0.899 ± 0.094	-0.266 ± 0.121	**0.040**
	800	-2.439 ± 0.629	0.913 ± 0.095	-0.260 ± 0.120	**0.043**
	1000	-2.498 ± 0.635	0.922 ± 0.096	-0.237 ± 0.116	0.055
Heathland area only					
Combined	200	-1.757 ± 0.238	0.862 ± 0.042	-0.208 ± 0.054	**0.001**
	400	-1.810 ± 0.242	0.871 ± 0.043	-0.208 ± 0.057	**0.001**
	600	-1.812 ± 0.241	0.874 ± 0.042	-0.195 ± 0.052	**0.001**
	800	-1.835 ± 0.243	0.879 ± 0.042	-0.188 ± 0.052	**0.001**
	1000	-1.855 ± 0.242	0.883 ± 0.042	-0.178 ± 0.050	**0.001**
Dorset	200	-1.696 ± 0.265	0.845 ± 0.048	-0.186 ± 0.060	**0.003**
	400	-1.716 ± 0.269	0.847 ± 0.049	-0.194 ± 0.064	**0.004**
	600	-1.701 ± 0.266	0.847 ± 0.048	-0.191 ± 0.060	**0.002**
	800	-1.695 ± 0.266	0.847 ± 0.048	-0.197 ± 0.060	**0.002**
	1000	-1.701 ± 0.264	0.849 ± 0.047	-0.193 ± 0.058	**0.002**
TBH	200	-1.839 ± 0.553	0.890 ± 0.092	-0.272 ± 0.123	**0.038**
	400	-1.960 ± 0.556	0.915 ± 0.092	-0.274 ± 0.135	0.055
	600	-2.017 ± 0.559	0.927 ± 0.093	-0.226 ± 0.122	0.067
	800	-2.101 ± 0.569	0.942 ± 0.094	-0.211 ± 0.122	0.101
	1000	-2.161 ± 0.575	0.950 ± 0.095	-0.185 ± 0.118	0.135

As a simpler alternative to the extra-Poisson GLM statistical likelihood approach, model equations (E1) and (E1H) could also be fitted by ordinary un-weighted least squares regression by regressing the logarithm of the number of nightjars (+1 to cope with zero values) on log area and housing density, namely:

log_e(Nightjar numbers on patch +1) = a + b log_e(Patch area) + c (Housing density) (E2)

and

log_e(Nightjars on heathland + 1) = a + b log_e(Heathland area) + c (Housing density) (E2H)

Fitting models using this approach assumes errors in predicting nightjar numbers have a constant variance on the log scale (i.e. errors are proportional to predicted values); this may be reasonable for moderate nightjar numbers but can be inaccurate for situations where very low numbers are expected, as occurs for nightjar numbers on many patches (Table 11).

Table 15 summarises the results of fitting model equations (E2) and (E2H) by ordinary least squares multiple regression. The negative effect of housing density on nightjar numbers was statistically significant up to distances of 1000m (and beyond) for the Dorset patches and for the combined Dorset and TBH dataset, whether based on the whole patch area or restricted to the nightjars on the heathland habitats area only.

Amongst the smaller set of 23 TBH patches, nightjar numbers were not related to housing density within any of the distance limits when based on the whole patch area, but when restricted the heathland habitats area, nightjar numbers declined significantly (i.e. $p < 0.05$) with housing within distance limits of 200m, 400m and 600m (Table 15).

Figure 18 and Figure 19 are intended to help understand and assess these observed relationships between nightjars and housing density by colour coding patches in the log nightjar numbers versus log area plots according to the housing density within 400m of the patch. The patches with housing densities greater than 3 ha^{-1} (shown in blue in Figures 18 and 19) show some tendency to have fewer nightjars for any given patch size.

Table 15: Multiple regression relationship between nightjar numbers ($\log_e(X+1)$) and the combined effect of ($\log_e$) patch area and housing density within a distance of 200m, 400m, 600m, 800m and 1000m; regression coefficient of determination R^2 range from 77%-80%.

		regression coefficient (± S.E.)			
	distance (m)	constant	$\log_e$(Area)	house density	house density test *p*
Whole patch area					
Combined	200	-0.984 ± 0.206	0.630 ± 0.043	-0.088 ± 0.026	**0.001**
	400	- 0.990 ± 0.210	0.613 ± 0.044	-0.099 ± 0.032	**0.003**
	600	-0.970 ± 0.207	0.632 ± 0.043	-0.109 ± 0.032	**0.001**
	800	-0.971 ± 0.207	0.633 ± 0.042	-0.111 ± 0.033	**0.001**
	1000	-0.979 ± 0.205	0.636 ± 0.042	-0.113 ± 0.033	**0.001**
Dorset	200	-0.877 ± 0.215	0.620 ± 0.048	-0.083 ± 0.026	**0.002**
	400	-0.882 ± 0.221	0.619 ± 0.049	-0.093 ± 0.032	**0.006**
	600	-0.860 ± 0.217	0.619 ± 0.048	-0.103 ± 0.032	**0.002**
	800	-0.854 ± 0.218	0.618 ± 0.049	-0.107 ± 0.034	**0.002**
	1000	-0.855 ± 0.215	0.621 ± 0.048	-0.110 ± 0.033	**0.002**
TBH	200	-1.879 ± 0.618	0.777 ± 0.107	-0.100 ± 0.094	0.301
	400	-1.901 ± 0.614	0.782 ± 0.106	-0.108 ± 0.106	0.319
	600	-1.911 ± 0.610	0.786 ± 0.105	-0.104 ± 0.102	0.322
	800	-1.937 ± 0.606	0.792 ± 0.104	-0.104 ± 0.108	0.345
	1000	-1.981 ± 0.603	0.799 ± 0.103	-0.095 ± 0.110	0.401
Heathland area only					
Combined	200	-0.697 ± 0.176	0.627 ± 0.043	-0.097 ± 0.024	**0.001**
	400	-0.709 ± 0.181	0.629 ± 0.044	-0.107 ± 0.030	**0.001**
	600	-0.687 ± 0177	0.630 ± 0.043	-0.118 ± 0.030	**0.001**
	800	-0.693 ± 0.179	0.632 ± 0.043	-0.118 ± 0.031	**0.001**
	1000	-0.699 ± 0.177	0.635 ± 0.043	-0.119 ± 0.031	**0.001**
Dorset	200	-0.601 ± 0.179	0.605 ± 0.047	-0.081 ± 0.024	**0.001**
	400	-0.610 ± 0.184	0.606 ± 0.048	-0.091 ± 0.029	**0.003**
	600	-0.588 ± 0.180	0.606 ± 0.046	-0.102 ± 0.029	**0.001**
	800	-0.585 ± 0.182	0.605 ± 0.047	-0.104 ± 0.030	**0.001**
	1000	-0.584 ± 0.179	0.607 ± 0.046	-0.107 ± 0.030	**0.001**
TBH	200	-0.986 ± 0.473	0.719 ± 0.100	-0.237 ± 0.085	**0.011**
	400	-1.079 ± 0.502	0.734 ± 0.105	-0.228 ± 0.101	**0.036**
	600	-1.076 ± 0.498	0.741 ± 0.104	-0.225 ± 0.098	**0.032**
	800	-1.124 ± 0.508	0.751 ± 0.105	-0.220 ± 0.106	0.051
	1000	-1.165 ± 0.511	0.761 ± 0.106	-0.212 ± 0.109	0.067

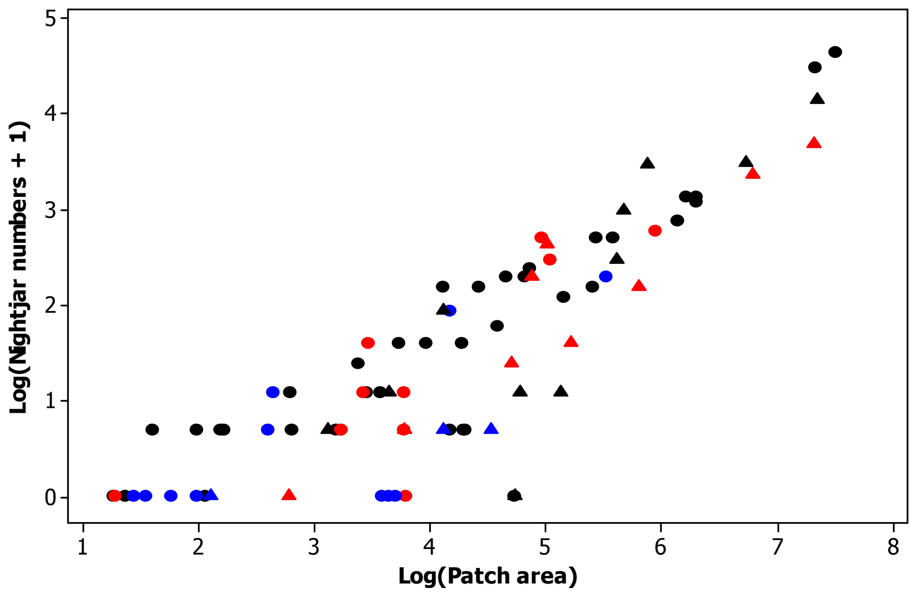


Figure 18: Plot of nightjar numbers per whole patch ($log_e(X+1)$) versus (log_e) whole patch area (ha) for patches in Dorset (circle) and TBH (triangle); symbols coloured by housing density within 400m (black = <1 ha^{-1}, red = 1-3 ha^{-1}, blue = >3 ha^{-1}).

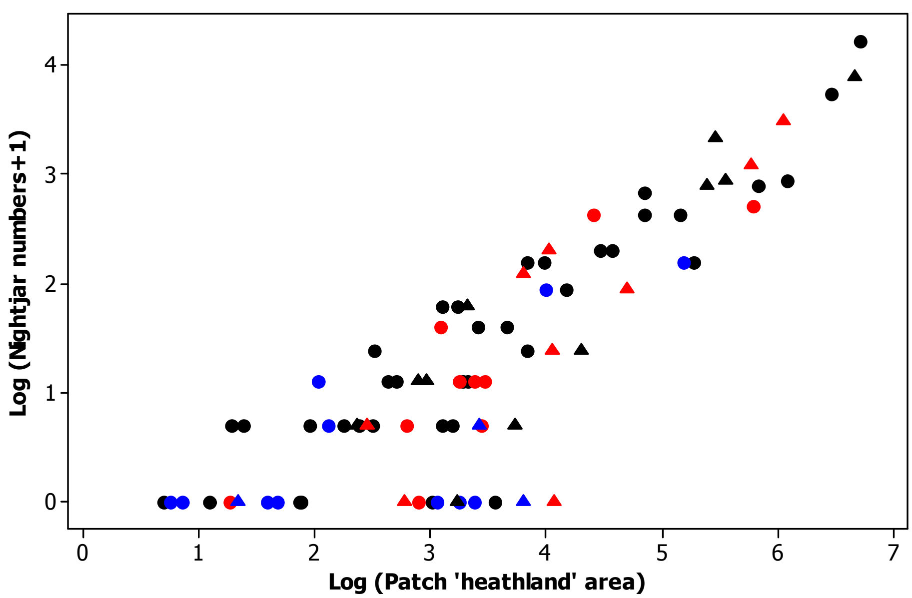


Figure 19: Plot of nightjar numbers per 'heathland' within patch ($log_e(X+1)$) versus (log_e) patch 'heathland' area (ha) for patches in Dorset (circle) and TBH (triangle); symbols coloured by housing density within 400m (black = <1 ha^{-1}, red = 1-3 ha^{-1}, blue = >3 ha^{-1}).

The correlation between nightjar numbers and housing density within 400m, adjusted for patch size, is best illustrated by a double-residual plot of the residuals of each variable from a regression on log patch area (Figure 20). This shows that over both SPAs combined, there is a statistically significant (partial) correlation of -0.372 ($p < 0.001$), in agreement (as must occur) with the results of the corresponding multiple regression in Table 15. (Figure 20 is analogous to Fig. 6 in Liley and Clarke (2003) for this newer combined SPA dataset). Figure 20 essentially shows the correlation between urban development and nightjar numbers, taking into account the size of each patch. The apparent 'outlier' point in Figure 20 marked '0' is Alder Hills in Dorset, which is very small, surrounded by housing and has no nightjars, and therefore is not a real outlier – this highlights the statistical problem of fitting ordinary regression models with such low numbers !

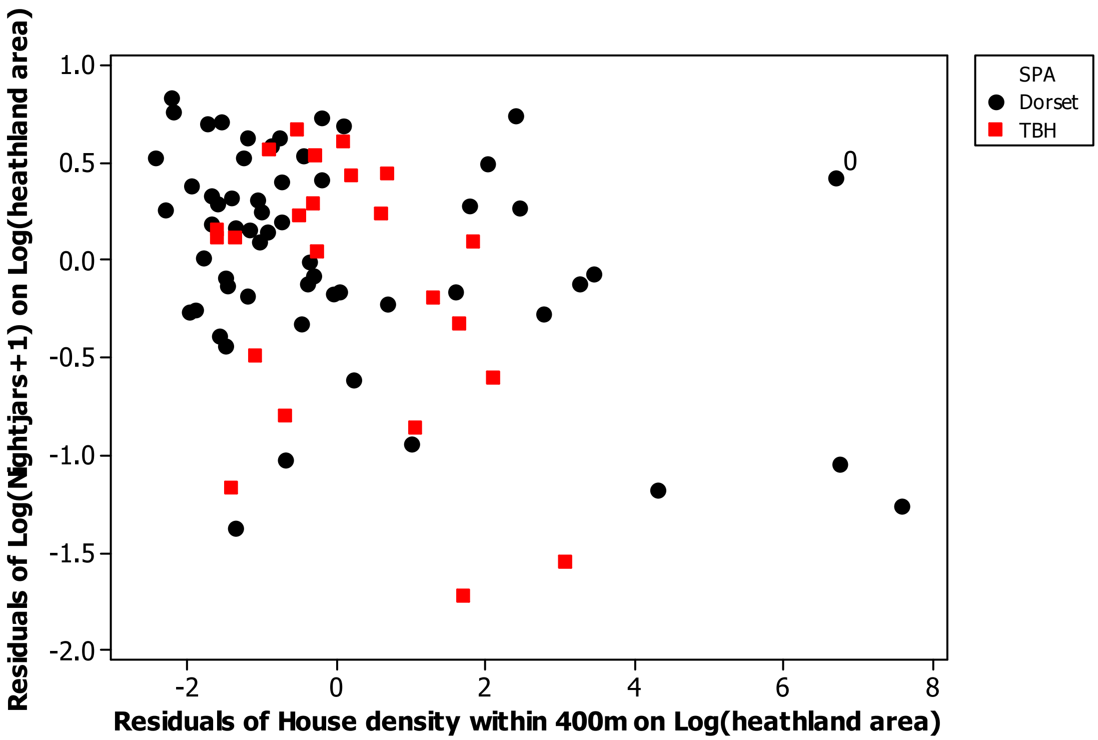


Figure 20: Double residual plot showing the partial correlation (r = -0.372, p = 0.001) between log(nightjar numbers on heathland +1) and housing density (ha^{-1}) within 400m, allowing for each variable's regression relationship with the log(Patch heathland area (ha)) for 58 Dorset patches (●) and 23 Thames Basin Heath patches (■); 0 denotes Alder hills patch in Dorset with no nightjars

Changes in nightjar density, per patch, between 1992 and 2004

The 2004 national survey recorded a 36% national increase in nightjar numbers compared to the previous survey in 1992 (Conway et al., (in prep)). For the Dorset patches (directly comparable data for 1992 – 2004 was obtained for 43 Dorset patches only) the density of nightjars per patch in 1992 significantly correlated with the number in 2004 (Correlation coefficient = 576, p < 0.001).

There was some evidence that the increase in density mostly occurred on larger sites as of the 18 sites larger than 75ha, increases in nightjar density between the two surveys occurred on 12 sites (Figure 21). Similarly, for those sites surrounded by higher levels of housing within 200m, increases in nightjar density occurred on 7 out of 12 patches (Figure 23). There was no clear pattern for sites with high or low visitor levels (Figure 22).

In Figures 22 - 24 (which show identical data) the two outlying points again highlight the problems with small counts on particular sites. These two points are Bank Gate Common at Arne, Dorset (a small site which held one nightjar in 1992 and none in 2004) and King's Barrow, Alderholt, Dorset (which held three nightjars in 1992 and one in 2004).

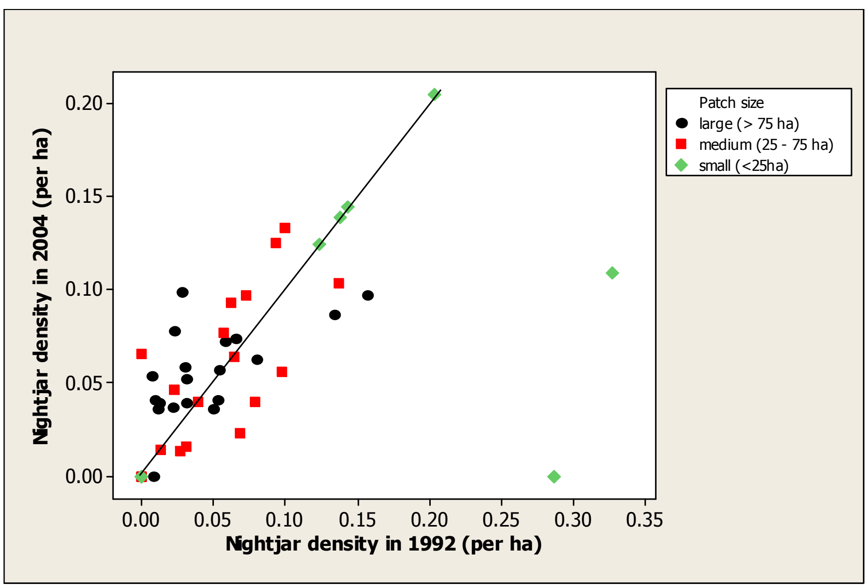


Figure 21: Nightjar density (per ha for each patch) in 1992 and 2004, coded according to patch size (coding splits the data into approximately 3 equal classes). Data are for Dorset sites only, using the patch boundaries drawn for this study (i.e. 'visitable patches') for patches completely surveyed in both years (n = 43). The line indicates the 1:1 ratio, i.e. patches below the line had a higher density of birds in 1992 whereas those above the line had a higher density in 2004.

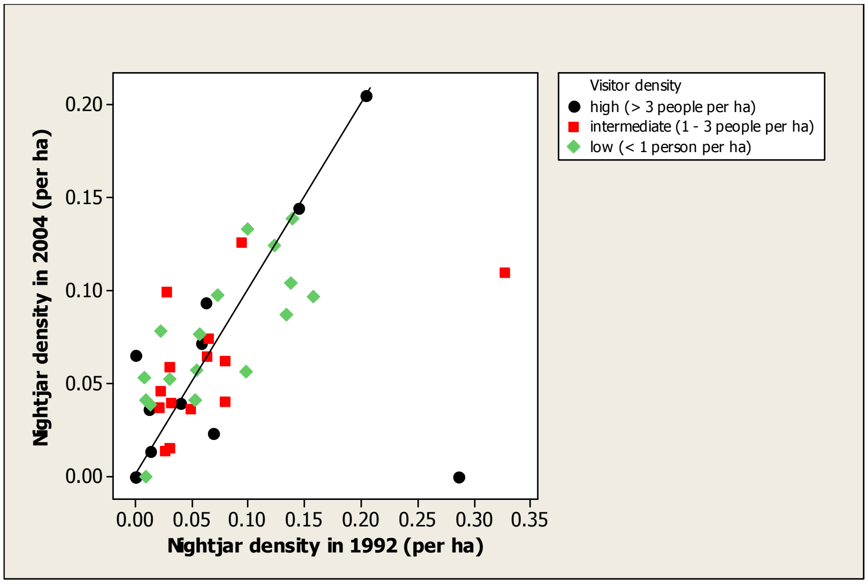


Figure 22: Nightjar density (per ha for each patch) in 1992 and 2004, coded according to visitor density (number of visitors predicted from model C3 per ha). The coding splits the data into approximately 3 equal classes. Data are for Dorset sites only, using the patch boundaries drawn for this study (i.e. 'visitable patches') for patches completely surveyed in both years (n = 43). The line indicates the 1:1 ratio, i.e. patches below the line had a higher density of birds in 1992 whereas those above the line had a higher density in 2004.

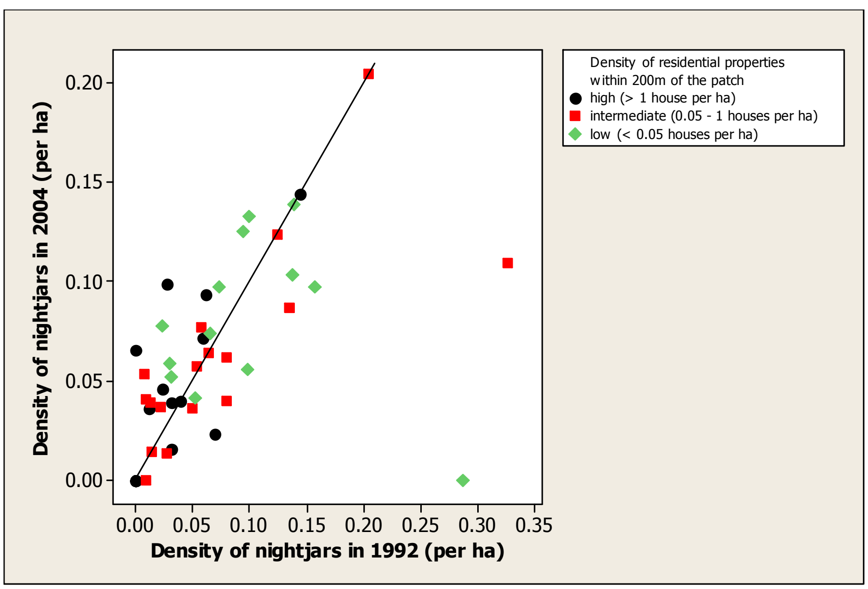


Figure 23: Nightjar density (per ha for each patch) in 1992 and 2004, coded according to housing density within 200m(coding splits the data into approximately 3 equal classes). Data are for Dorset sites only, using the patch boundaries drawn for this study (i.e. 'visitable patches') for patches completely surveyed in both years (n = 43). The line indicates the 1:1 ratio, i.e. patches below the line had a higher density of birds in 1992 whereas those above the line had a higher density in 2004.

Within-site analyses

Comparison of visitor pressure within, and outside of, 150m of nightjar points

As one method of assessing whether nightjar tend to avoid areas of relatively high pressure within a patch, we determined all 50m cells which were within 150m of a recorded nightjar, and then, for each patch, we calculated the mean predicted visitor pressure (MVP_{150}) of cells within 150m and mean pressure (MVP_{other}) for all other cells. If the ratio RMVP (= MVP_{150} / $MVP_{other,}$) is less than unity, this may suggest that nightjar are more likely to occur where (predicted) visitor pressure is relatively low. Wilcoxon signed rank tests were used to test whether the median of the ratios across the 67 patches with nightjar present was, statistically, significantly different from unity (Table 16).

Table 16: Median of the ratios RMVP of mean predicted visitor pressure of cells within 150m to mean pressure for all other cells in a patch, plus corresponding ratio RDIST (= $MDist_{150}$ / $MDist_{other}$) of mean distances to patch edge, separately for the *n* patches in each SPA with nightjars, and overall; *p* values for Wilcoxon signed ranked test that the null hypothesis that median log ratio is zero (i.e. median ratio is unity); percentage of patches with RMVP<1, or with RDIST>1 indicated in brackets.

		Median ratio RMVP			Median of the ratios RDIST = $MDIST_{150}/MDIST_{other}$
	n	Model			
		C3	C5	C0	
Dorset	45	0.888 (58%)	0.905 (69%)	0.926 (64%)	1.230 (84%)
TBH	20	0.801 (95%)	0.822 (95%)	0.881 (70%)	1.332 (100%)
All	65	0.858 (69%)	0.871 (78%)	0.913 (66%)	1.238 (88%)
		Wilcoxon test *p*			Wilcoxon test *p*
		C3	C5	C0	$Dist_{150}/Dist_{other}$
Dorset	45	0.020	0.005	0.005	<0.001
TBH	20	0.001	0.001	0.004	<0.001
All	65	<0.001	<0.001	<0.001	<0.001

Under predictive model C3, the ratio of mean predicted visitor pressure within 150m of nightjars to mean pressure in other 50m cells of the patch was less than unity in 58% of the 45 patches in Dorset with nightjars, in all except one (95%) of the 20 TBH patches with nightjars, and 69% over both SPAs. For visitor numbers based on predictive model C5, the corresponding percentages are higher for Dorset (69%), the same for TBH (95%) and thus higher overall (78%) (Table 16). Wilcoxon signed rank tests indicated that the median of these ratios was statistically, significantly less than unity for each SPA separately and overall for visitor pressure based on either model C3 or C5.

These results could be interpreted as indicating that nightjars are more likely to occur in those parts of a patch which have the least (predicted) visitor pressure. However, because the proportion of people travelling to a point on a patch decreases with its distance from their access point (based on the observed ‘penetration distance distribution’), there will be a natural tendency for predicted visitor pressure to be lower in 50m cells further from access points. If the spatial distribution of nightjars is related to distance from access points and, more generally, the edge of patches, rather than specifically to the number of visitors to the access points and parts of the heath, then this could cause an apparent association of nightjars with relatively low visitor numbers – as we have detected.

We tried to assess this potentially confounding effect in two ways. First we ran a null version (model C0) of the spatial model to predict visitor pressure per 50m cell assuming an equal number of visitors at each access point on each heath, regardless of car park spaces or local housing density (10 visitors per access point was used but the number is irrelevant because we are only interested in relative pressure close to and away from nightjars). With both individual and combined SPA regions, the mean predicted visitor pressure (under null model C0) was less within 150m of nightjars than elsewhere in the majority of patches (64% of patches in Dorset, 70% in TBH and 66% overall) and Wilcoxon signed-rank tests for a median ratio of unity were statistically significant (Table 18). This indicates there is some tendency for nightjars to be further from access points than random points on the patch, regardless of any differences between visitor numbers to access points. However, the nightjar preference for places away from access points (i.e. model C0) appears to be less strong than the preference for areas with relatively low 'best' predicted visitor pressure (under models C3 or C5), especially for the TBH.

As a test of the potential relationship with visitor pressure, rather than simply with distance from access points, we assessed the extent to which the preference for relatively low visitor pressure under model C3 was greater than the preference under null model C0. This was done by dividing the RMVP for model C3 by RMVP for model C0 for each patch to give $PREF_{C3/C0}$; similarly for model C5 to give preference index $PREF_{C5/C0}$. If $PREF_{C3/C0}$ is less than one for significantly more than half of all patches, this suggests that nightjar distribution is related to (predicted) visitor pressure rather than just distance from access points (Table 19).

Table 17 Median of the preference index values ($PREF_{C3/C0}$ or $PREFP_{C5/C0}$) measuring preference for relative low (predicted) visitor pressure (adjusted for purely distance from patch access points), separately for the *n* patches in each SPA with nightjars, and overall; *p* values for Wilcoxon signed ranked test that the null hypothesis that median of log PREF values is zero (i.e. median PREF value is unity), [1] denotes appropriate one-sided test; percentage of patches with PREF values less than unity indicated in brackets.

		Median value of		***Wilcoxon test* p**	
	n	$PREF_{C3/C0}$	$PREF_{C5/C0}$	$PREF_{C3/C0}$	$PREF_{C5/C0}$
Dorset	45	1.014 (38%)	0.999 (53%)	0.958[1]	0.946
TBH	20	0.942 (85%)	0.953 (75%)	0.018	0.070
All	65	0.999 (51%)	0.983 (60%)	0.789	0.210

This tough test for nightjar preference for relative low (predicted) visitor pressure was statistically significant (i.e. $p < 0.05$) only for predictive model C3 for the Thames Basin Heaths ($p = 0.018$) - 15 of the 20 patches with nightjars had $PREF_{C3/C0}$ values less than 1.0. This suggests that visitor pressure is sufficiently high on parts of the majority of the Thames Basin heaths that nightjar show some preference for the relative low areas of visitor pressure over and above their general preference for areas away from heath access points.

We also calculated the distance of every 50m cell from the nearest edge of the patch (in 50m classes), and then calculated the ratio RDIST of the mean distance to the patch edge ($MDIST_{150}$) of cells within 150m of a nightjar to the mean distance to the patch edge ($MDIST_{other}$) for other cells on the same patch. The ratio RDIST was greater than one for 84% of patches in Dorset and all 20 patches within nightjar in Thames Basin Heaths, leading to statistically significant Wilcoxon signed-rank tests and the conclusion that nightjar distribution is higher away from patch edges.

The joint relationship between the selection for lower visitor pressure ($RMVP_{C3}$) and the selection for parts of patches away from the edges is shown in Figure 24. This shows clearly that for 19 of 20 patches on the Thames basin Heaths, the nightjars show a preference for areas of relatively low visitor pressure (under model C3), but these areas are also further away from the patch edge (than random points on the patch). Interestingly, the only Thames Basin Heaths patch with model C3 visitor pressure greater in areas within 150m of nightjar than further away is ‘Bramshill and Warren heath’ which has relatively low housing density surrounding it compared to the other Thames Basin Heaths.

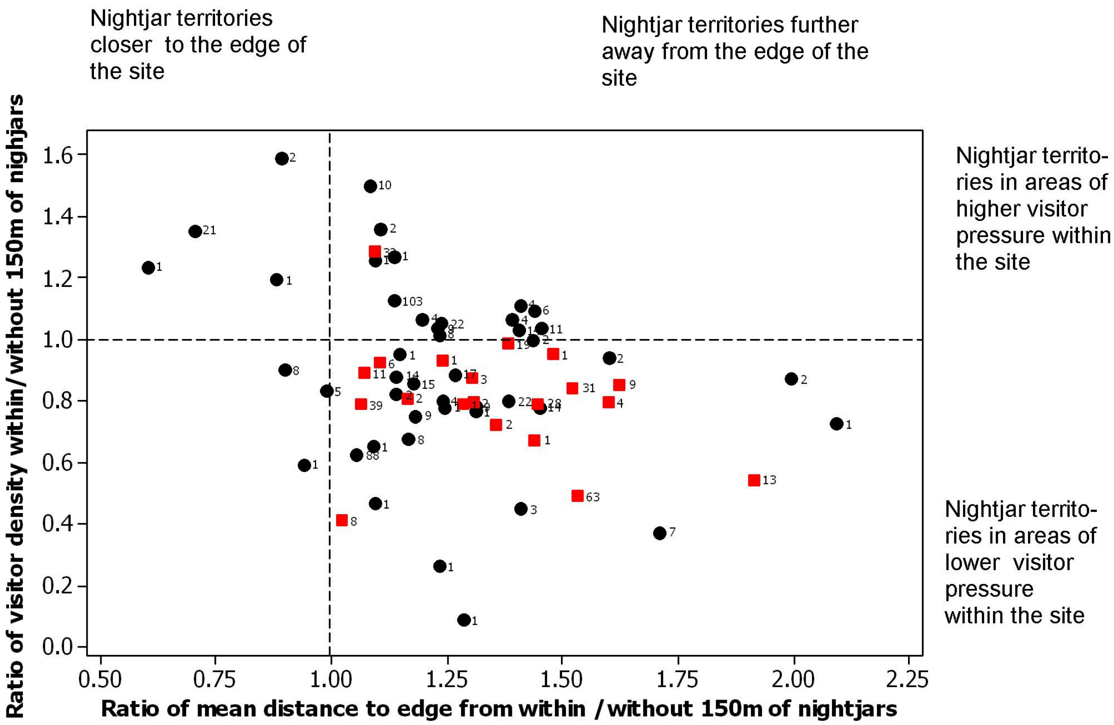


Figure 24: Relationship between the ratio $RMVP_{C3/C0}$ of mean visitor pressure within 150m of nightjars to mean visitor pressure elsewhere and the equivalent ratio RDIST for mean distance to patch edge, for the 45 Dorset patches (●) and 20 Thames Basin Heath patches (■) with nightjars; dashed lines denote "null hypothesis" lines of 1.0; numbers indicate nightjar numbers.

Figure 24 is repeated as Figure 25, but with the patches colour-coded by their mean level of predicted visitor pressure. There appears to be some tendency for nightjars on the patches with the higher overall levels of visitor pressure to show more preference for the areas of relative low visitor pressure (Figure 25). Specifically, 82% of the 33 patches with mean pressure greater than 10 people (per cell per 16 hr period) shown signs of nightjar selection for relative low pressure (i.e. $RMVP_{C3} < 1$) compared to only 56% of the 32 patches with mean pressure less than 10 ha^{-1}. This suggests that the influence of visitor pressure on nightjar distribution within a patch will only begin above some threshold levels of visitor pressure levels, as one might expect. Note that the appropriate real threshold for effects is not necessarily the cut-off value of 10 people per cell per 16hr period, predicted from model C3, that was used here for illustration.

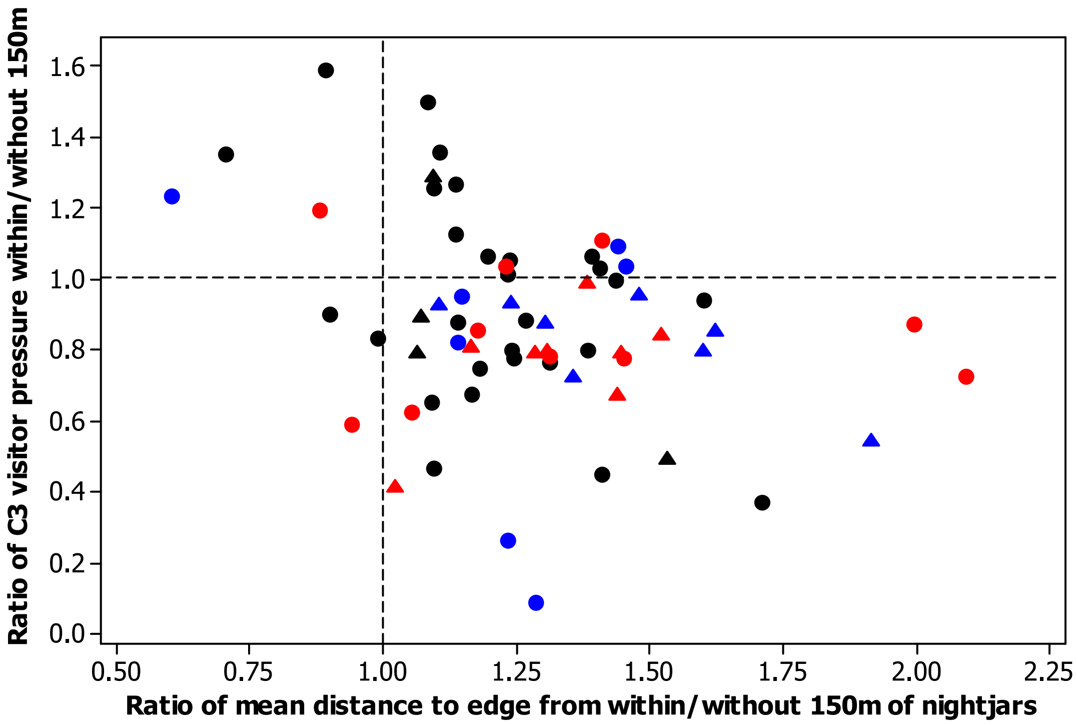


Figure 25: Relationship between the ratio $RMVP_{C3/C0}$ of mean visitor pressure within 150m of nightjars to mean visitor pressure elsewhere and the equivalent ratio RDIST for mean distance to patch edge, for the 45 Dorset patches (circles) and 20 Thames Basin Heath patches (triangles) with nightjars; dashed lines denote "null hypothesis" lines of 1.0; symbols coloured by mean model C3 visitor pressure per cell per 16 hour period on whole patch (black = <10, red = 10-30, blue = >30).

Visitor pressure within and outside nightjar territories in different habitats

Simple, univariate comparisons of the predicted visitor pressure for cells containing nightjars and those more than 150m from a nightjar territory showed some significant differences. Across all habitats the visitor pressure was significantly higher outside nightjar territories than for cells containing nightjars, for both model C3 (Mann-Whitney test, adjusted for ties, $p = 0.012$) and for C5 ($p < 0.001$). Taking just the key habitats (Figure 26 and Figure 27), there were significant differences within clearfell (for C3 $p = 0.021$, for C5 $p = 0.049$); for conifer (for C3 and C5 $p < 0.001$); for deciduous woodland (for C3 $p = 0.214$, for C5 $p = 0.016$); for dry heathland (for C3 = 0.211, for C5 $p = 0.006$); and within young conifer there was no significant difference in visitor pressure for either model (for C3 $p = 0.864$, for C5 $p = 0.199$).

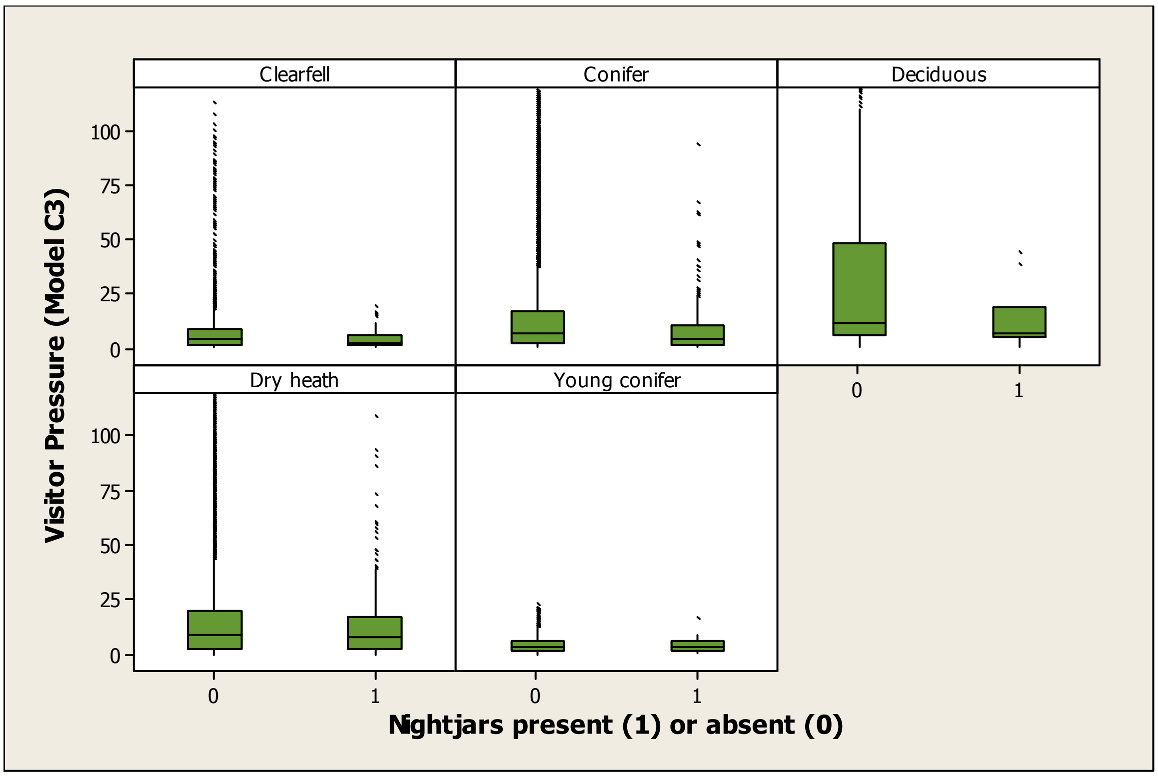


Figure 26 Visitor pressure (Model C3) for cells containing nightjar territory centres compared to cells beyond 150m from territory centres.

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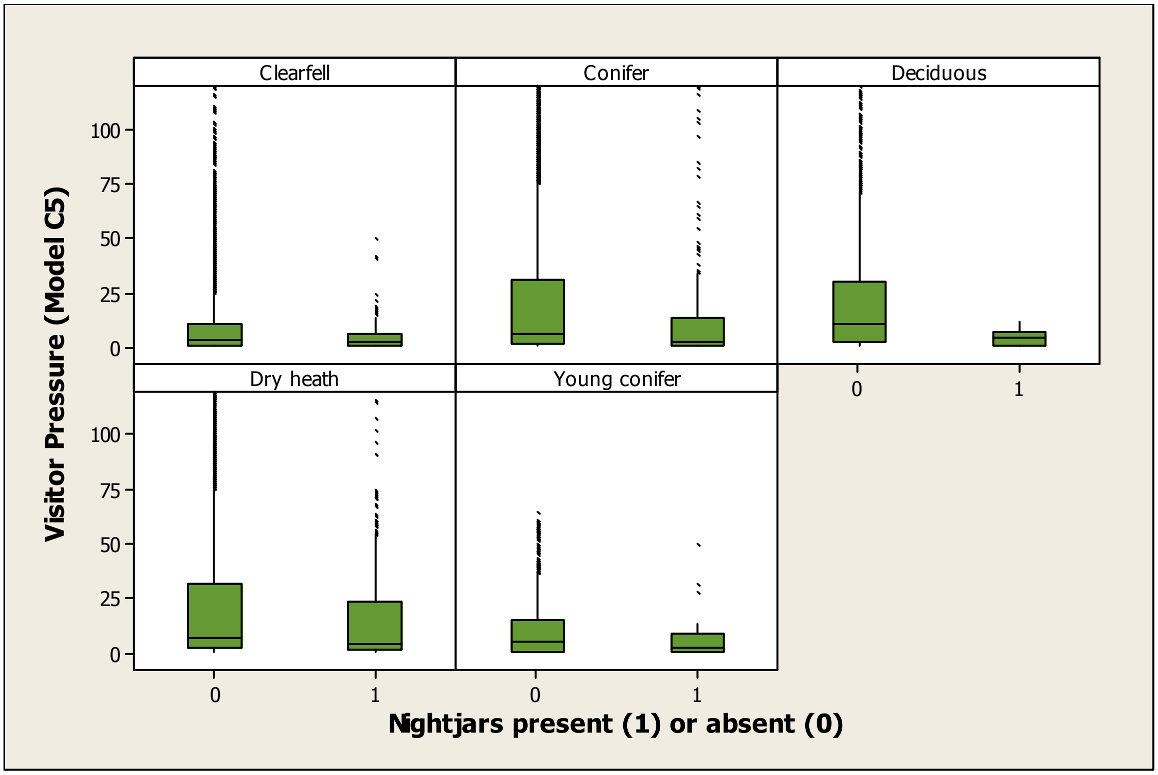

Figure 27: Visitor pressure (Model C5) for cells containing nightjar territory centres compared to cells beyond 150m from territory centres.

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Nightjar density by visitor pressure

When predicted visitor pressure and nightjar distribution are mapped together, it does appear by eye that most nightjars occur in areas with lower visitor pressure (see Maps 9-24). However as the frequency distribution of visitor pressure is highly skewed; most of the land area has relatively low visitor pressure and therefore most of the nightjars would be expected to occur where visitor pressure appears to be lower. We therefore grouped cells according to their visitor pressure, allowing us to look at nightjar density at different levels of visitor pressure.

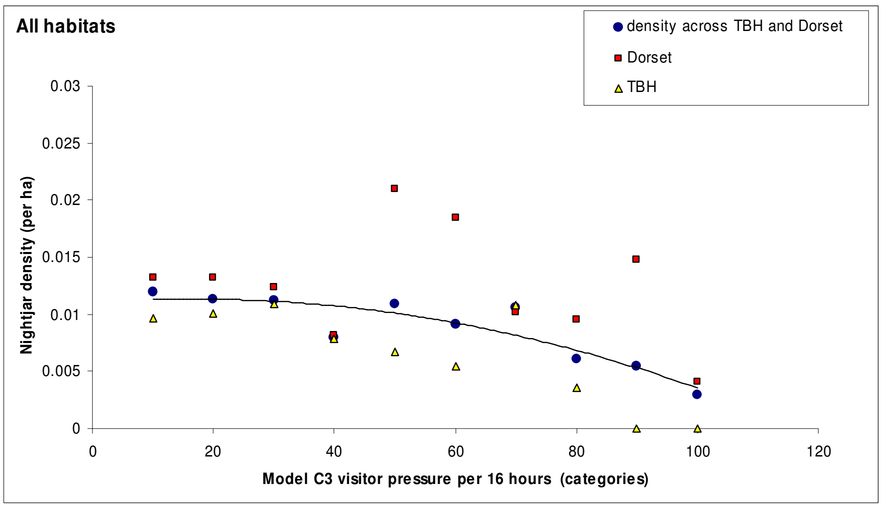
Taking the summed data for all patches across both the Dorset and Thames Basin Heaths, there was clear trend for nightjar density to be lower where visitor pressure is higher (Table 18 and see the fitted regression lines in Figure 28). However, when the data are viewed separately the trend is not clear across the Dorset Heaths patches. The pattern is similar both when the density is calculated for all habitats and also when only the open heathland habitats (including clearfell) are used. It is clear that nightjars do occur, albeit at a lower densities, in areas with high levels of predicted visitor pressure, at least on the Dorset Heaths. There is no clear 'threshold' or distinct point at which density markedly declines, however, from Figure 28 it would appear that (overall average) nightjar density is reduced where visitor pressure is more than about 40 people per 50m pixel (per 16 hour period) – a level which 10% of the Thames Basin Heaths and 6% of the Dorset Heaths currently exceed (as predicted by model C3).

Table 18: Nightjar density for different levels of visitor pressure. 50x50m cells are grouped according to the predicted level of visitor pressure, as calculated by Model C3; data based on (a) all habitats in patches and (b) only cells in open heathland habitats (including clearfell). These data are also shown graphically in Figure 28.

(a) Visitor pressure (Model C3)	no. 50x50m cells			no. nightjar			nightjar density		
	Dorset	TBH	total	Dorset	TBH	total	Dorset	TBH	total
<10	26803	14366	41169	353	139	492	0.0132	0.0097	0.0120
10-20	4922	6769	11691	65	68	133	0.0132	0.0100	0.0114
20-30	1212	3401	4613	15	37	52	0.0124	0.0109	0.0113
30-40	613	2032	2645	5	16	21	0.0081	0.0079	0.0080
40-50	428	1036	1464	9	7	16	0.0210	0.0068	0.0109
50-60	217	550	767	4	3	7	0.0184	0.0055	0.0091
60-70	197	464	661	2	5	7	0.0102	0.0108	0.0106
70-80	209	283	492	2	1	3	0.0096	0.0035	0.0061
80-90	135	231	366	2	0	2	0.0148	0	0.0055
>90	975	366	1341	4	0	4	0.0041	0	0.0030

(b) Visitor pressure (Model C3)	no. 50x50m 'heathland' cells			no. nightjar			nightjar density		
	Dorset	TBH	total	Dorset	TBH	total	Dorset	TBH	total
<10	12977	5937	18914	233	101	334	0.0180	0.0170	0.0177
10-20	3069	2820	5889	52	55	107	0.0169	0.0195	0.0182
20-30	781	1364	2145	14	26	40	0.0179	0.0190	0.0186
30-40	367	657	1024	3	11	14	0.0082	0.0167	0.0137
40-50	267	256	523	7	3	10	0.0262	0.0117	0.019
50-60	154	190	344	4	2	6	0.0260	0.0105	0.0174

(b) Visitor pressure (Model C3)	no. 50x50m 'heathland' cells			no. nightjar			nightjar density		
	Dorset	TBH	total	Dorset	TBH	total	Dorset	TBH	total
60-70	125	164	289	1	2	3	0.0080	0.0122	0.0104
70-80	122	112	234	2	1	3	0.0164	0.0089	0.0128
80-90	77	82	159	2	0	2	0.0260	0	0.0126
>90	396	93	489	3	0	3	0.0076	0	0.0061



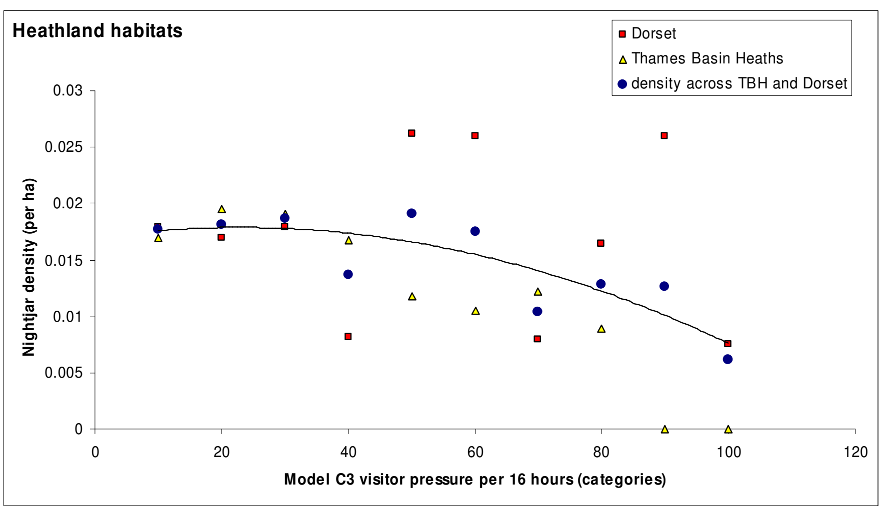


Figure 28: Nightjar density and visitor pressure. Data are for all habitats (top) and heathland habitats only (lower), with 50x50m cells categorised into different groups according to their predicted level of visitor pressure (0-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-70, 71-80, 81-90 and greater than 90). The quadratic regression lines are shown for the grouped data (i.e. for both areas – the blue dots): for all habitats: $y = 0.011 + 0.00004x - 0.000001x^2$; $R^2 = 81\%$; for heathland habitats:. $y = 0.017 + 0.00008x – 0.000002x^2$; $R^2 = 72\%$.

Nightjar density and distance from edge of site

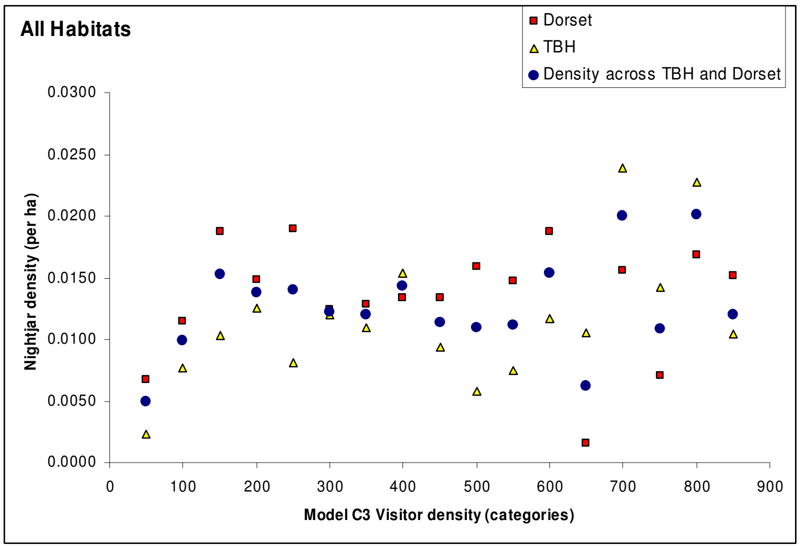
When density was calculated for different distance bands away from the patch edge there was a clear trend in the first 150m, for nightjar densities to increase with distance from edge. However at distances beyond 150m there was considerable variation and no clear pattern; this is partly due to the fact that only a few large patches will have any cells at large distances from any edge, and thus the number of nightjars expected at such distance will be relative small and densities estimates will be therefore be susceptible to stochastic variability between these patches. Male nightjars typically chur from a number of different locations around the edge of the territory, and these territories can encompass an area of 5 to 6 ha (equivalent to circles of radii 126m and 138m) (Berry, 1979). It would therefore seem sensible that few centres of territories are located within 150m of the site edge.

Table 19: Nightjar density in relation to distance away from the site patch edge. 50x50m cells are grouped according to their distance from the edge; data based on (a) all habitats in patches and (b) only cells in open heathland habitats (including clearfell). These data are also shown graphically in Figure 29.

(a)	no. 50x50m cells			no. nightjar			nightjar density		
Distance from edge	Dorset	TBH	total	Dorset	TBH	total	Dorset	TBH	total
<50	7286	4724	12010	49	11	60	0.0067	0.0023	0.0050
100	5758	3911	9669	66	30	96	0.0115	0.0077	0.0099
150	4484	3201	7685	84	33	117	0.0187	0.0103	0.0152
200	3377	2718	6095	50	34	84	0.0148	0.0125	0.0138
250	2642	2233	4875	50	18	68	0.0189	0.0081	0.0139
300	2090	1835	3925	26	22	48	0.0124	0.0120	0.0122
350	1719	1457	3176	22	16	38	0.0128	0.0110	0.0120
400	1424	1300	2724	19	20	39	0.0133	0.0154	0.0143
450	1200	1170	2370	16	11	27	0.0133	0.0094	0.0114
500	1070	1038	2108	17	6	23	0.0159	0.0058	0.0109
550	947	937	1884	14	7	21	0.0148	0.0075	0.0111
600	800	767	1567	15	9	24	0.0188	0.0117	0.0153
650	626	666	1292	1	7	8	0.0016	0.0105	0.0062
700	513	587	1100	8	14	22	0.0156	0.0239	0.0200
750	427	494	921	3	7	10	0.0070	0.0142	0.0109
800	357	440	797	6	10	16	0.0168	0.0227	0.0201
>=850	991	2020	3011	15	21	36	0.0151	0.0104	0.0120

(b)	no. 50x50m 'heathland' cells			no. nightjar			nightjar density		
Distance from edge	Dorset	TBH	total	Dorset	TBH	total	Dorset	TBH	total
<50	2985	1079	4064	30	3	33	0.0101	0.0028	0.0081
100	2903	1412	4315	56	22	78	0.0193	0.0156	0.0181
150	2400	1257	3657	64	24	88	0.0267	0.0191	0.0241
200	1842	1095	2937	37	27	64	0.0201	0.0247	0.0218
250	1432	889	2321	36	11	47	0.0251	0.0124	0.0202
300	1118	699	1817	16	15	31	0.0143	0.0215	0.0171
350	944	589	1533	14	11	25	0.0148	0.0187	0.0163
400	767	566	1333	13	13	26	0.0169	0.0230	0.0195

(b) Distance from edge	no. 50x50m ‘heathland’ cells			no. nightjar			nightjar density		
	Dorset	TBH	total	Dorset	TBH	total	Dorset	TBH	total
450	638	536	1174	8	9	17	0.0125	0.0168	0.0145
500	596	485	1081	11	3	14	0.0185	0.0062	0.0130
550	543	484	1027	9	7	16	0.0166	0.0145	0.0156
600	467	390	857	8	6	14	0.0171	0.0154	0.0163
650	349	353	702	0	5	5	0.0000	0.0142	0.0071
700	288	308	596	5	12	17	0.0174	0.0390	0.0285
750	236	243	479	0	7	7	0.0000	0.0288	0.0146
800	206	220	426	6	9	15	0.0291	0.0409	0.0352
>=850	621	1070	1691	8	17	25	0.0129	0.0159	0.0148



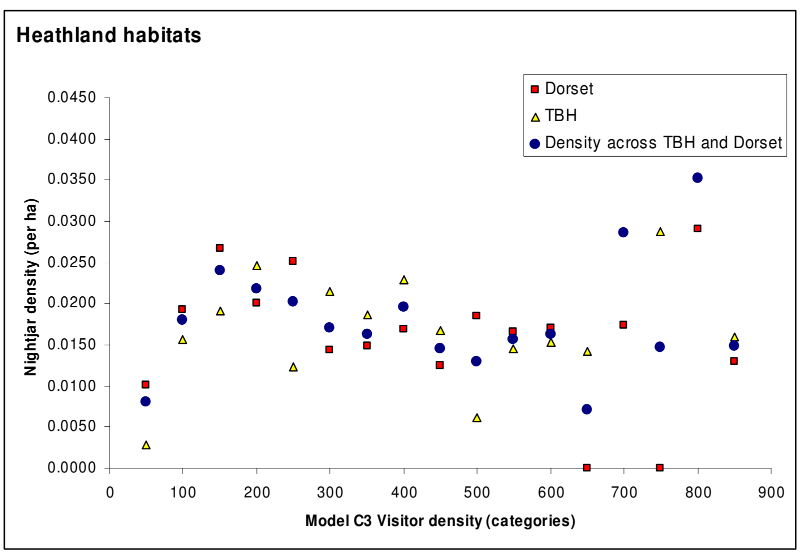


Figure 29: Nightjar density for different distance bands away from the site edge. Data are for all habitats (top) and heathland habitats only (lower), with 50x50m cells categorised as to which 50m band they fall into, in 50m increments from the patch boundary. The last group includes all cells further than 1000m from the patch boundary.

Discussion

We present data on approximately 18,000 ha of SPA designated heathland and associated habitats in Dorset and the Thames Basin Heaths. The 81 patches included in our analysis support approximately 1/6th of the UK nightjar population (see Conway et al., (in prep)). We examine complex spatial data relating to habitat, housing and recreational access in an attempt to determine their relative impacts on nightjar distribution and abundance. The analyses highlight the following key points:

- Most Dorset Heaths patches have lower visitor levels than the Thames Basin Heaths. However, within the Dorset patches there are localised areas and some sites with very high visitor numbers. Visitor levels vary much less across the Thames Basin Heaths.
- Visitors travel to sites mainly on foot and by car; foot visitors travel from nearby housing, whereas the pattern with car drivers is more complex, but can be predicted from car-park capacity.
- The number of nightjars per patch is negatively correlated to the amount of housing around patches, for both the Thames Basin Heaths and the Dorset Heaths.
- Nightjar numbers have increased between the two national surveys (in 1992 and 2004), and it appears that the increases have occurred on larger sites and those sites with more housing in their vicinity
- Within sites, nightjar territories are located within areas of lower visitor pressure, away from access points and away from the edges of sites.

For the first time in one study we show the links between housing levels, recreational access and bird numbers. We develop a model of visitor pressure that uses housing levels and features of a site (car-parking capacity). This model allows us to predict access levels on a site, or within parts of a site. We show that, within sites, nightjars are found in the areas of lower visitor pressure and that across sites nightjar density is lower where visitor pressure is predicted to be high . These results have important consequences for access management and future housing development in both areas.

The visitor models, interpretation, use and applicability

The visitor models provide an estimation of likely visitor levels at individual access points and then how those visitors may spread out from a site. The approach allows relative comparisons between different areas and sites. We found considerable variation in visitor numbers at different access points, especially with car driving. Close examination of the postcode data from the visitor questionnaires has revealed that only 5% of car drivers were interviewed at the nearest access point to their home (see Liley et al., 2006, in press). Given that visitors arriving by car typically travel a few kilometres to reach the heath, residents at particular locations will usually have a variety of access points within an acceptable radius. Choice may ultimately be down to factors such as ease of route, attractiveness of the destination, ease of parking, familiarity, facilities provided or perceptions of safety (for examples see Edwards & Knight, 2006; Entec Ltd., 2002; Liley *et al.*, 2006b; Maginnis, 2003; Morgan, 1999). The model does not take into account other types of countryside that people may choose to visit, nor does it address the impact of choice of paths or routes within heaths. The model's attractiveness lies in its potential to provide an estimate of visitor pressure in a particular location for many sites and across large swathes of countryside. We suggest caution when using the model predictions at a very local level, and it is important to understand the limitations of the model and how the estimates have been derived.

Despite their relative simplicity, the approach of modelling visitor numbers would appear to provide sensible predictions of relative visitor numbers to particular locations. For example the Lookout, to the south of Bracknell, received 601,570 visitors[3] in 2005/06. This figure is based on the number visiting the heritage centre, children's play area, café, Go Ape and associated attractions. Our visitor model C3 estimates 430 people per 16 hours and the C5 model predicts 547 per 16 hours. Extrapolating these to give an annual figure gives 118,000 and 149,741 visits per annum respectively. These are considerably lower than the actual figure, but as many people will stray no further than the café, kids play park, etc. the estimated figure may well be correct for the actual number of people who stray beyond the visitor centre and other facilities.

Moors Valley Country Park, in Dorset, is a similar centre, and has a larger car-park (800 spaces). Visitor model C3 predicts a total of 1,179 people to Moors Valley per 16 hours, (approximately 323,000 visits per annum) whereas visitor model C5 predicts just 140 people (38,325 per annum). Actual counts of people using the car-park are 700,000 per annum[4]. As with the Lookout, it is likely that only a small proportion of people stray beyond the visitor centre and other facilities, but it would appear that the C5 prediction is low. This is because there is relatively little housing nearby, and the centre attracts many tourists and people from a much wider radius than the model can consider. Sites such as Studland and Hengistbury Head, which are on the Dorset coast, have exceptionally large car-parks (both with over 800 spaces) and are known to attract visitors from a very wide radius. The car-parks at these sites are far larger than the largest sites at which any interviews were conducted. Both sites are known to receive in the region of 1 million visitors per annum (Griffiths, 2004; Purbeck Heritage Committee, 2002). Model C3 predicts 577,447 visitors per annum to Hengistbury and 877,843 visitors to Studland. Model C5 makes much lower predictions, 233,500 per annum for Hengistbury and 150,557 for Studland. Model C3 copes with these car-parks much better, where as Model C5 only accounts for people living within 10km, and therefore the estimates produced by Model C5 for these sites are perhaps best thought of as estimates of local use only, rather than tourists.

The importance of car-park size is difficult to interpret and this result does not mean that car-park size is limiting visitor numbers. It is likely that the distribution of car-parks and car-park size has evolved and developed to reflect where people tend to visit. Neither of the two models predicts a number of visitors at an access point that would suggest that the parking is over capacity. For example Model C3 predicts that any access point with 1 parking space is likely to receive 7 visitors over 16 hours in August. A typical dog walk (Clarke *et al.*, 2006; Liley *et al.*, 2006a) would take less than an hour. Even assuming only one person arriving per car, the parking space would clearly not have to be permanently occupied for seven people to visit over a 16 hour period.

Model C3 would imply that were housing levels to increase, visitor numbers (arriving by car) would not increase, and this is clearly incorrect. We suggest that car-park capacity

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[3] http://www.bracknell-forest.gov.uk/the-look-out-facts-and-figures-2006.pdf
[4] Unpublished data (Bruce Rothnie *pers. comm..*)

acts as a surrogate for visitor numbers at particular locations, and were housing levels different it is possible that the equation for car visitors that we use in Model C3 would also be different. Model C5 does include the number of houses surrounding access points, and therefore does have the potential to predict changes in visitor numbers as a result of housing. It is interesting that this model predicts particularly high levels of current visitor pressure across the Thames Basin Heaths and it would be useful to have more data on actual visitor levels to test the extent to which this model is accurate.

Definition of patches

Liley and Clarke (2003) used the CEH heathland survey as a way of defining heathland patches. The heathland survey provides a baseline data set for the Dorset Heaths and has been widely used in ecological studies (Chapman *et al.*, 1989; Rose *et al.*, 2000; vandenBerg *et al.*, 2001; Webb & Haskins, 1980; Webb & Vermaat, 1990). The survey is based on 200m x 200m grid squares and only includes squares with heathland vegetation, and therefore the patches are consistent and defined by their vegetation. No such survey exists for the Thames Basin Heaths, and because the Dorset Heaths and Thames Basin Heaths SPAs are comprised of different habitats, in order to conduct our analysis across both geographical areas it was necessary to define sites ourselves in a compatible manner. We have used ‘visitable area’, using the areas open to the public as our boundaries. Where there are barriers across the middle of heaths (such as motorways or railway lines) we have split the heaths. This is necessary because the component patches either side of the barrier are likely to have different visitor pressure and the barrier will affect the spatial distribution of people within the site. We chose to only use sites that had public access in our analyses because most of the sites without public access are used by the MOD for military training, and such sites are likely to have a whole suite of different impacts (such as regular use of explosives and tanks) to sites with public access. The alternative to using ‘visitable areas’ would have been to use SSSI boundaries, which would have been inappropriate to the analysis as the boundaries are determined in a different fashion in the Thames Basin Heaths and the Dorset Heaths. Further problems, if we had based our analysis on SSSI boundaries, would have been caused by the fact that some parts of SSSIs have no public access and also that some individual SSSIs comprise several spatially isolated units, some of which are isolated from each other by housing.

There is potentially the problem of spatial autocorrelation (Fortin & Dale, 2005), but this will be encountered with any approach as many patches are within 5km of each other (and therefore are likely to have related levels of urban development surrounding them). Nightjars are trans-Saharan migrants and will forage up to 8km away from their nest site at night to feed (Cresswell, 1996), the birds therefore clearly move considerable distances and it is perhaps likely that there is mixing between birds from different patches. It would therefore seem unlikely that different patches, by any definition, support independent populations of nightjars. The key problem caused by spatial autocorrelation would be where a group of sites differed in their vegetation, or some other factor which might influence nightjar numbers. We believe this in unlikely to be the case and previous analyses have confirmed the lack of spatial autocorrelation in the relationship between development and nightjar numbers (Liley & Clarke, 2003).

Nightjar ecology and population impacts

The 2004 national nightjar survey has shown an increase of 36% on the last national survey, conducted in 1992 (Conway et al., (in prep); Morris et al., 1994). Given the substantial increase in nightjar numbers it is interesting that the effect of occurs when there are more birds present.

It would appear that the increase between the two surveys has occurred on sites surrounded by higher levels of housing, but that such sites still support fewer nightjars than less urban sites. Numerous examples with different bird species have shown, both through field-based studies and through theoretical modelling, that as population size increases, poorer quality sites are likely to be filled (for examples see Gunnarsson *et al.*, 2006; Kokko & Sutherland, 1998; Rodenhouse *et al.*, 1997; Sutherland, 1996). When poorer quality sites are occupied, breeding success for individuals on these sites will be reduced and therefore density-dependent population regulation occurs. It would appear that, at patch level, nightjars select sites with less housing and that only when there is competition for sites on the other heaths, will the more urban heaths be likely to be occupied.

By simply looking at the number of territory holding individuals, as we do in this study, we are not looking at actual population size and we are not able to differentiate between breeding success at different locations. By showing that there are fewer nightjars on sites with high levels of housing in their vicinity we are highlighting that there is the potential for a nightjar population level impact, even with the current high numbers of birds. There is evidence that nightjar breeding success is lower on more urban sites and is related to access levels, as for example nests close to footpaths are more likely to fail (Langston et al., 2006; Murison, 2002).

Through the development of our visitor model we have shown that access levels are related to housing levels, and therefore the reduced density on sites could be due to nightjars avoiding areas with high human disturbance levels. However, there are other impacts of housing besides disturbance (see Underhill-Day, 2005 for a review), which include an increased incidence of fires, increased abundance of certain predators such as cats and foxes, noise pollution and light pollution. These may also account for the reduced density on more urban sites. It might, of course, be that different factors influence nightjar settlement at a patch level than at the within-patch level. Within this study we have not directly shown the link between recreational access levels and settlement at a patch level.

We do show that nightjar territories occur in those parts of sites with the lowest visitor pressure, i.e. at a local level, within sites, nightjars show a preference for areas with lower disturbance. The limited data from nightjars ringed in the UK shows that birds are very site faithful. Birds ringed during their first breeding season have been shown to move further (median distance 1.6km) than birds known to be at least two years old when first ringed (median distance moved between years = 200m) (Cresswell, 2002). They are reasonably long lived with the maximum recorded age being 11 years[5] . It would seem plausible that individual birds would therefore have good local knowledge of their breeding sites, developed over time, and therefore are able to select areas within sites with the least visitor pressure.

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[5] http://blx1.bto.org/birdfacts/results/bob7780.htm

Differences between Dorset and the Thames Basin Heaths

By applying the same analyses and visitor model across both SPAs we have been able to compare the two regions. The spatial distribution of housing and access points across the two regions is different. In the Thames Basin Heaths there is a more uniform spread of visitor pressure, typically higher than in Dorset. In Dorset there are many sites with low visitor pressure, but also some sites and parts of sites with very high visitor pressure.

On the Thames Basin Heaths there is a clear trend that nightjar density declines with visitor pressure, this is less clear-cut on the Dorset Heaths (see Figure 28). This pattern is repeated in Figure 24, where the preference for nightjar territories to be in areas with lower visitor pressure appears more marked for the Thames Basin Heaths patches. It is interesting to speculate why this may occur. Visitor pressure levels are consistently higher, over much more of the Thames Basin Heaths patches. For half of the Thames Basin Heaths 88% or more of the patch is above a visitor level of 20, as predicted by Model C3. Hence where large areas of patches are uniformly of high visitor pressure it perhaps makes sense that nightjar territories (which are reasonably large) are located in areas with reduced visitor pressure. In Dorset the areas of higher visitor pressure are much more localised, half the Dorset patches have 4% or less of their area at a visitor level of 20 (Model C3). Where visitor pressure is particularly high in Dorset the sites are the urban heaths but also sites such as Studland and Hengistbury, where very large car-parks are located adjacent to sandy beaches. The visitor model is likely to over estimate visitor numbers inland on these sites as visitors will stick largely to the beach. Because there are relatively few cells in the higher disturbance categories, very small numbers of nightjars in such locations can complicate the analysis, and therefore any biases in visitor distribution at high visitor levels are likely to have a particularly strong influence. This may be the case on some Dorset sites.

Implications for access management and for nightjar conservation

The models we have developed provide a clear and strong visual presentation of visitor pressure and allow direct comparison between geographical areas. We have shown that the areas predicted to have high visitor pressure are also partially avoided by nightjars. While there is no clear threshold above which we can show nightjars do not settle, we are able to show the levels of visitor pressure at which nightjar numbers decline (Figure 28). We also show that nightjar densities are higher in certain habitats. We look at an SPA scale and demonstrate the scale of current visitor pressure and its relative impact on nightjar numbers. We also demonstrate the extent to which visitor pressure and housing are linked. The maps of current visitor pressure, location of current access points and the distribution of the different habitats provide a tool kit for strategic management across the sites concerned, and we hope these will be of use to those responsible for managing the sites in question. The following practical suggestions result from our work:

- Routing visitors around the edges of sites may allow or maintain areas of low disturbance at the centres of sites, especially where sites are not long and thin in shape.
- Young conifer supports relatively high densities of nightjars. It is also a habitat type that is difficult for people to walk through, and therefore people are perhaps more likely to remain on paths in such habitats. Allowing such thick vegetation

cover in the areas we predict to have high visitor pressure may therefore be beneficial.
- Nightjar numbers seems to decline where visitor pressure is predicted to occur at levels of approximately 40 or more people with Model C3. This is the number of visitors that would typically occur at a car-park with 15 car-park spaces.
- Patches surrounded by high levels of housing (i.e. 'urban heaths') will support fewer nightjars and are likely to be occupied only when population levels are high. Within sites, nightjar territories are located in areas of lower disturbance, therefore on more urban sites it might be beneficial to maintain some areas with lower visitor pressure, and these areas would need to be consistently low between years.

Relevance of this analysis for woodlark and Dartford warbler

National survey data for woodlark and Dartford warblers was collected in the summer of 2006, and was not available in time to be included in this analysis. Each species has a very different ecology, and such analyses would provide a useful addition to the our understanding of disturbance effects for these species. Woodlarks are selective in their choice of habitats and a single pair may utilise different, very small patches within a large block of habitat (for example fire-breaks within heathland). The species occurs in areas where a very short sward is present, and such habitats are difficult to determine from aerial photographs. However, it would be possible to isolate all patches of clearfell and explore the effect of visitor pressure and urban development for this species.

Dartford warblers are currently at high levels (Van den Berg et al., 2001). An analysis similar to this one suggested urbanisation around the Dorset heaths decreased the density of Dartford warbler territories (Van den Berg et al., 2001) while more recent work has confirmed this and suggested mechanisms. Nest building and onset of breeding are delayed by increased number of visitors passing through a Dartford warbler territory, to the extent that the average number of broods can be decreased from three to two in the most heavily disturbed territories (Murison et al., in press, Murison unpublished / in prep.). This leads to lower production of young, which combined with lower territory density in more disturbed heaths mean that disturbance has a large impact of the number of young produced per unit area of heathland.

Murison's studies are beginning to combine an understanding of behavioural responses to disturbance with population level impacts through the medium of density dependence. This confirms that the lower density of birds in disturbed areas has two linked components: avoidance behaviour and poor performance of birds that do settle. Furthermore, by gaining understanding of the behavioural and demographic impacts of disturbance we can see this is a general effect, which is not specific to particular landscapes. This raises issues for further work on Dartford warblers as well as nightjars and woodlarks. 1) There is a need to develop models of the population effects of disturbance which are explicitly based on density dependence to gain predictions of impacts on long-term population trends. 2) Because birds are mobile, studies which use ringing or radio-tracking are necessary to understand dispersal and settling behaviour in response to disturbance and density. For example, Murison's studies (in prep) suggest juveniles will respond by dispersing while settled adults are very reluctant to leave territories. This could use methods developed for radio-tracking of farmland birds which have refined our understanding of how they respond to distribution of high- and low-quality habitat in relation to agri-environment schemes (Siriwardena et al., 2006) 3. These birds are responding to other pressures such as climate change which is changing habitat quality (e.g. through increased heathland fires, Stokes et al., 2004). Disturbance may have much greater impacts against a background of changing habitat quality and so models should be developed which combine these various pressures.

Appendix 1: Data used to derive the visitor models

Visitor data from visitor surveys

These are the actual data from the questionnaire / counts conducted as part of the visitor surveys for the two SPAs (Clarke *et al.*, 2006; Liley *et al.*, 2006a). Other visitors are those arriving by bicycle, public transport, horse-back etc.

SiteName	CPType	CPCapacity	SPA	Foot visitors	Car visitors	Other visitors
Avon Heath South Park, Boundary Lane	Official	16	Dorset	1	118	0
Belben road	Unofficial	2	Dorset	0	23	0
Black Hill	No parking	0	Dorset	0	11	0
Canford Gravel Hill	Official	12	Dorset	0	61	3
Ferndown	Unofficial	3	Dorset	22	1	1
Godlingston	Unofficial	2	Dorset	10	15	12
Great Ovens (Sandford)	Unofficial	2	Dorset	29	0	2
Hartland tramway	Unofficial	15	Dorset	1	51	2
Holt (Whitesheet Hill)	Official	20	Dorset	0	80	7
Lions Hill	Unofficial	1	Dorset	28	3	0
Morden	Official	7	Dorset	1	36	11
Parley (Lone Pine Drive)	Unofficial	6	Dorset	21	37	5
Sopley (Ramsdown Car Park)	Official	22	Dorset	3	63	0
St Catherine's	No parking	0	Dorset	22	52	0
Stoborough New Road	Unofficial	4	Dorset	28	5	1
Tadnoll	Official	6	Dorset	4	45	0
Talbot Heath	Unofficial	3	Dorset	14	8	2
Turbary Common	Unofficial	2	Dorset	44	4	8
Upton	Unofficial	2	Dorset	41	8	7
Winfrith	Unofficial	1	Dorset	7	19	2
B3011 opposite Arrow Lane	Unofficial	4	TBH	5	12	0
Black Bushes Road	Unofficial	2	TBH	1	29	0

Bourley Road	Official	36	TBH	1	100	12
Burdenshott Road	Official	25	TBH	3	36	0
Car Park off Cricket Hill Lane	Official	8	TBH	14	60	9
Car Park off the A30	Official	22	TBH	18	10	11
Chobham Road, chobham common	Official	35	TBH	2	77	0
Chobham Road, Horsell	Official	18	TBH	9	122	9
Currie’s Clump (Boldermere CP)	Official	65	TBH	2	112	1
E of Aberconway House (Wrens Nest CP)	Official	12	TBH	4	36	0
Lightwater Country Park entrance	Official	120	TBH	24	92	0
Mytchett Place Road	Unofficial	10	TBH	12	62	0
N entrance to Warren Heath	Official	7	TBH	2	49	9
Nightingale Road / A325	Unofficial	4	TBH	15	4	0
Off Crowthorn Road	Official	12	TBH	7	70	1
Play area, Springfield Avenue	Unofficial	2	TBH	22	0	3
Queens Road, Cowshot Common	Unofficial	3	TBH	29	19	3
S entrance to Bramshill Plantation	Unofficial	1	TBH	0	2	0
Salt Box Road	Official	18	TBH	3	167	3
Sandpit Hill	Official	8	TBH	14	29	1
Shore’s Road	Official	40	TBH	1	211	18
South Road	Unofficial	5	TBH	18	4	22
Staple Hill	Official	15	TBH	27	3	0
The Lookout	Official	200	TBH	3	309	5
Top of Bracknell Road	Unofficial	3	TBH	31	2	5
Top of Kings Ride	Unofficial	1	TBH	25	53	9

Appendix 2: Predictions by site for the two visitor models

This table gives the predictions (from Models C3 and C5) for the total numbers of visitors to each patch.

				Model C3			Model C5		
	Area (ha)	No. Access Points	No. CP Spaces	Visitors per 16 hours in August	Density (people per ha)	Annual Total	Visitors per 16 hours in August	Density (people per ha)	Annual Total
DORSET									
Alder Hills	5	1	24	122	26	33,391	204	44	55,804
Arne: Arne Heath	52	2	0	12	<1	3,279	7	0	1,934
Arne: Bank Gate	3	2	2	21	6	5,731	5	1	1,410
Arne: Bank Gate Cottages, north of triangle	7	1	0	6	1	1,548	2	<1	557
Arne: Combe, Grip and Shipstal	122	6	75	245	2	67,172	62	1	16,945
Arne: Crichton's Heath	29	1	0	6	<1	1,614	4	<1	1,175
Avon Common	4	1	1	15	4	4,017	14	4	3,873
Avon Heath North Park	142	6	134	405	3	110,944	175	1	47,901
Avon Heath South Park	104	2	16	69	1	18,833	31	<1	8,530
BlackHill, Bere Regis	71	7	2	57	1	15,549	22	<1	6,075
Blue Pool	73	7	52	184	3	50,335	17	<1	4,710
Bourne Valley	38	16	33	981	26	268,501	1,922	51	526,090
Bourne Valley / Talbot Heath	36	13	21	605	17	165,676	1,437	40	393,350
Canford Heath	381	24	22	748	2	204,798	1,464	4	400,652
Combe Heath	41	3	3	31	1	8,487	4	<1	1,094
Corfe Hills Golf Course	43	7	8	159	4	43,581	283	7	77,444
Corfe Hills School	6	5	0	165	29	45,168	250	43	68,383
Dewlands	14	11	10	375	27	102,790	398	29	108,870
Dunyeats	31	5	5	98	3	26,960	197	6	53,801
edge of Lulworh Ranges, nr East holme firing range	4	2	0	11	3	3,142	4	1	1,185
Ferndown	64	21	33	596	9	163,052	869	14	238,003
Ferndown Forest	263	10	14	183	1	50,168	229	1	62,732

				Model C3			Model C5		
	Area (ha)	No. Access Points	No. CP Spaces	Visitors per 16 hours in August	Density (people per ha)	Annual Total	Visitors per 16 hours in August	Density (people per ha)	Annual Total
Grange Heath	60	3	8	50	1	13,789	6	<1	1,646
Ham Common	25	9	152	532	21	145,535	402	16	110,097
Hengistbury Head	72	6	1277	2,109	29	577,447	853	12	233,500
Hethfelton Plantation	171	3	7	49	<1	13,403	10	<1	2,685
Higher Hyde and Gallows Hill	129	3	14	71	1	19,429	7	<1	1,911
Holt Heath & Whitesheet	541	25	46	343	1	93,994	213	<1	58,214
Horton Common	96	5	1	37	<0.5	10,151	34	<1	9,307
Hurn Forest	494	19	52	353	1	96,515	357	1	97,606
King Barrow, Alderholt	9	3	1	24	3	6,648	12	1	3,159
Leybrook Common	5	1	18	66	13	17,976	21	4	5,620
Lion's Hill	43	4	1	64	1	17,620	77	2	21,200
Lytchett	4	1	4	56	13	15,424	69	16	18,860
Lytchett adjacent to sewage station	7	2	10	101	14	27,512	111	15	30,499
Merritown	83	2	0	13	<0.5	3,644	24	0	6,690
Moreton Plantation and Bryants Puddle Heath	541	25	81	432	1	118,323	56	0	15,445
Mount Pleasant	13	5	8	186	14	50,857	244	18	66,907
nr Dorey's Farm, edge of Lulworth Ranges	8	1	0	6	1	1,634	3	0	760
Parley	153	21	26	682	4	186,715	901	6	246,770
Ringwood Forest and Moors Valley	1,514	31	871	1,774	1	485,504	551	0	150,947
Sandford Heath	65	4	12	104	2	28,404	62	1	16,952
Scotland	16	3	4	35	2	9,556	5	0	1,378
Slop Bog and Uddens	44	10	8	271	6	74,251	383	9	104,930
south of Horton Common	16	1	0	9	1	2,393	9	1	2,576
Stoborough (RSPB)	221	18	20	231	1	63,272	93	0	25,345
Stoborough and Hartland	461	21	92	483	1	132,113	94	0	25,596
Stoke Heath	24	1	1	10	<0.5	2,834	2	0	491
Studland and Rempstone	1,502	29	1732	3,207	2	877,843	550	0	150,557
Tadnoll, Winfrith and Knighton	226	15	54	317	1	86,732	48	0	13,067
Three legged Cross	32	4	6	70	2	19,237	61	2	16,760

	Area (ha)	No. Access Points	No. CP Spaces	Model C3: Visitors per 16 hours in August	Model C3: Density (people per ha)	Model C3: Annual Total	Model C5: Visitors per 16 hours in August	Model C5: Density (people per ha)	Model C5: Annual Total
Town Common & St Catherine's	172	11	21	314	2	85,849	489	3	133,963
Turbary Common	40	24	16	1,318	33	360,672	2,606	64	713,421
Upton Heath and Beacon Hill	249	17	61	755	3	206,741	1,007	4	275,599
Verwood	25	2	2	29	1	7,865	31	1	8,416
Wareham Forest	1,808	32	130	683	<0.5	187,071	149	0	40,740
Warmwell	31	3	8	51	2	13,887	11	0	3,014
Week Common	112	2	2	22	<0.5	6,115	19	0	5,128
Week Common II	9	2	0	12	1	3,418	10	1	2,608
West Moors Plantation	126	8	12	224	2	61,362	262	2	71,815
Worgret Heath	35	2	2	23	1	6,300	8	0	2,265
DORSET TOTAL	**10,718**	**531**	**5215**	**20,211**		**5,532,772**	**17,450**		**4,776,963**
THAMES BASIN HEATHS									
Edgbarrow Woods (Owlsmoor)	93	9	13	365	4	99,799	983	11	269,055
Sheet's Heath	44	6	82	326	7	89,355	482	11	131,946
Bisley Common	16	8	30	270	17	73,896	515	32	140,889
Lightwater Country Park	61	15	134	679	11	185,829	1,316	21	360,375
Cuckoo Hill	85	16	21	544	6	148,908	1,099	13	300,905
Pirbright Common & Ash Ranges	1,543	75	197	1,868	1	511,346	3,834	2	1,049,487
Bourley and Long Valley	886	94	327	2,713	3	742,748	6,484	7	1,775,046
Hazeley Heath	169	34	24	399	2	109,255	411	2	112,527
Bramshill and Warren Heath	841	52	70	698	1	191,023	753	1	206,081
Yateley Heath Wood	275	10	36	214	1	58,476	293	1	80,265
Yateley Common (north)	185	58	86	1,937	10	530,389	4,674	25	1,279,479
Yateley Common (south) & Hawley Common	331	28	84	1,006	3	275,476	2,702	8	739,546
Bullswater Common	61	22	31	355	6	97,147	604	10	165,369
Whitmoor Common (West)	132	21	76	601	5	164,390	1,391	11	380,722
Whitmoor Common (Eastt)	39	13	5	179	5	49,015	603	16	165,192
Wisley Common	114	19	36	287	3	78,685	484	4	132,362

	Area (ha)	No. Access Points	No. CP Spaces	Model C3 Visitors per 16 hours in August	Model C3 Density (people per ha)	Model C3 Annual Total	Model C5 Visitors per 16 hours in August	Model C5 Density (people per ha)	Model C5 Annual Total
Ockham and Boldermere	119	29	167	667	6	182,719	617	5	168,790
Crowthorne Wood & Bagshot Heath	1,500	49	263	1,649	1	451,469	3,839	3	1,050,916
Horsell Common	149	52	68	1,222	8	334,654	3,953	26	1,082,007
Chobham Common south of M3	359	64	160	1,140	3	312,067	1,406	4	385,008
Chobham Common north of M3	290	40	88	625	2	171,225	784	3	214,639
Broadmoor Bottom	8	4	0	122	15	33,490	317	39	86,838
Lucas Green	23	7	0	86	4	23,514	253	11	69,202
TBH TOTAL	**7,322**	**725**	**1,998**	**17,954**		**4,914,874**	**37,796**		**10,346,645**

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