Effect of bulb type on moth trap catch and composition in UK gardens

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Abstract

1. A wide variety of light sources are employed to trap moths, differing in brightness and spectrum. Relatively little is known about how these factors affect the resulting sample.
2. We analyse 7 moth trap bulb types using 10 years of records from the Garden Moth Scheme to provide the largest and most comprehensive comparison of moth trap bulb types to date.
3. 125W Mercury Vapour (MV) bulbs collected the largest samples. The next largest samples were collected by 60W Actinic bulbs (67.80% of 125W MV catch), followed by 15W Actinic (56.66%), 80W MV (55.91%), 40W Actinic (49.12%), 20W Actinic (36.56%) and 6W Actinic (34.33%).
4. We demonstrate that MV bulbs, which emit a larger proportion of long wavelength radiation, collected a distinct fauna to Actinic bulbs, which emit primarily short-wave radiation. Species composition also varied between Actinic bulbs which differ in brightness, with brighter Actinic traps tending to collect a larger proportion of large-winged species.
5. We provide robust support for the ‘mobility hypothesis’ whereby large-winged, strong flying moths are more strongly affected by artificial light (in moth traps or from other sources), suggesting selective pressure against large winged species in landscapes affected by artificial light at night (ALAN). Our findings have significant consequences for survey design, citizen science projects, and for understanding the impact of ALAN on the moth community.

Introduction

As the largest single radiation of plant-feeding insects (Mitter et al., 2017), the order Lepidoptera comprises one tenth of all described species on Earth, the vast majority of which are moths (Van Nieukerken et al., 2011; Wagner et al., 2021). Diurnal lepidoptera (butterflies) are frequently employed as an indicator of the health of insect communities, or of biodiversity more generally (Fleisman and Murphy, 2009). Moths share many of the features which make butterflies attractive in this regard (Table 1): Lepidoptera tend to respond rapidly to environmental change (New, 1997), are distributed globally (Fleishman and Murphy, 2009), and among insect groups, are uniquely taxonomically tractable (Thomas, 2005). However, moths present some distinct advantages over butterflies: they are dramatically more diverse (Wagner et al. 2021) and, importantly, can be sampled in large numbers with relative ease using a light trap - even in highly anthropogenically modified areas such as gardens (Bates et al., 2013).

As well as being conducive to the indicator potential of the group, the ease with which moths can be collected and identified are among the reasons why light trapping has become a popular activity among naturalists. As many as 2000 volunteers regularly run moth traps in the UK, many of which submit their records to biodiversity databases or other citizen science organisations (Fox *et al.,* 2011), represent a compliment to the Rothamsted Insect Survey light trap network. This long-running monitoring program uses a 112-node standardised network of 200W clear tungsten filament moth traps to monitor moth abundance across the country (Conrad *et al.,* 2006; Bell *et al.,* 2020). However, standardised Rothamsted traps are rarely used by citizen scientists or in field experiments due to their large size and 200W Tungsten bulb. Instead, a great variety of alternative designs and light sources are employed, hampering standardization and therefore wider use of community science datasets to monitor moth abundance. In contrast to butterflies, for which standardised 'Pollard walks' (Pollard and Yates, 1993) facilitate inclusion of volunteer records in large-scale abundance monitoring, volunteer moth records of have only recently been included in Butterfly Conservation's annual The State of Britain's Larger Moths (Fox *et al.,* 2021) thanks to new statistical techniques which treats citizen science data as opportunistically gathered (occurrence only) records (Dennis *et al.,* 2017). A more complete understanding of the factors affecting moth trap catch size is required to expand these analyses to abundance as well as occurrence.

Previous studies have shown that various trap parameters can impact catch size, including receptacle design (e.g. Robinson, Heath, Skinner, Rothamsted; Bates *et al.,* 2013), period of the night for which the trap is running (Nowinszky *et al.,* 2007; Axmacher and Fiedler, 2004), time at which the trap is emptied (Fry and Waring, 2020), presence and colour of vanes (Singh *et al.,* 2022), height of the trap (Intachat and Woiwod, 1999), presence and position of packing material (usually egg boxes) inside the trap (Fry and Waring, 2020), manual versus automatic collection of samples (Axmacher and Fiedler, 2004) and, perhaps most importantly, the brightness and emission spectra of the light source used (Fayle *et al.,* 2007; Bates *et al.,* 2013; Somers-Yeates *et al.,* 2013; Donners *et al.,* 2018; van Grunsven *et al.,* 2014; van Langevelde *et al.,* 2011).

Further, as moth species are thought to differ in their attraction to light (Merckx and Slade, 2014), mediated by variation in mobility (Van de Schoot et al. 2024; Aiello *et al.,* 2021) and possibly spectral sensitivity (Somers-Yeates *et al.,* 2013), it is likely that the species composition, as well as size, of trap catches will be affected by the bulb type used (van Langevelde *et al.,* 2011; Donners et al. 2018; Somers-Yeates *et al.,* 2013). Anecdotal evidence from naturalists has long suggested that traps using different bulbs will produce different samples (Frank, 1988; Fry and Waring, 2020; Altermatt and Ebert, 2016). At the very least, some species are rarely collected at light but appear more abundant using other collection methods (see Sterling and Parsons, 2012). However, as Brehm (2017) notes, field comparisons regularly find little compositional differences between bulbs with fundamentally different light spectra. For example, Infusino et al. (2017) found localized habitat conditions to be a stronger determinant of moth trap composition than light source, and the Geometrid assemblages attracted to MV in comparison to incandescent lamps have been found to be surprising similar (Intachat and Woiwod 1999; Jonason et al. 2014). In the more controlled environment of an indoor choice experiment, Brehm et al. (2021) found that moths are preferentially attracted to lamps that emit a high proportion of short-wave radiation. However, in a similar field-based comparison, Niermann and Brehm, (2022) found that different LED lamps collected similar numbers and assemblages of moths, independent of whether strong or weak lights were used or if the lamps were of a mixed radiation or UV type, despite the traps being placed close together (26.4m - 46.9m). It therefore appears that small variations in micro-habitat can obscure differences between bulb types, especially in short-term experiments. Additionally, the effective range of moth traps appears to vary between families (Merckx and Slade, 2014) and traps placed close together will suffer from light competition effects (Brehm et al. 2021). These difficulties make designing a field experiment capable of detecting abundance and compositional differences between moth trap light sources a significant logistical challenge, that is yet to be surmounted in a comprehensive comparison of commonly used trap types. For these reasons, a quasi-experimental approach is taken here to quantify differences between moth traps.

Describing catch size and compositional differences is important for insect monitoring programmes and the design of ecological experiments; it is desirable that widely used sampling methods are fully understood. However, moth trap composition can also be used to make inferences about the impact of artificial light at night (ALAN) on the moth community. This is because near-identical mechanisms are responsible for both the functioning of moth traps and the disruptive effects of ALAN. As such, traps of different spectra are frequently used to explore the effect of ALAN on moths in choice experiments (e.g. Somers-Yates et al. 2013; van Langevelde et al. 2011; Brehm et al. 2021; Altermatt and Ebert, 2016). It has been found that larger moth species have declined more dramatically than smaller-winged species in the UK (Coulthard, et al. 2019). Recent work (Van de Schoot et al. 2024) has shown that smaller moths are less sensitive to artificial light. As a result, spindle ermine moths (*Yponomeuta cagnagella*) have adapted by reducing wing size in response to ALAN (Altermatt and Ebert, 2016). These studies advance the ‘reduced mobility hypothesis’ whereby moths adapt to ALAN by reducing wing size and mobility.

Here, 10 years of moth trap catches in a single land use type (gardens in the United Kingdom) from seven bulb types are used to explore the impact of spectrum and brightness on the attraction of moths to artificial light. We use weather and bulb type variables to examine how moth abundance changes night-to-night and collate garden habitat variables with information about surrounding land uses to partition garden-to-garden variation attributable to bulb type, urbanisation, and distance to street lighting. As such we provide the largest comparison of moth trap types to date, producing robust estimates of how moth trap bulb types compare to one another in terms of catch size, with the aim of assisting in the development of standardised monitoring programs and the selection of moth trap types for field studies. Using the species-composition of moth traps, we also test two hypotheses regarding the impact of ALAN on moths. Firstly, we test whether moths display species-specific responses to light of different spectra by comparing catch and composition from traps using Actinic (emitting predominantly UV) and Mercury Vapor (emitting UV plus broader spectrum light) bulbs. Secondly, we test the community-wide implications of the reduced mobility hypothesis by comparing the size distribution of samples from different bulb types and different levels of ALAN exposure while controlling for other habitat, landscape and geographic variables in ordination models.

Methods

The Garden Moth Scheme dataset

The Garden Moth Scheme (GMS) is a citizen science surveying project (2003 – present), which asked participants to sample moths with a light trap in their garden each Friday between March and November. Participants are encouraged to report all (including negative) records, to sample regardless of weather conditions and are given a prescribed list of common and readily identifiable species on which to focus. The scheme has engaged hundreds of participants, producing a large collection of c.36-week time-series of moth trap catches from a variety of trap types, distributed across Great Britain, Ireland and the Channel Islands. Participants also report information about their garden: the distance to green space, farmland, street lighting, water, woodland and to the coast. Participants provide a list of their garden microhabitats: presence of a bird table, Buddleia, compost heap, >25m^2 lawn, log pile, long grass, pussy willow, trees over 10m, oak trees over 10m, wild honeysuckle, wild ivy, wildflower meadow are recorded. Timeseries with this information and 34 or more sample weeks were included in the analysis and were placed in one of 7 bulb categories, corresponding to the most frequently used bulb types. In total, 108,438 trap nights were included across 2862 time-series in 704 British gardens from 2012 to 2022.

Statistics

All analyses were conducted in R version 4.4.1 (R Core Team, 2024). The percentage landcover in a 100m radius surrounding each site was extracted from the UK CEH Land Cover Map 2021 for each of the 21 landcover classes in the CEH dataset (Marston, 2022). Daily 1km resolution rainfall volume and minimum temperature variables were extracted from the CEDA Archive HadUK Gridded Climate Observations v1.2.0 (Hollis et al., 2019). Moonlight intensity was estimated for each sample night using the package ‘moonlit’ (Śmielak, 2023), which calculates the percentage of full moonlight intensity based on moon phase, elevation, latitude, and longitude (compared to the average full moon value of 0.32 lx), not accounting for cloud cover.

To estimate differences in catch between a range of trap types across each covariate (model 1), a hierarchical generalised additive mixed model (GAM) was fit to time series from each site which completed the full 34-36 weeks of sampling across 10 years of GMS data (2012-2022) using the function ‘bam’ (‘Big Additive Model’) from the 'mgcv' package in R (Wood, 2017). Data consisted of counts which showed overdispersion in preliminary Poisson models and so a negative binomial error term was selected (Ver Hoef *et al.,* 2007). The hierarchical GAM (HGAM; Pedersen *et al.,* 2019) allows random effect terms in these models. As samples are nested within sites (participants’ gardens), a site-year ID variable was created and used as a random effect to account for repeated measures (Hurlbert, 1984). Using cubic regression splines, the smoothing parameter (λ) was fit with fast Restricted Maximum Likelihood ("fREML") to avoid overfitting. The maximum number of basis functions, *k,* was determined iteratively with gam.check, a diagnostic tool which determines if the *k* value is sufficient to model the ‘wiggliness’ of each covariate. Values of 30 were used for week and rainfall, 20 for minimum temperature, and 3 used for moonlight in order to approximate a polynomial function. Multicollinearity between variables was tested on preliminary GLMs using variance inflation factors (Fox and Weisberg, 2011) and concurvity (a generalised form of collinearity) was tested using ‘concurvity’ from ‘mgcv’ (Wood, 2017). Diagnostics throughout the modelling process were conducted by regularly examining Q-Q plots. Fitted values were generated across the range of each predictor while excluding random effects using R package ‘gratia’ (Simpson, 2023). Predictions were made for each bulb category while specifying the covariates to their August 1st average. Predictions for each bulb category were then converted to a percentage of the mean 125W MV prediction.

Ordination was conducted on samples pooled by site and year to examine species composition variation attributable to bulb type. Only sites with complete GMS microhabitat information were used (n = 2862 34-36 week timeseries). Categorical distance to feature variables were converted to numerical by taking an average of the distances in the range category. The furthest option in the survey response, “>2km”, was converted to equal 2km. To determine the ordination method, Decorana (DCA) was performed on the log-transformed species matrix as a measure of heterogeneity. A DCA axis 1 value of 2.54 indicated beta-diversity was suitably homogenous for constrained linear ordination (RDA rather than CCA). Using the function ‘ordiR2step’ with 49,999 permutations (Oksanen et al., 2022), a global model with all available variables was compared to an intercept-only model using forward selection to identify and remove extraneous variables. In this procedure variable selection stops if a new variable is either non-significant or if the adjusted R^2 of the model including the new variable exceeds that of the global model. The function provides a test of the significance of each variable to the selected model with an ‘anova-like’ Monte-Carlo test using 999 permutations (Oksanen et al., 2022), which was then adjusted for multiple comparisons using Holm’s correction. Multicollinearity was assessed with variance inflation factor; in the selected model all variables took a value less than 8. Ten variables with the highest contribution to model adjusted R2 are provided in Table 4. A full list of selected variables is provided in Supplementary Table 1.

After initial model selection, partial ordination was used to identify the effect of bulb type on species composition. In a partial ordination, conditioning variables (selected CEH landcover variables, latitude, longitude, year, the GMS microhabitat variables and GMS distance to feature variables) are ‘partialled out’ before analysis by comparing models with and without the variables, leaving only the contribution of the selected constraining variable(s) (Borcard et al., 2018). Following this procedure, the ‘mobility hypothesis’ was tested by regressing species’ typical wing size on to RDA axes one and two using vegan function ‘envfit’. This function is suitable for calculating the regression of supplementary variables which pertain to species by setting the ‘display’ argument to ‘species’ (Oksanen et al., 2022). Typical wing size was calculated by averaging minimum and maximum forewing length gathered from Cook et al., (2021) with additional data from Waring and Townsend (2018) and Sterling and

Parsons (2012). Significance of these trait variables were assessed by Monte Carlo simulation (999 permutations).

The inertia explained by the selected model was evaluated by calculating an unconstrained (PCA) model with no explanatory variables and extracting the first two axes. PCA axes were then used as variables in an RDA to determine the maximum inertia that could be explained by the theoretical best orthogonal explanatory variables. The model R^2 value was then calculated as a proportion of this maximum explicable variation. Significance of the R^2 value was evaluated by comparison to the distribution of 999 R^2 values generated by Monte Carlo simulation using randomised environmental variables, implemented in vegan function ‘anova’ (Oksanen et al., 2022).

Results

Abundance analysis

In total, 4,600,999 individual moths were included in the abundance analysis across 105,630 samples. The GAM model (model 1) explained 63.3% of the deviance. Percentage 125W MV catch is provided in Table 2 to facilitate comparison of abundance between traps. Predicted values show catch generally increased with wattage (Fig. 1a; Table 2). However, two trap types fell outside of this pattern: 80W MV and 15W Actinic. For 80W MV, lower than expected catch is likely due to low sample size (n = 1991). 15W Actinic, by contrast, was well represented in the GMS: it is the second most widely used trap (n = 15814 trap nights) and, consistent with a previous analysis (Bates *et al.,* 2013), produced larger than expected samples with the smallest standard error of the traps modelled (0.03). 15W Actinic bulbs tended to be placed in Skinner-type traps (83.32% of samples where this information was provided), compared to 20W (34.38%) and 40W (45.96%), which may retain a higher proportion of caught moths than Heath-type traps, which comprised just 15.99% of 15W Actinic samples, compared to 100% of 6W, 61.12% of 20W and 45.96% of 40W Actinic traps. Further, 15W Actinic bulbs can be powered easily battery, they can be positioned more freely than those with higher wattages, which may be conducive to higher catches. This flexibility, allowing traps to be placed away from mains power and therefore competing light sources also makes the bulb type an excellent option for surveys where mains power is not available.

In line with previous results (Jonason et al., 2014; Holyoak et al., 1997; Puskas et al., 2006; Bates et al., 2013; McGeachie, 1987), after an early peak in March, catch was highest in midsummer, generally decreased with rainfall, increased with minimum temperature, and decreased with moonlight (Table 3; Fig. 1B, C, D, E). Extreme values of temperature and rainfall were poorly represented in the GMS, reflected in large confidence intervals at high values for these variables.

Species composition.

For the unconditioned model, all included variables were selected and highly significant ($p< 0.006$). Percentage suburban landcover had a variance inflation factor of 12.43 and was removed, lowering the variance inflation factor of all variables to below 2.4. All variables excluding suburban landcover were therefore selected. The overall model was highly significant ($p<0.001$) and the adjusted R^2 was 0.29. Based on adjusted R^2 the five primary determinants of species composition were bulb category (adj-R^2=0.0619), latitude (adj-R^2=0.0589), distance to farmland (adj-R^2=0.0473), and longitude (adj-R^2 = 0.0373; Table 4).

Model 2 (fig. 2) was generated by conditioning variance attributed to all variables aside from bulb category, which was constrained. Model 2 was highly significant ($p<0.001$). 26.57% of the inertia was conditioned and 4.40% was constrained. The adjusted R squared was 0.044, representing 29.71% of the maximum variation explicable by two axes. For constrained axes, Eigenvalues were 8.78 for RDA1, 0.515 for RDA2, and 0.233 for RDA3.

Variation between MV and Actinic traps aligned with RDA1 (which contained the majority of the total model variance), while centroids of Actinic traps were similar in RDA1, but showed variation in RDA2 (Figure 2). The higher wattage Actinic traps took lower RDA2 scores, but broadly similar RDA1 scores. RDA1 was therefore interpreted as species composition variation attributable to use of MV bulbs, and RDA2 was interpreted as variation attributable to Actinic wattage, representing differences in brightness. The ordination therefore demonstrates that MV and Actinic bulbs generate samples that are compositionally distinct.

The average of each species' reported minimum and maximum forewing length (size) was regressed onto the ordination axes using 'envfit'. Species' position on the ordination was significantly related to their size ($p > 0.023$, $r = 0.065$). The regression aligned with RDA2, the axis partitioning bulbs by brightness. Size was aligned with the ordination arrow for 60W Actinic bulbs and positioned opposite to lower Actinic bulbs and 80W MV bulbs. This indicates that larger species have an increased propensity to be caught in high wattage Actinic bulbs in comparison to those of lower wattage and brightness. This may be due to larger wings and body sizes providing higher mobility (see Discussion).

Extracting species' RDA scores (Fig. 3), there was no significant difference in the RDA1 scores of species belonging to Noctuidae or Geometridae, indicating that Mercury Vapor traps showed no increased propensity to catch moths of either family compared to Actinic traps. There was, however, a small significant difference in RDA2 scores between the families ($W = 8424$, $p = 0.0075$), with Geometridae taking higher scores in RDA2. This indicates that dimmer Actinic traps tended to collect a larger proportion of geometrids than brighter Actinic traps. As geometrids tend to be weaker fliers than noctuid moths, this may represent the action of the mobility mechanism postulated above (see Discussion).

Model 3 (Fig. 4) constrained the variables ‘distance to street lighting’ and ‘percentage urban landcover’, with all other variables conditioned. The resulting ordination was highly significant ($p<0.001$). The adjusted R2 was 0.0033, representing 29.71% of the maximum variance explicable by two axes. Overall, 29.75% of the variance was conditioned; 0.37% of the variance was constrained. Eigenvalues for the constrained axes were: RDA1 = 0.4052; RDA2 = 0.3397. The regressed vector for species’ size was significantly related to the ordination ($p = 0.0019$, $R^2 = 0.0288$) and aligned with distance to street lighting, indicating that gardens further from street lighting were characterised by larger species than those close to streetlighting. Significantly, these arrows approached orthogonality to percentage urban landcover, indicating that street lighting, rather than any other aspect of the urban environment, produced the observed effect.

Discussion

By modelling moth trap catches in relation to bulb type, weather and week of the year, model 1 confirms that 125W MV traps produce the largest samples, followed by 60W Actinic, 15W Actinic, 80W MV, 40W Actinic, 20W Actinic and 6W Actinic traps. We find that catch is negatively affected by moonlight, rainfall, and low temperature, in line with previous studies (Jonason et al., 2014; Holyoak et al., 1997; Puskas et al., 2006). Here, improved estimates over previous comparisons of trap types (Bates et al., 2013) are provided by parametrising the important determinants of moth abundance over 10 years.

Significantly, model 2 shows that these traps produce samples that differ in not only catch size, but in composition also. Previous reports conflict over compositional differences between moth traps. Between traps of different spectra, several field experiments have found little or no difference in assemblage (Niermann and Brehm, 2022; Brehm, 2017;

Infusio et al., 2017; Brehm et al., 2021) while others note differences, but conflict over their cause and content (cf. Fayle et al., 2007; Blomberg et al., 1976; Merckx and Slade, 2014; Van Grunsven et al., 2014; Somers-Yeates et al., 2013; see Introduction). Here, robust evidence of compositional differences between bulbs are provided (Fig. 2).

What underlies this compositional variation? Model 2 indicated that brighter, higher wattage, Actinic traps collected a higher proportion of large-winged species (Fig. 2B). In brighter traps which sample a larger area, the ‘mobility hypothesis’ states that strong-flying species can travel from further to reach artificial light. This hypothesis predicts that large moths should be over-represented with respect to weak-flying species in bright traps, a prediction confirmed here. Another mechanism that could explain this observed pattern is allometry: all else equal, smaller eyes are less sensitive to light as they can collect and focus fewer photons (Warrant, 2017; 2022). As eye size appears to scale with wing size allometrically in moths (Stöckl et al. 2022), we are unable to distinguish between these two mechanisms - both may play a role. However, as forewing length rather than eye diameter was used in analyses, and accords with previous results, variation in mobility is the more parsimonious explanation.

Comparing high-pressure sodium floodlights to shorter wavelength metal halide floodlights, Somers-Yates et al. (2011) found significantly more noctuids were attracted to the metal halide lighting than geometrids, which they tentatively attribute to flight strength. Here, Geometridae took higher RDA2 values in model 2, suggesting that dimmer traps collected a larger proportion of geometrids than noctuids. Van Langevelde (2011), comparing traps of different spectra, find that the bulbs with higher short-wavelength emissions collected the most moths, which were on average larger in body mass, eye size, and wing dimensions. In both studies, more large moths were attracted to lights brighter in the short-wave and UV portion of the electromagnetic spectrum, as observed here.

Altermatt and Ebert (2016) established that in the spindle ermine moth (*Yponomeuta cagnagella*), ALAN exposure precipitated behavioural and morphological changes causing urban-collected individuals to display 30% reduced flight-to-light response compared to those collected in dark rural areas. Van de Schoot et al. (2024) measured the wing length, width, and area of these moths, finding that those collected from ALAN-affected areas showed a significant reduction in forewing length. This reduced wing size was associated with reduced flight-to-light response. This suggests that large, mobile species are more negatively affected by ALAN. Findings presented here, that larger winged moths form a larger proportion of brighter traps, supports this ‘mobility hypothesis’. We suggest an extension of the hypothesis to include community-wide effects: Model 3 showed that in gardens closest to street lighting, the moth community included a larger proportion of small species, independent of urbanisation more generally. This hypothesis goes some way to explain why large-winged moth species have declined more quickly than small-winged species in the UK (Coulthard, et al. 2019). This suggests that ALAN profoundly alters the moth community, exerting selective pressure against large winged species which are more mobile and sensitive to ALAN.

Here we show that MV traps collect larger samples than all Actinic traps compared (model 1) and that MV traps collect a distinct assemblage (model 2). However, factors underlying compositional differences between MV and Actinic traps are less clear than those between Actinic traps of different wattages. MV bulbs emit a larger proportion of non-UV and longer wavelength light than Actinic. Brehm et al. (2021), Van Langevelde et al. (2011) and Somers-Yates et al. (2011) find that light sources of longer wavelength collected fewer species, suggesting the UV portion of the spectrum is most attractive to moths. Our findings support this conclusion. However, not tested is the combination of UV and longer wavelength light. Here, model 2 showed that 80W MV bulbs were positioned closest to 125W MV bulbs along RDA1, indicating that despite the tendency of these traps to collect smaller samples than 60W Actinic bulbs, their composition was more similar to 125W MV bulbs than Actinic bulbs. This indicates that a portion of the variation between these bulb types is attributable to emission spectra rather than simply sample size. One study, comparing blacklight-coated (excluding all but UV radiation) MV bulbs to non-coated MV bulbs (Fayle et al., 2007) found that excluding the human-visible portion of the spectrum decreased catch size and diversity. Together with ordination model 2 presented here, this supports the hypothesis that UV in concert with longer-wavelength light produces a characteristic MV species assemblage, possibly including species which are more sensitive to longer-wavelength light. Further work is required to evaluate traits underlying this variation.

In 2015, MV bulbs were banned in the EU for general purpose use and are no longer widely manufactured (Bates et al., 2013). Here it is shown that the trap type producing the next largest samples is 60W Actinic, but this comes with the significant caveat that MV and Actinic bulbs will sample different sections of the moth fauna. For field studies where mains power is not available, 15W Actinic traps performed surprisingly well in the GMS and can be battery powered. An alternative not evaluated are LED traps (White et al., 2016; Brehm, 2017; Infusino et al., 2017). These traps can be designed to output a great variety of spectra by combining diodes, are energy efficient, and typically lightweight. Several designs are currently available, such as the LepiLED (Brehm, 2017), but the ideal spectral profile of LED lamps is yet to be determined (but cf. Niermann and Brehm, 2022; Brehm, 2017). Results presented here support the idea that inclusion of LW-emitting diodes are likely to broaden the fauna which LED traps sample (Brehm, 2017). Also not evaluated here are 200W tungsten bulbs used by the Rothamsted Insect Survey light trap network. These bulbs emit substantially less UV and a broader range of LW radiation than MV traps and are therefore likely to sample a distinct fauna.

Conclusions

Overall, our results highlight that moth trap bulb selection is not an arbitrary decision or one that can be made solely based on the exigencies of fieldwork. Portability, expense, and mains power availability are important considerations, but these choices will also affect composition of the resulting samples. For standardised comparisons of moth diversity and abundance, it is therefore imperative that: (1) the same bulb type is used between sites or treatments, (2) that bulb type is fully reported and (3) that traps are run concurrently to minimise differences in temperature, moonlight, and rainfall. The finding that brighter Actinic traps collect more large species and ALAN affected gardens contain fewer larger species strongly suggests that larger species are more sensitive to artificial light. This results in samples with a distinct (non-cross comparable) composition. Further, it appears that ALAN affects moth species assemblage by selecting against mobility, generating communities depauperate in large, mobile species. It is therefore likely that ALAN exposure has profound and potentially long-lasting impacts on the moth community, affecting species to different degrees based on size.

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Conflict of interest statement

The authors declare no conflicts of interest.

Data availability statement

Species occurrence data in this study were used under licence from a citizen science recording scheme and are available (to a data sharing agreement) from the Garden Moth Scheme (https://gardenmothscheme.org.uk). Code used to produce this manuscript are available via FigShare, DOI:10.6084/m9.figshare.27727659

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Figures

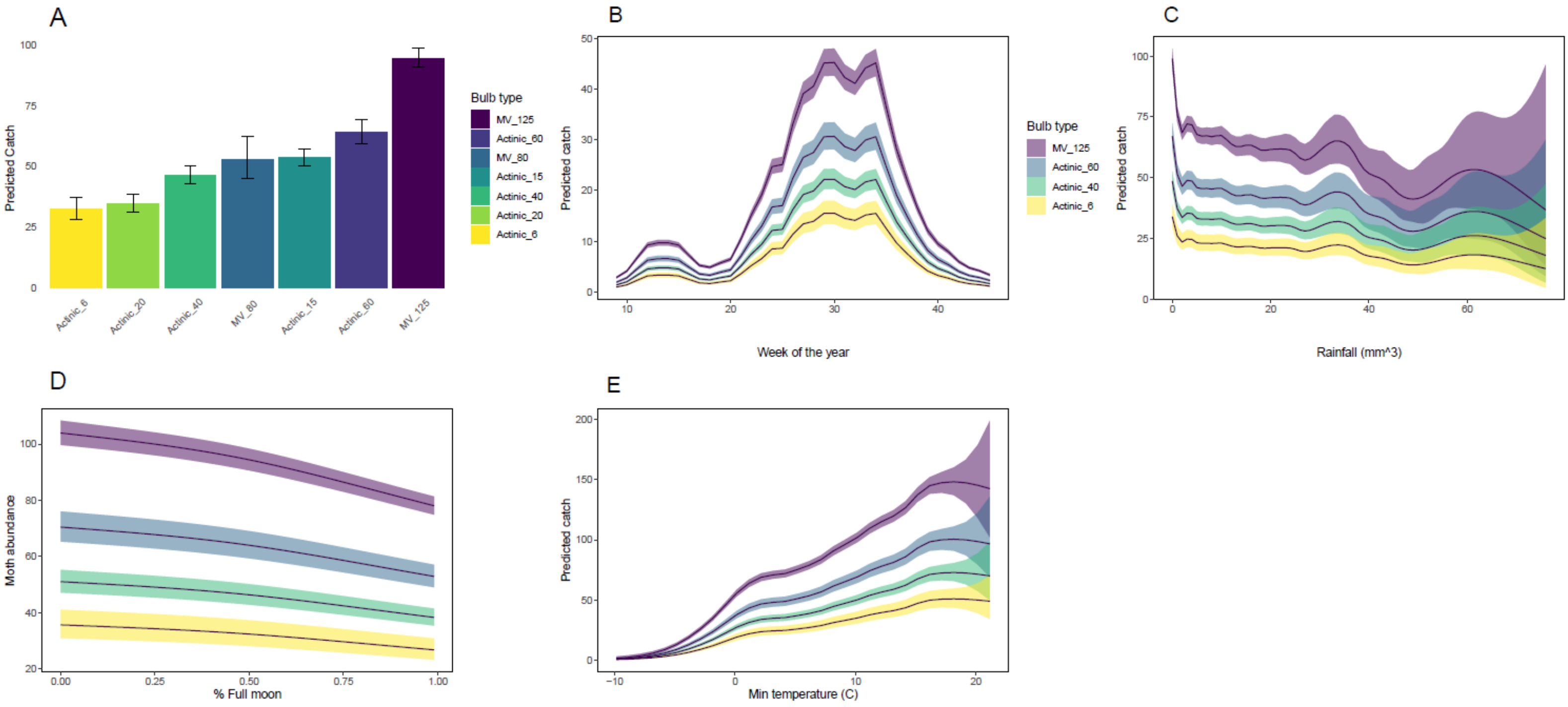


Figure 1. Predicted catch by bulb (A), week (B), rainfall (C), moon phase percentage (D) and temperature (E). Four bulb types (125W Mercury-vapor and 60, 40, and 6W Actinic) are displayed, reflecting the upper, lower and two of the middle values for predicted catch volume.

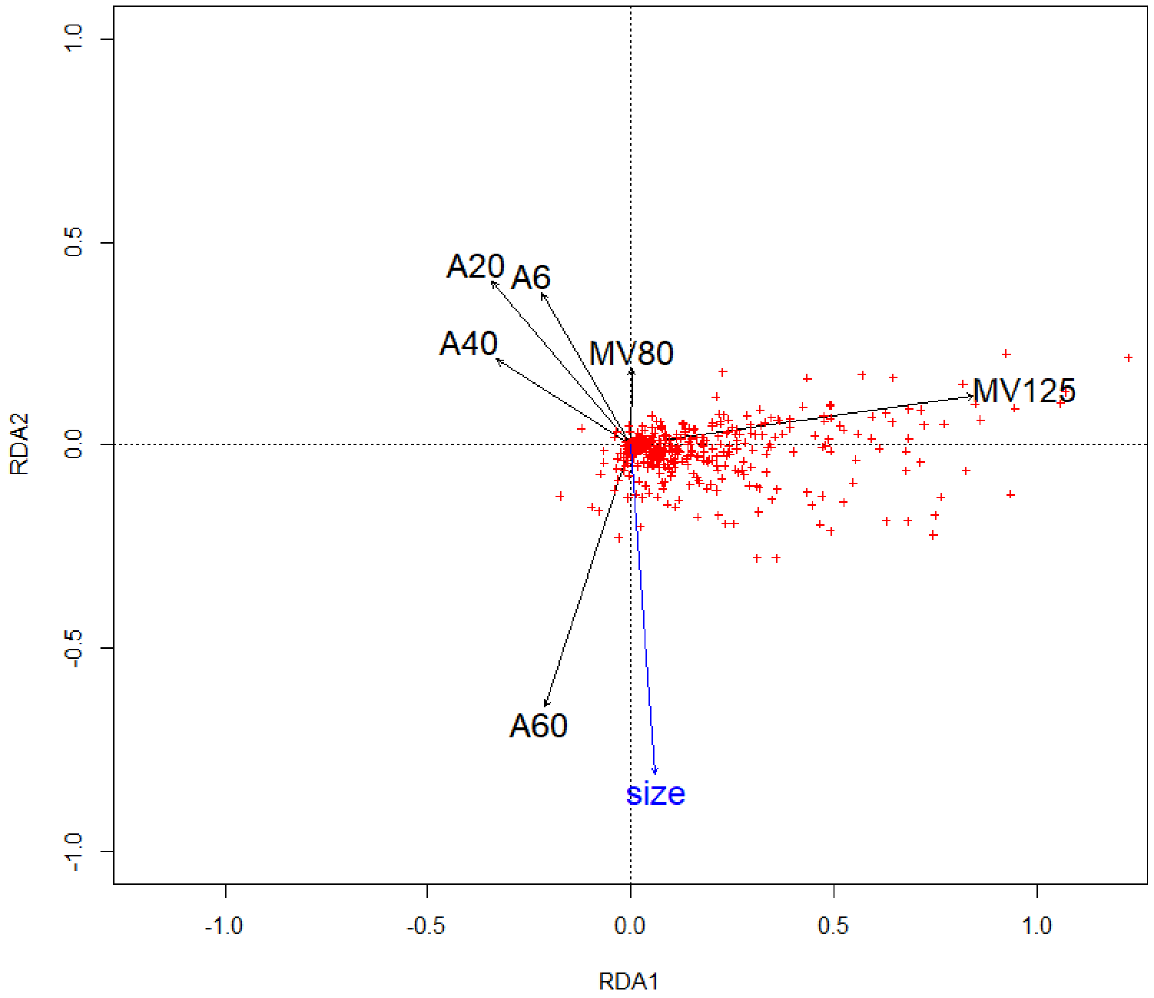
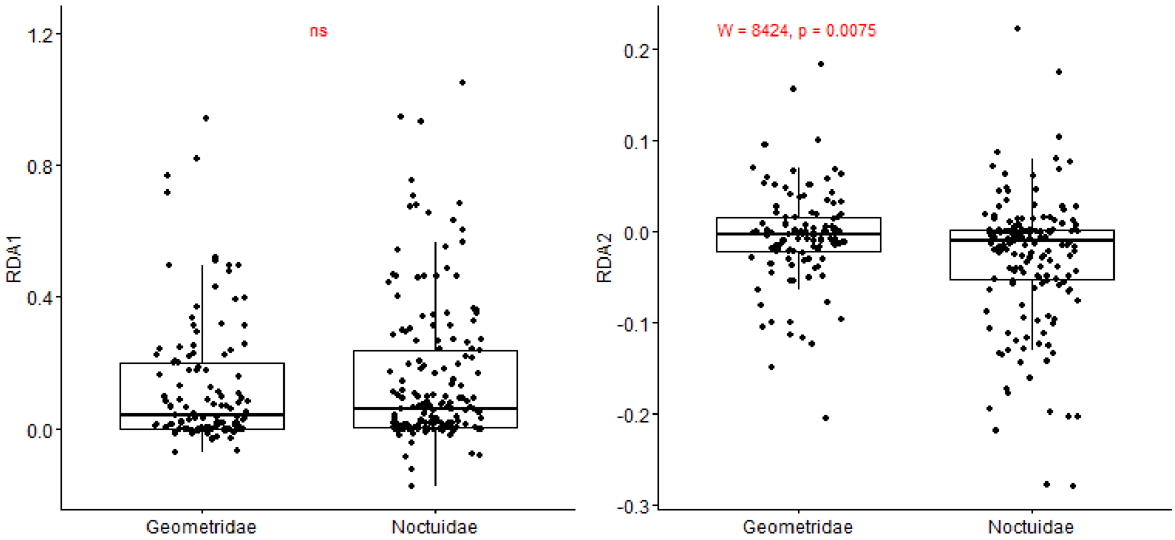


Figure 2. Model 2 partial log-transformed RDA ordination with regressed arrow for size. The effect of all sample variables besides bulb category was ‘partialled out’ before plotting. Arrow ‘size’ shows the effect of species’ size regressed on to the ordination result.



823

824 Figure 3: Comparison of RDA scores between moth families. Species of Geometridae had

825 significantly higher RDA2 scores than those of Noctuidae.

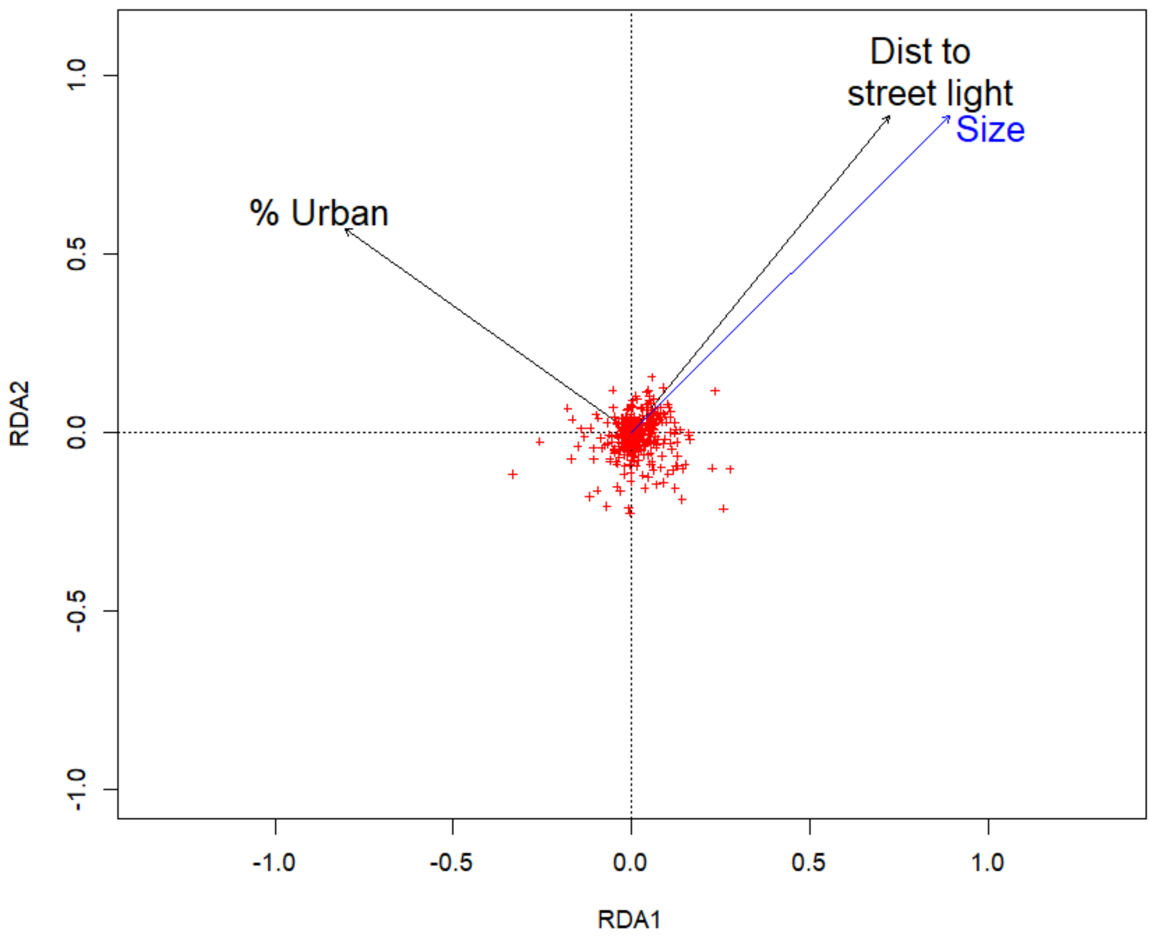


Figure 4. Model 3 RDA ordination. All variables besides percentage urban landcover and distance to streetlighting were 'partialled out' before plotting. Arrow 'size' shows the effect of species' size regressed on to the ordination result.

Table 1. Evaluation of moths against the indicator selection criteria provided by McGeoch (1998). Criteria only applicable for environmental indicators were excluded and those with significant overlap were collated into a single category for brevity.

#	Criterion	Evidence
1	Cost efficient and effective (time, funds, personnel), sampled easily	As a passive surveying method, sampling can be done more quickly and in larger numbers than butterflies, even over a single night (Duran et al. 2022). For example, Ricketts et al. (2002) were able to sample more than seven times the number of moths than butterflies over a 2-month period. While traps can be expensive, costing between £100 and £600 well-constructed and maintained traps can be used for many seasons (Nowinszky, 2003). Cost effective designs are also available, for example, a design by White et al. (2016) can be constructed for under £30.
2	Be abundant	Lepidoptera is among the most successful taxa worldwide and are unusual among insects as they are abundant on every continent (Fleishman and Murphy, 2009). Moths are especially abundant in tropical climates - Axmacher et al. (2009) were able to collect upwards of 200 individuals in their nightly 3-hour sampling period. In temperate locations, moths are likely to be among the taxa with the largest biomass in grasslands and woodlands (Macgregor et al. 2019).
3	Readily identified, taxonomy well known.	Among insects, lepidoptera may be the most taxonomically tractable group (Thomas, 2005). At least for temperate species, excellent moth identification resources are available (e.g., Waring and Townsend, 2018). Time required to sort and identify insect samples may be inversely related to body size (Lawton et al. 1996), as light traps sample only macro-moths, time to identify samples may be better than indicator groups that include very small members, such as Coleoptera.
4	Sufficiently sensitive to provide early warning	The rapid responses of Lepidopterans to environmental changes is widely acknowledged (New, 1997). The small size of invertebrates such as moths means they are particularly effective environmental and ecological indicators as they are sensitive to local conditions.Their mobility also allows them to disperse from unfavourable habitats, and their short generation times results in rapid adjustment to changes (Gerlach et al. 2013)
5	Able to differentiate between natural cycles and those produced by anthropogenic stress factors	Butterflies and moths are highly sensitive to daily and seasonal weather patterns, which some authors have used to criticise their use as indicators (e.g. Fleishman and Murphy, 2009). However, long-term data on the distribution of moths is available, especially in the UK, meaning that the responses of lepidoptera to stochastic weather variation is well understood (Gould and Woiwod, 2009). Using a very large dataset from eastern Germany, Jonason (2014) quantified the typical responses of moths to regional weather variation, fog, rain, the presence of the moon, finding each to have large effects on moth abundance. This confines moth trapping to dry nights without a full moon, limiting the seasonal sampling window (Nowinszky, 2003).
6	Representative of critical components, functions and processes.	Many lepidopteran species are closely co-evolved with their feedplants (Blair, 1999) and cannot persist without highly specific resources (Ricketts, Daily and Ehrlich, 2002), meaning that the presence or absence of specialist species is correlated with the presence or absence of the plant species on which they rely (Nowinszky, 2003). Thus, collection of rare or notable Lepidopteran species denotes the persistence of specialized resource suites (New, 1997), a key feature of well-functioning complex ecosystems. Lepidoptera may also be the most diverse pollinator taxa (Katumo et al. 2022). While nocturnal pollination is understudied (Hahn and Bruhl, 2016), certain orchid species such as the rare western prairie fringed orchid (Platanthera praeclara) depend exclusively on moths for pollination (Travers et al. 2011). 76% (196 of 257) of light-trap sampled moths analysed by Banza et al. (2015) carried pollen. A large portion (40%) of moth-pollinated plants can occur in grassland and meadow habitats (Hahn and Bruhl, 2016). Moths also form an important part of ecosystems as prey items birds, bats and herptiles (Waring and Townsend, 2018)
7	Representative of all trophic levels and major functional guilds.	While a very small number of moths have carnivorous larval stages (Montgomery, 1983), lepidoptera is primarily comprised of phytophagous species, moths are not representative of all tropic levels and functional guilds.
8	Representative of other taxa	The relationship between moths and other taxa is poorly understood. However, studies have found no correlation between moths and butterflies (Ricketts et al. 2002) and between moths and birds (Grand et al. 2004).
9	Tend to be distributed over range of habitats or environments	A cosmopolitan taxa, moths can be found over a range of common habitats, including many types of forest and grassland; riparian adapted, xerophilic and mesophilic guilds are well represented in the taxon (Gould and Woiwod, 2009). Importantly, they display high abundance at a variety of successional stages (Habel et al. 2019), meaning, unlike butterflies, they can be used as an indicator taxon in both grass and woodland habitats (Rákosy and Schmitt, 2011).

Table 2. GAM model 1 parametric terms, with sample size and predicted values for all 7 bulb types in the comparison. Predicted catch gives the number of moths predicted to be caught by each trap type on August 1st. This prediction was made with the average value taken for rainfall, moonlight and temperature on August 1st across all sites over 10 years, with the random effect excluded. Confidence intervals (CIs) for this value are at 95% level. % 125MV catch shows this predicted catch value expressed as a percentage of the predicted 125W MV catch.

Bulb	# samples	Estimate	SE	*T*	*P*	Predicted catch	Lower CI	Upper CI	% 125W MV catch
Intercept (125W MV)	60163	-40.08	7.35	-5.46	**<0.001**	**94.59**	90.78	98.56	100.00
80W MV	1991	-0.58	0.08	-7.02	**<0.001**	**52.88**	44.96	62.20	55.91
60W Actinic	10371	-0.39	0.04	-10.00	**<0.001**	**64.14**	59.45	69.20	67.80
40W Actinic	9807	-0.71	0.04	-17.54	**<0.001**	**46.46**	42.93	50.29	49.12
20W Actinic	4864	-1.01	0.05	-18.36	**<0.001**	**34.58**	31.07	38.48	36.56
15W Actinic	15814	-0.57	0.03	-17.31	**<0.001**	**53.59**	50.26	57.15	56.66
6W Actinic	2620	-1.07	0.07	-14.82	**<0.001**	**32.48**	28.19	37.41	34.33

Table 3. Approximate significance of smooth terms in HGAM model 1. All of the included smooth terms (week of the year, rainfall, temperature, moon phase, and the site-level random effect) had a significant impact on catch size.

Smooth term	Degrees of freedom	*F*	*p*
s(Week)	27.86	1678.75	**<0.001**
s(rainfall)	18.61	169.74	**<0.001**
s(temperature)	12.78	322.48	**<0.001**
s(moon phase)	1.98	713.50	**<0.001**
Random effect	2894.21	15.37	**<0.001**

Table 4. Source, significance, adjusted R^2, AIC, F values of the 10 variables with the largest impact on moth community composition, measured by adjusted R^2. Variables were evaluated OrdiR2step with 49,999 permutations. R2 was adjusted using Holm's correction. GMS variables originate from the Garden Moth Scheme survey dataset; CEH variables were extracted from the 2021 CEH Landcover map. A full list evaluated variables is available in supplementary information.

Variable	Cumulative adjR^2	Adj R^2	Df	AIC	F	Pr(>F)	Source
Bulb category	0.0619	0.0619	6	15268.43	32.47	0.00112	GMS
Latitude	0.1208	0.0589	1	15083.9	192.20	0.00112	
Distance to farmland	0.1681	0.0473	1	14926.7	163.19	0.00112	GMS
Longitude	0.2054	0.0373	1	14796.34	135.00	0.00112	
Year	0.2210	0.0156	1	14740.7	58.00	0.00112	
Garden size	0.2302	0.0092	3	14709.73	12.34	0.00112	GMS
Distance to woodland	0.2380	0.0079	1	14681.37	30.36	0.00112	GMS
% Suburban landcover	0.2443	0.0063	1	14658.7	24.64	0.00112	CEH
Distance to coastline	0.2499	0.0057	1	14638.19	22.46	0.00112	GMS
Soil Type	0.2554	0.0054	2	14619.41	11.36	0.00112	GMS

Supplementary information

Supplementary Table 1. Extended version of Table 3. Source, significance, adjusted R2, AIC, F values of available variables, produced by OrdiR2step with 49,999 permutations. R2 was adjusted using Holm's correction. GMS variables originate from the Garden Moth Scheme survey dataset. CEH variables were extracted from the 2021 CEH Landcover map. Full data available in supplementary information.

Variable	Cumulative adjR^2	Adj R^2	Df	AIC	F	Pr(>F)	Source
Bulb category	0.0619	0.0619	6	15268.43	32.47	0.00112	GMS
Latitude	0.1208	0.0589	1	15083.9	192.20	0.00112	
Distance to farmland	0.1681	0.0473	1	14926.7	163.19	0.00112	GMS
Longitude	0.2054	0.0373	1	14796.34	135.00	0.00112	
Year	0.2210	0.0156	1	14740.7	58.00	0.00112	
Garden size	0.2302	0.0092	3	14709.73	12.34	0.00112	GMS
Distance to woodland	0.2380	0.0079	1	14681.37	30.36	0.00112	GMS
% Suburban landcover	0.2443	0.0063	1	14658.7	24.64	0.00112	CEH
Distance to coastline	0.2499	0.0057	1	14638.19	22.46	0.00112	GMS
Soil Type	0.2554	0.0054	2	14619.41	11.36	0.00112	GMS
% Broadleaved woodland	0.2589	0.0036	1	14606.62	14.73	0.00112	CEH
% Arable and horticultural landcover	0.2622	0.0032	1	14595.11	13.44	0.00112	CEH
Native species hedgerow (y/n)	0.2649	0.0027	1	14585.41	11.63	0.00112	GMS
Distance to street lighting	0.2672	0.0023	1	14577.41	9.94	0.00112	GMS
Oak tree over 10m (y/n)	0.2693	0.0020	1	14570.43	8.91	0.00112	GMS
% Urban landcover	0.2711	0.0018	1	14564.34	8.04	0.00112	CEH
Wild ivy (y/n)	0.2728	0.0017	1	14558.62	7.66	0.00112	GMS
% Coniferous woodland	0.2744	0.0016	1	14553.22	7.35	0.00112	CEH
Pussy willow (y/n)	0.2759	0.0015	1	14548.12	7.03	0.00112	GMS
% Littoral rock	0.2774	0.0014	1	14543.49	6.57	0.00112	CEH
% Neutral grassland	0.2787	0.0014	1	14539.08	6.35	0.00112	CEH
% Improved grassland	0.2800	0.0013	1	14534.91	6.11	0.00112	CEH
% Acid grassland	0.2813	0.0013	1	14530.76	6.08	0.00112	CEH
Bird table (y/n)	0.2826	0.0013	1	14526.72	5.98	0.00112	GMS
% Supralitoral sediment	0.2838	0.0012	1	14522.76	5.90	0.00112	CEH
Tree over 10m (y/n)	0.2849	0.0011	1	14519.31	5.38	0.00112	GMS
Distance to water	0.2860	0.0011	1	14516.06	5.19	0.00112	GMS
Lawn over 25m (y/n)	0.2870	0.0011	1	14512.79	5.21	0.00112	GMS
Buddleia (y/n)	0.2879	0.0009	1	14510.25	4.48	0.00112	GMS
Nettle patch (y/n	0.2889	0.0010	1	14507.29	4.90	0.00112	GMS
% Saltmarsh	0.2898	0.0009	1	14504.78	4.45	0.00112	CEH
% Heather grassland	0.2906	0.0008	1	14502.43	4.29	0.00112	CEH
Heather (y/n)	0.2914	0.0008	1	14500.18	4.18	0.00112	GMS
Pond (y/n)	0.2922	0.0008	1	14497.93	4.19	0.00112	GMS

Compost heap (y/n)	0.2931	0.0009	1	14495.43	4.44	0.00112	GMS
Log Pile (y/n)	0.2940	0.0009	1	14492.77	4.59	0.00112	GMS
% Freshwater	0.2947	0.0007	1	14490.93	3.79	0.00112	CEH
Wildflower meadow (y/n)	0.2953	0.0007	1	14489.2	3.66	0.00112	GMS
Distance to green space	0.2960	0.0006	1	14487.55	3.59	0.00112	GMS
% Littoral sediment	0.2966	0.0006	1	14486.11	3.39	0.00112	CEH
% Inland rock	0.2971	0.0006	1	14484.81	3.24	0.00032	CEH
% Saltwater	0.2977	0.0006	1	14483.52	3.24	0.00112	CEH
% Calcareous grassland	0.2981	0.0005	1	14482.63	2.84	0.00528	CEH
Wild honeysuckle (y/n)	0.2986	0.0005	1	14481.74	2.83	0.00112	GMS
Long grass (y/n)	0.2990	0.0004	1	14480.96	2.74	0.00112	GMS