Entomologia
Experimentalis et Applicata

DOI: 10.1111/eea.12038

Assessing the value of the Garden Moth Scheme citizen science dataset: how does light trap type affect catch?

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Accepted: 6 December 2012

Key words: actinic bulb, community science, Heath trap, Lepidoptera, mercury vapour bulb, moth sampling, Open Air Laboratories, Robinson trap, scientific literacy, Skinner trap, voluntary biological monitoring

Abstract

Done well, citizen science projects can gather datasets of a size and scope far larger than would be possible using professional researchers. This study uses data gathered in Britain by the Garden Moth Scheme (GMS). Participants run garden light traps for at least 26 weeks a year and complete garden questionnaires detailing garden habitat and nearby landscape features. We used data exploration and generalised linear modelling (GLM) to investigate whether the data can be used to generate reliable research findings, testing the effect of moth light trap type on moth catch. Robinson traps, then Skinner traps, then Heath traps were found to catch the highest abundance and diversity of moths. Mercury vapour bulbs, then blended light bulbs, then actinic bulbs collected the highest abundance and diversity of moths. The GMS dataset can be used to generate useful and reliable research findings, and can be used in the future to investigate temporal and spatial trends in moth assemblage. Under international law, the use of mercury vapour bulbs will be phased out in coming years, leading to changes in the way moth assemblages are sampled. Information on the relative efficacy of different bulb types will aid the analysis of long-term moth datasets after these changes.

Introduction

'Citizen science' is not a new phenomenon, with various accounts tracing its origins back to the Audubon Christmas Bird Count of 1 900 (Seattle Audubon Society, 2011), or the American Ornithologist Union's migratory bird lighthouse deaths surveys some 20 years earlier (Bonney et al., 2009). It has been implemented in less familiar forms for more than a millennium (Miller-Rushing et al., 2012). However, the abundance and scope of citizen science projects is burgeoning (Silvertown, 2009; Miller-Rushing et al., 2012), with some projects enjoying the participation of tens to hundreds of thousands of people (e.g., Cannon et al., 2005; Lintott et al., 2011). The participation of citizens in gathering data for scientific research is increasingly regarded as essential, because communities can gather data across scales of space, time, and numbers of observations that would be unimaginable using only professional scientists (Cohn, 2008; Silvertown, 2009; Miller-Rushing et al., 2012). Engagement with citizen science can also educate and enthuse participants about science, so raising their scientific literacy and environmental awareness (Cohn, 2008; Bonney et al., 2009).

In 2007, the Open Air Laboratories (OPAL) project (OPAL, 2012) began in England using a range of regional partners based at UK universities (Silvertown, 2009; Davies et al., 2011). The project aimed to enhance community understanding and enjoyment of the local natural environment, particularly through community participation in environmental science investigations. An important project component aimed to support natural history societies and recording groups. OPAL in the West

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Midlands (OPAL WM) chose to support the Garden Moth Scheme (GMS, 2012) by advising on survey design, helping to increase participant recruitment, and helping to analyse and disseminate the data gathered by the scheme. This collaboration is therefore a 'co-created' citizen science scheme in the terminology of Miller-Rushing et al. (2012), where most stages of the research have received input from both professional scientists and highly skilled volunteers. When the GMS started in 2003 it was exclusively based in a region of England called the West Midlands (centred around Birmingham and the Black Country), but after continued growth in the number of participants, in 2007 it expanded to cover the whole of the UK and Ireland. In 2010, there were 314 active participants who in total provided ca. 21 000 h of recorder effort. This level of recording is rarely obtained using professional scientific researchers.

The vast majority of the 160 000 described species and estimated total of half a million or so species of Lepidoptera worldwide are moths (Kristensen et al., 2007), but moths are most often only studied because of the damage that some species cause to economically important crops (e.g.,Verkerk & Wright, 1996). However, moths can be very abundant in the landscape, and are (1) known to pollinate several plant species (e.g., Pettersson, 1991), (2) important specialist or generalist herbivores of wild plants and (3) are food for a wide range of species including small rodents (e.g., Elkinton et al., 1996), birds (e.g., Buse et al., 1999; Visser et al., 2006), and bats (e.g., Vaughan, 1997). Through these multiple trophic interactions with a large range of species, moths are critical components of many ecosystems. Moth assemblages are therefore good indicators of the effects of habitat degradation and fragmentation (Ricketts et al., 2001) and climate change (e.g., Visser et al., 2006), which have been suggested as likely causes of known declines of many species in recent decades (Conrad et al., 2004, 2006; Groenendijk & Ellis, 2011). On a practical front, moths are usually easy to sample as adults, have a stable taxonomy, are relatively easy to identify based on colour and pattern, and have easily available identification guides in many countries. Moths are therefore an excellent study group well deserving more investigation (see also Fox et al., 2011).

The GMS potentially represents an important dataset that can be used to explore the effects of garden and landscape conditions on a broad suite of indicator species and, in the long term, to explore the effects of changing landscape and climate. However, citizen science projects tend to produce 'coarse' datasets that can be challenging to analyse and interpret (Bonney et al., 2009; Miller-Rushing et al., 2012), and therefore require careful validation (e.g., Bonter & Cooper, 2012). The GMS data are gathered by community volunteers, usually with little formal training in biological recording or species identification. In addition, the data are gathered from sites spread over a wide geographical area, with highly differing habitat character and landscape context, using a wide array of different types of light trap. Light trap structure and bulb type are well known to influence the abundance and diversity of moths sampled. Early research (summarised by Bowden, 1982; Fry & Waring, 2001) has shown that moth attraction is a function of bulb illumination, particularly in the ultraviolet A (UVA) part of the spectrum, and catch is a function of trap design. However, trap design and bulb type always co-varied in early tests (e.g., Robinson traps usually fitted with 125 W mercury vapour bulbs), so that the independent effects of trap design and bulb type could not be investigated. The large increase in the choice of trap and bulb combinations currently available makes it possible to investigate the effect of trap design and bulb type independently.

This article documents the actions taken by OPAL WM and the GMS to encourage recruitment and continued participation in the scheme. It discusses steps taken to ensure quality and comparability, both through GMS sampling methodology and methods of data analysis, for GMS data from 2010. It addresses the following research question: can the effect of the wide-ranging trap type in the GMS dataset be successfully incorporated into analyses, so that the effect of trap type on moth catch can be quantified?

Materials and methods

Encouraging community participation

Taking part in the GMS involves significant commitments of time, energy, and skill, which represent potential barriers to participation. Most effort is therefore invested in recruiting the most likely participants: those already having existing interests in wildlife and biological recording. However, everyone is encouraged and welcome to join the scheme. Approximately 2 000 people regularly run moth light traps (Fox et al., 2011) in the UK, so there are many more potential GMS participants who might be encouraged to take part. OPAL WM encouraged GMS recruitment with leaflets, posters, and display boards detailing the work of the GMS and how to participate. These resources were displayed and distributed by GMS volunteers at various environmental fairs around the country (e.g., the Rutland Birdfair). OPAL WM and the GMS also ran training courses in the region to encourage recruitment.

Moth light trap start-up kits retail at £100–300, which is a significant barrier to beginning moth trapping for some people. Therefore, OPAL has thus far purchased 30 start-up kits for people who would have liked to take part, but were unable to afford the equipment. To aid new participants, OPAL WM commissioned the GMS to produce start-up guides that provide advice on moth trapping and identification. Participants are encouraged by the knowledge that the data that they collect will be analysed and reported (Bonney et al., 2009; Fox et al., 2011). As such, participants receive regular newsletters, a yearly report, and an invitation to the annual GMS conference. At all stages, the important hard work of participants underpinning the GMS is given due recognition.

Improving data quality and comparability

Some moths are difficult to identify to species, many requiring dissection for accurate identification. The GMS focuses on species easily identified when alive using readily available identification guides (e.g., Waring et al., 2009), species such as *Eupithecia subfuscata* (Haworth) and *E. vulgata* (Haworth) were excluded from the study species, despite being commonly trapped in gardens. Most species are 'macro' moths, but some easily identified 'micro' moths (e.g., *Tachystola acroxantha* Meyrick) are included. For ease of data management, the GMS was split into 12 regions, with the data from each managed by a separate volunteer regional leader. Each regional coordinator checks submitted data for unusual records, taking into account rarity, phenology, and distribution, and data are further checked by the national coordinators. Unusual records are queried with the participant, and if found to be unsupported by photographs or visual confirmation from a volunteer expert, are removed from the database. Within each survey period, identification training is supported using a GMS on-line forum where participants can post photographs, with more experienced participants guiding new participants to further improve identification reliability. Each region has its own list of easily identifiable species that can be found in that region, which includes a 'core' set of 195 species common to all regions (Supporting Information 1), all data analyses reported here are based on this core list.

Sampling at exactly the same time over the entire GMS is impractical; instead, a set of guidelines were created to standardise the timing of sampling as far as practicable. Participants were asked to sample moths one night every week from March to November. Friday night is the target night, but participants are able to sample up to 3 days early or late if this is impractical. Participants are encouraged not to record on successive nights, and not to 'cherry pick' the best nights in terms of weather conditions, but instead do the closest night to Friday possible. Expecting every one of the GMS volunteers to sample for all 36 weeks would be unreasonable. Therefore, recorders are asked to record for at least 26 weeks, to miss no more than three consecutive weeks, and to sample for as many weeks as possible. On average, recorders in 2010 sampled for 33.6 weeks. To further standardise the data samples obtained, sampling guidelines required participants to sample for all hours of darkness, to check the traps as early as possible after dawn to reduce predation, to include moths resting in the immediate surroundings of the trap, and when submitting information on two or more traps, to make sure that they are separated by at least 50 m or a large light-proof object (e.g., a house). One common problem with citizen science data is that participants tend not to report 'negative' results (e.g., no moths captured) (Bonney et al., 2009); GMS guidelines strongly stress the importance of recording events when a trap was run, even when no moths were found.

The scope of research questions that could be investigated was expanded from 2006, when each participant was asked to fill in a GMS garden questionnaire (Supporting Information 2). The questionnaire asks the participant to record/estimate site: grid reference, trap and bulb type, urbanisation level, soil acidity, distance from the nearest open country, distance to nearest woodland, distance to nearest water, distance to nearest coast (high-tide mark), distance to nearest green space, distance to nearest street-light (all distances = adjacent, <50 m, 50 m–2 km, >2 km), size of garden (<50 m^2, 50–200 m^2, 200–400 m^2, >400 m^2), and presence of the following microhabitats: lawn >25 m^2, log pile, pond, bird table, tree >10 m, oak tree >10 m, compost heap, long grass, native species hedgerow, wildflower meadow, honeysuckle (*Lonicera periclymenum* L.), ivy (*Hedera helix* L.), pussy willow (flowering *Salix* spp.), common nettle (*Urtica dioica* L.) patch, and butterfly bush (*Buddleja davidii* Franch.).

Data preparation for analysis

The whole 2010 GMS dataset included data from 314 sites and 510 164 records of moth individuals. However, despite the care taken by the GMS to standardise this large dataset, some initial data rationalisation was required prior to statistical analysis. This process was about striking a balance between standardising sampling effort to ensure comparability between the different samples, and not removing so many samples such that useful environmental data were lost. In-flight moth abundance and light trap efficiency are known to vary markedly from one night to the next due to changes in air temperature, wind speed, cloud cover, and lunar phase (Bowden, 1982; Fry & Waring, 2001). To time-average this un-parameterised variation, species counts from the 2010 data were summed. If only sites with the full 36-weeks of data were analysed, the dataset would comprise only 66 sites (21% of whole dataset), so a compromise was needed.

Figure 1 shows the percentage of the total (314) number of traps running on each sample week. Data returns were high and apart from 2 weeks, always over 90%. Generally, more moths fly during warmer nights and more people travel away from home for short holidays during warmer weather. Therefore, one might expect lower returns during warmer weather. However, returns were lowest when average per trap moth total abundance and species richness were lowest (i.e., fewer participants were trapping on cold/wet nights when they might expect to catch fewer moths). Although any missing data reduces the level of between-site comparability, these recording weeks were the weeks that least-strongly influenced the total abundance or species richness at each sample site. Sample-based rarefaction (interpolated species accumulation) curves (Gotelli & Colwell, 2001) were calculated for sites with 36 weeks of data following the methods in Colwell et al. (2004) in the freeware program EstimateS (Colwell, 2009). Curves were plotted for each site after removing successive weeks' worth of data in the order of declining percentage returns (shown in Figure 1) to 26 weeks. Figure 2 shows an example set of species accumulation curves for a site in Wales. Curves tended to change strongly in terms of shape, species richness, and total abundance at about the 30 week mark, so sites with 30 or fewer weeks of data were removed from further analyses. In addition, because of the importance of the weeks 14–28 (1 June–7 September) in terms of the number of species and abundance of moths captured (Figure 1), sites with more than 2 weeks' data missing in this period were also removed from further analyses.

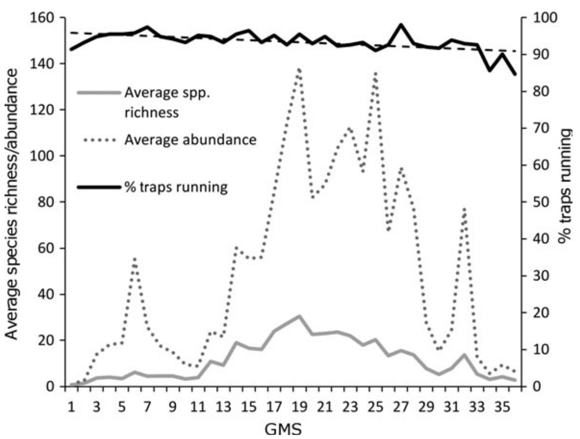

Figure 1 The percentage of Garden Moth Scheme (GMS) traps running in each GMS week (dashed line = fitted linear regression for % traps running) compared with the average species richness and average total abundance.

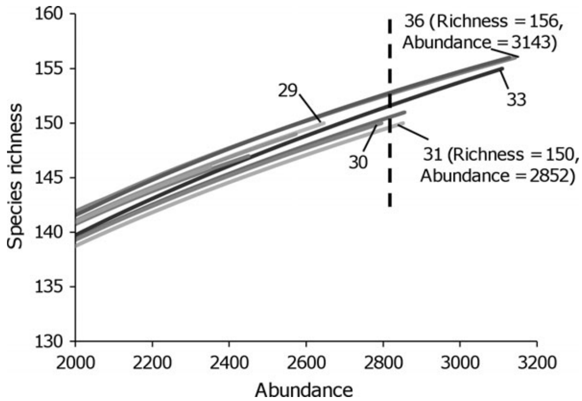

Figure 2 The upper end of the interpolated species accumulation curve set for an example Garden Moth Scheme sample site, showing the effect on abundance and species richness of removing successive weeks' data (labels for different weeks' curves only shown on some curves for clarity). In this example, species richness and total abundance changed particularly between 33 and 32 weeks, and then again between 29 and 30 weeks. For the whole dataset, the decision was made to include datasets in analyses that had at least 31 weeks' worth of data (shown by the dashed line).

In addition to the data gathered from the GMS garden survey sheets, several explanatory variables were calculated for each sample site independently. UK national grid references were converted to latitude and longitude in decimal degrees to provide continuous numeric figures for spatial location. The altitude of each sample site was measured using Google Earth. The categorisation of a location as urban, suburban, or rural is open to a degree of interpretation, so one researcher (AJB) categorised the sites as urban, suburban or rural using Google Earth as a visual aid. Rural sites were considered those that were in countryside or villages less than 1 × 1 km; urban sites were considered those that were located towards the core of large towns in areas of dense (>50% impermeable surface) development; suburban sites were the remaining intermediate sites.

Statistical analysis

A Generalized Linear Modelling (GLM) approach was used. Data were analysed, except where mentioned otherwise, in Brodgar v2.7.2 (Brodgar, 2010), which is a user interface that relies heavily on the freeware R v2.9.1 (R Development Core Team, 2006). Data were explored extensively prior to final analysis following the protocols of Zuur et al. (2010), whereby co-plots, Pearson correlations, and variance inflation factors (VIFs) in preliminary GLMs were used to identify explanatory variables that displayed strong collinearity. The presence of most garden habitat features were strongly collinear, so these were summed (except for the presence of a bird table) to give one 'garden microhabitats' variable; this variable therefore was a measure of diversity of microhabitats in each garden.

The whole 2010 dataset was collected using seven different light traps, six different types of bulb, and 19 different bulb wattages. Many of the types of light trap and bulb only had a small number of observations (small cells). These data were removed from the analysed dataset. The remaining bulb types were aggregated to produce six categories of bulb: 15 W actinic, 20–40 W actinic, 60 W actinic, 80 W mercury vapour, 125 W mercury vapour, and 160 W blended. The variable 'Heath trap' was strongly correlated with measures of urbanisation intensity (urbanisation, distance to street light, distance to field) and bulb type. As a result, data collected from sample sites running Heath traps were removed from the main dataset used for analysis (termed 'full dataset'). The relative effectiveness of Heath traps against Skinner traps was instead assessed on a sub-set of the data (termed 'reduced dataset') with comparable bulb types and wattages, and with a reduced set of explanatory variables because of stronger collinearity issues in this smaller dataset.

There were few observations from the Channel Islands and Ireland so data from these regions were removed from the analysed dataset. Further small cells were removed from the dataset by aggregating different classes of nominal variable. There were few 'urban' sites, so 'urban' and 'suburban' were aggregated to produce 'developed'; there were also few sites adjacent to, or within 50 m of the coast, thus sites less than 2 km from the coast were aggregated to produce 'coastal' sites. The final explanatory variables used for both the full and reduced datasets are shown in Table 1. The final full dataset comprised 214 sites, which contained 388 163 individual moths, and 66 sites in the reduced dataset, which contained 73 042 individuals (Figure 3).

Sites were distributed over a wide geographical area and at varying proximities to other sample sites; the data therefore might be expected to show evidence of spatial autocorrelation. Bray-Curtis similarity values and Euclidian spatial distances were calculated for all site pairs. The similarity distance matrices produced were tested for spatial autocorrelation using a Mantel test (9 999 permutations). This test showed significant autocorrelation in the data ($r = 0.29$, $P<0.001$), so sites near to one another had more similar species assemblages than those further away. As a result we included latitude and longitude in the set of explanatory variables to model this spatial variation. Thereafter, we examined the model outputs for spatial structuring using bubble plots (Zuur et al., 2009) of Pearson model residuals created using the gstat package (Pebesma, 2004) in R v2.14.1 (R Development Core Team, 2006).

Data were visually inspected for interactions between the effects of explanatory variables using coplots, but no interactions were found, so interaction terms were not included in the analyses. All final GLMs had VIFs for explanatory variables of less than 3. Model validation was implemented using visualisation tools to check for normality, homogeneity, data fit, large outliers, and data points with large leverage. The deviance/degree of freedom ratio was used to assess possible over-dispersion in the models. All data were over-dispersed, and negative binomial distributions were found to be most appropriate for all models (Zuur et al., 2010). Competing model fit and parsimony were assessed using small sample unbiased Akaike information criterion (AICc) to generate sets of competing models (Burnham & Anderson, 2002). Akaike 95% confidence set of models were created based on calculated Akaike weights including the 'best' (lowest AICc) and competing models.

Bulb and bulb type

Following data rationalisation, three types of trap, viz., Heath (Heath, 1965), Skinner (designed by Bernard Skinner), and Robinson (Robinson & Robinson, 1950), and three types of bulb (of varying wattages), viz., mercury vapour (high pressure mercury blended filament), actinic (low pressure fluorescent tubes), and blended (equivalent of 80 W mercury vapour and 80 W tungsten filament incandescent bulbs) were used in analyses. The wattage of some actinic bulb classes represented the combination of two separate actinic bulbs. These trap and bulb types represent a large majority of the types used in the UK. Both mercury vapour and actinic bulbs produce a proportion of their output as the UVA radiation most effective at attracting moths; tungsten filaments produce their light in the less effective, visible part of the spectrum (Fry & Waring, 2001).

Results

The minimum, average, and maximum total moth abundances for the full dataset were 187, 1 814, 6 129; and 102, 1 107, 4 500 for the reduced dataset, respectively. Minimum, average, and maximum total species richness for the full dataset were 45, 112, 171, and 33, 95, 144 for the reduced dataset, respectively. Full 95% confidence sets of GLM models are shown in the supporting information for the full dataset (Supporting Information 3) and the reduced dataset (Supporting Information 4). The only results discussed are those relating to bulb and light trap type; further results are outside the scope of this article.

Table 1 Final explanatory variables used in the analyses

Variable	Type	Level	Different name in GMS garden survey?
Trap type	Nominal	Full dataset: Skinner & Robinson Reduced dataset: Heath & Skinner	–
Bulb type	Nominal	Full dataset: 15 W act, 20–40 W act, 60 W act, 80 W MV, 125 W MV, 160 W blended Reduced dataset: 15 W act, 20–30 W act, 40 W act	Trap type & wattage
Altitude[1]	Continuous, m asl	–	–
Garden microhabitats	Continuous, count	–	–
Garden size[1]	Nominal	>50 m^2, 50–200 m^2, 200–400 m^2, >400 m^2	–
Latitude	Continuous, decimal degrees	–	–
Longitude	Continuous, decimal degrees	–	–
Soil type	Nominal	Acid, neutral & basic	–
Urbanisation[1]	Nominal	Developed & rural	Urban, suburban, rural
Distance to field	Nominal	Adjacent, <50 m, 50 m–2 km, >2 km	Distance from open country
Distance to streetlight[1]	Nominal	Adjacent, <50 m, 50 m–2 km, >2 km	–
Distance to wood	Nominal	Adjacent, <50 m, 50 m–2 km, >2 km	–
Distance to water[1]	Nominal	Adjacent, <50 m, 50 m–2 km, >2 km	–
Distance to coast	Nominal	Adjacent, <50 m, 50 m–2 km, >2 km	–
Distance to green space[1]	Nominal	Adjacent, <50 m, 50 m–2 km, >2 km	–

act, actinic; MV, mercury vapour; GMS, Garden Moth Scheme.
[1]Not used in the reduced dataset analyses.

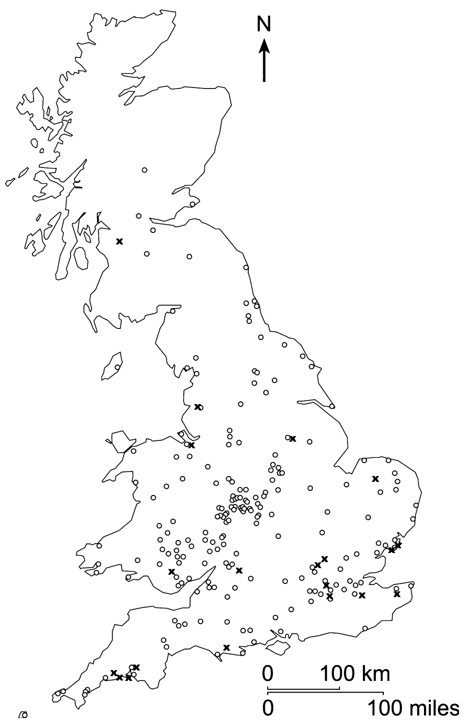

Figure 3 The spatial distribution of the 214 sample sites used in the full dataset analyses (open circles), and an additional 20 sites used only in the reduced dataset analyses (crosses).

What is the effect of trap and bulb type on moth catch?

Despite the variation in sampling, timing, location, and method, it was still possible to construct valid GLMs that demonstrate the effects of different bulb and light trap type on catch. The inclusion of spatial variables in the models removed the problem of spatial autocorrelation in the data by incorporating the spatial patterning into the final models. The example spatial bubble plot of the model residuals for the 'best' GLM for total abundance (Supporting Information 5) shows this; the distribution and magnitude of positive and negative residuals showed no clear spatial pattern.

Robinson traps tended to capture a greater species richness than Skinner traps (Figure 4A), but this effect was not significant ('best model' $P = 0.12$, d.f. residual = 199, included in two of three valid models; $n = 214$). Heath traps captured significantly ('best model' $P = 0.016$, d.f. residual = 57, included in all valid models; $n = 66$) fewer species than Skinner (Figure 4B) and, by extension, Robinson traps. There was also a highly significant ('best model' $P<0.001$, d.f. residual = 199, included in all valid models; $n = 214$) difference between the species richness of moths measured using different bulb types. Mercury vapour 125 W bulbs attracted significantly more species of moth than all the three strengths of actinic and the 160 W blended bulb (Figure 4C). It is worth noting here the effect

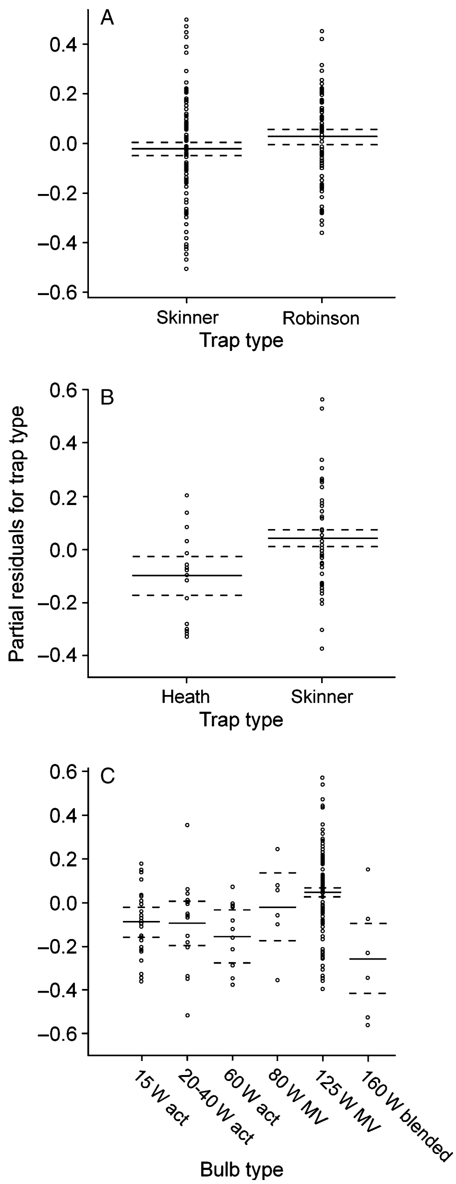

Figure 4 Partial residual plots of the effects of trap and bulb type on species richness within the 'best' GLM models. (A) Non-significant (P = 0.12; n = 214) effect of trap type Skinner against Robinson within the full dataset. (B) Significant (P = 0.016; n = 66) effect of trap type Heath against Skinner within the reduced dataset. (C) Significant (P<0.001; n = 214) effect of bulb type within the full dataset (act = actinic, MV = mercury vapour). Solid lines are the mean residuals, dashed lines are 95% confidence intervals, and the open circles are individual sample residuals.

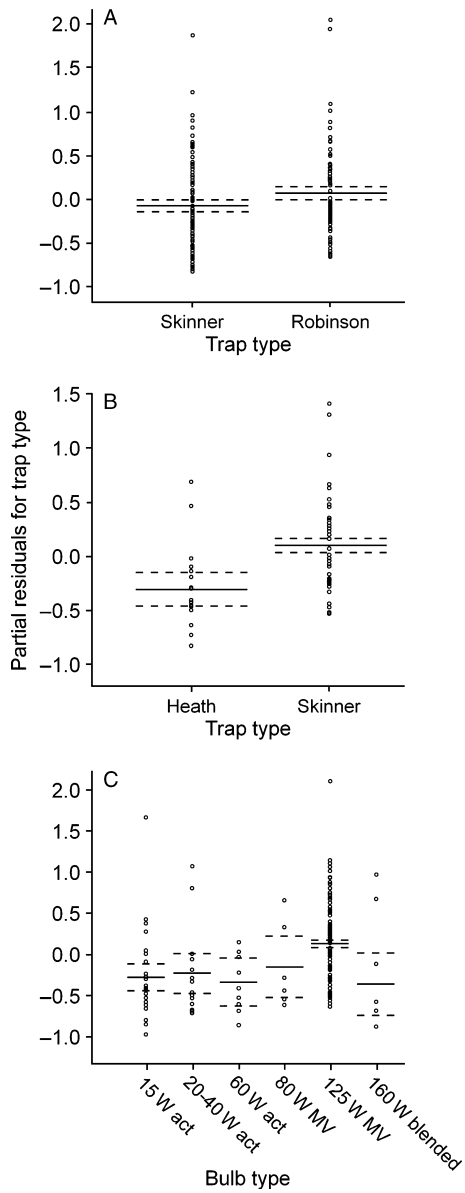

Figure 5 Partial residual plots of the effects of trap and bulb type on total abundance within the 'best' GLM models: (A) Significant (P = 0.038; n = 214) effect of trap type Skinner against Robinson within the full dataset. (B) Significant (P = 0.002; n = 66) effect of trap type Heath against Skinner within the reduced dataset. (C) Significant (P<0.001; n = 214) effect of bulb type within the full dataset (act = actinic, MV = mercury vapour). Solid lines are the mean residuals, dashed lines are 95% confidence intervals, and the open circles are individual sample residuals.

shown in Figure 4C of the number of samples on the confidence intervals and the associated power to detect significant differences between levels of nominal explanatory variables.

The effects of trap and bulb type on total moth abundance were similar to those for species richness. Robinson traps captured a greater abundance of moths than Skinner traps (Figure 5A; 'best model' P = 0.038, d.f.

residual = 197, included in all valid models; n = 214). Heath traps captured significantly ('best model' P = 0.002, d.f. residual = 57, included in all valid models; n = 66) fewer species than Skinner (Figure 5B) and, by extension, Robinson traps. There was also a highly significant ('best model' P<0.001, d.f. residual = 197, included in all valid models; n = 214) difference between the total abundance of moths captured using different bulb types. Mercury vapour 125 W bulbs attracted significantly more moths than all the three actinic categories and the 160 W blended bulb (Figure 5C). Figure 6 summarises the magnitude of the modelled effects of trap and bulb type on species richness and total abundance. The effects of trap and bulb type on total abundance were always more marked than the effect on species richness. Heath traps in particular performed poorly compared to Robinson and Skinner traps.

We constructed 14 Akaike 95% confidence sets for individual moth species using the full dataset, and seven for the reduced dataset. Table 2 shows the effects of trap and bulb type (only trap type is shown for the reduced dataset) on these species when these variables were included in the final model sets. For the full dataset, trap type was only included in three out of 14 model sets, and this variable was only significant (P = 0.010, d.f. residual = 202; n = 214) for *Noctua pronuba* L. In each case, Robinson traps caught more individuals than Skinner traps. In the reduced dataset, for every valid model set, Skinner and (by extension) Robinson traps captured more individuals than Heath traps. This effect was significant for three species: *Chloroclysta truncata* (Hufnagel) (P = 0.032, d.f. residual = 59; n = 66), *Agrotis exclamationis* (L.) (P = 0.007, d.f. residual = 59; n = 66), and *Orthosia cerasi* (Fabricius) (P<0.001, d.f. residual = 56; n = 66).

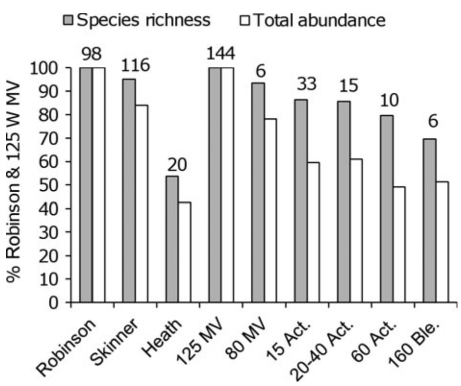

Figure 6 Percentage performance of different trap and bulb types relative to the 'best' trap (Robinson) and bulb type (125 W mercury vapour) in the 'best' fitted GLMs. Numbers above bars represent number of replicates. Abbreviations used: MV = mercury vapour, Act = actinic, Ble = blended.

Bulb type was included in the model sets for 13 out of 14 species, and was significant (P<0.05; n = 214) for 12 species (Table 2). Effects varied, but overall, 125 W mercury vapour tended to catch significantly more moths than the three strengths of actinic bulb. Mercury vapour 80 W and 160 W blended bulbs also tended to catch more moths than the actinic bulbs, but this was less often significant. Both wattages (80 and 125) of mercury vapour tended to sample more moths than blended bulbs. There were no consistent differences in the effect of bulb or trap type between species of Noctuidae and Geometridae.

Discussion

Due to careful design, participant support, data rationalisation, and data aggregation the GMS dataset can be used to successfully explore the effects of local habitat and landscape variables on moth assemblages. The results touched upon here will be explored in future papers, but it is clear that this dataset (see also Fox et al., 2011), collected solely by unpaid volunteers, is useful and can be used to explore some of the factors underlying the decline of common moth species (cf., Conrad et al., 2004, 2006). The quality of the data collected by the GMS has improved over time as extra data (garden habitat data and data on a core set of species) have been collected. More people join the scheme every year. This increase in sample size will allow researchers analysing GMS data to more easily detect significant environmental trends by decreasing confidence intervals associated with small cells. Data from future years will allow the robustness of identified trends to be tested with different semi-independent datasets.

The effect of trap and bulb type on species richness, total abundance, and the abundance of 14 species was successfully incorporated into valid GLM models and used to determine the relative efficacy of different trap and bulb types independently. Robinson traps were found to marginally outperform Skinner traps, but Robinson and Skinner traps markedly outperformed Heath traps in the number of species captured. Fry & Waring (2001) also found that Robinson traps outperformed Heath traps, but the two types of trap were fitted with very different bulb types so it was not possible to separate the effect of trap from the effect of bulb. Bulb type and wattage are known to affect moth catch because the spectral composition (especially the proportion of UVA radiation) and the area illuminated vary with different bulbs. The higher the amount of UVA emitted, and the larger the area illuminated, the higher the expected catch (Bowden, 1982; Fry & Waring, 2001; van Langevelde et al., 2011). We found bulb type to significantly affect the sampled species richness, with mercury vapour bulbs outperforming the various

Table 2 Effect of trap and bulb type on the abundance of moth species with valid GLMs. Probability values were calculated using the 'drop 1' function in Brodgar and are shown for the 'best' models. Trap 1 = Heath, trap 2 = Skinner, trap 3 = Robinson; bulb 1 = 15 W actinic, bulb 2 = 20–40 W actinic, bulb 3 = 60 W actinic, bulb 4 = 80 W mercury vapour, bulb 5 = 125 W mercury vapour, and bulb 6 = 160 W blended

Species	Common name	Family	Bulb	Trap	Effect – full dataset	Effect – reduced dataset
Eurrhypara hortulata (L.)	Small magpie	Crambidae	<0.001	–	Bulbs 4 & 5 sig. higher than bulbs 1–3	No valid model
Chloroclysta truncata (Hufnagel)	Common marbled carpet	Geometridae	0.044	–	Bulb 5 sig. higher than bulb 1	Trap 2 sig. (0.032) higher than trap 1
Idaea aversata (L.)	Riband wave	Geometridae	<0.001	–	Bulbs 4–6 sig. higher than bulbs 1 & 2. Bulb 5 sig. higher than bulb 3.	No valid model
Opisthograptis luteolata (L.)	Brimstone moth	Geometridae	<0.001	–	Bulb 5 sig. higher than bulbs 1–3	No valid model
Agrostis exclamationis (L.)	Heart and dart	Noctuidae	0.094	–	Bulbs 3–5 marg. higher than bulbs 1, 2 & 6	Trap 2 sig. (0.007) higher than trap 1
Apamea monoglypha (Hufnagel)	Dark arches	Noctuidae	0.001	[1]	Bulb 5 sig. higher than bulbs 1–3. Trap 3 marg. higher than trap 2.	No valid model
Axylia putris (L.)	Flame	Noctuidae	0.049	–	Bulb 5 sig. higher than bulbs 1 & 2	No valid model
Hypena proboscidalis (L.)	Snout	Noctuidae	<0.001	–	Bulb 5 sig. higher than bulbs 1–3. Bulb 4 sig. higher than bulbs 1 & 2.	No valid model
Lacanobia oleracea (L.)	Bright-line brown-eye	Noctuidae	<0.001	–	Bulb 5 sig. higher than bulbs 1–3. Bulb 4 sig. higher than bulbs 1 & 2. Bulb 6 significantly higher than bulb 1.	No valid model
Noctua comes Hübner	Lesser yellow underwing	Noctuidae	<0.001	0.07	Trap 3 marg. higher than trap 2. Bulb 5 sig. higher than bulbs 1 & 2.	No valid model
Noctua pronuba (L.)	Large yellow underwing	Noctuidae	–	0.01	Trap 3 sig. higher than trap 2.	[1]Trap 2 marg. higher than trap 1
Orthosia cerasi (Fabricius)	Common quaker	Noctuidae	0.006	–	Bulb 5 sig. higher than bulbs 1, 4 & 6	Trap 2 sig. (<0.001) higher than trap 1
Orthosia gothica (L.)	Hebrew character	Noctuidae	0.005	–	Bulb 5 sig. higher than bulbs 1 & 3	[1]Trap 2 marg. higher than trap 1
Xestia xanthographa (Denis & Schiffermüller)	Square-spot rustic	Noctuidae	<0.001	–	Bulb 5 sig. higher than bulbs 1–3	[1]Trap 2 marg. higher than trap 1

sig. = significant at P<0.05, marg. = marginal effect, not significant at P<0.05.
[1]Included in some models in the 95% confidence set, but not significant at P<0.05.

wattages of actinic bulbs and the 160 W blended bulbs. Fry & Waring (2001) found 160 W blended and 80 W mercury vapour bulbs to sample a similar number of species, which was expected because the bulbs output an equivalent amount of UVA radiation. The different outcome of this study could be a result of the relatively low number of replicates of each of these bulbs (n = 6). It is clear that of the bulbs tested, 125 W mercury vapour bulbs sample the highest species richness; a result supported by Fry & Waring (2001).

The effect of differing trap and bulb type on total abundance was more marked than for species richness, but the effects were largely the same. This might be expected because the return of successive samples and individuals has less effect on the total species richness as more of the assemblage is sampled and species accumulation curves start to decelerate. Robinson traps were found to catch more *Noctua pronuba* than Skinner traps, and these two types of traps captured significantly more *Chloroclysta truncata*, *Agrotis exclamationis*, and *Orthosia cerasi* than Heath traps. Observations of moth behaviour at traps has shown that it is not just the proportion of moths captured by a trap but also the proportion of moths retained by a trap, that combine to influence trap capture efficiency. Personal observation suggests that Skinner traps are less effective at retaining moths than Robinson traps. It could be that the lower number of *N. pronuba* (one of the largest and strongest flying of the British moths) sampled by Skinner traps was due to this species being more able to escape these traps. The effect of bulb type differed by species, but overall, mercury vapour 125 W, then mercury vapour 80 W and blended 160 W, then the various wattages of actinic bulbs tended to catch the highest abundances of individual species, supporting the patterns shown for species richness and total abundance.

Where the object of study is to maximise the abundance and species richness of catch, Robinson traps with 125 W mercury vapour bulbs are recommended. Skinner traps and 80 W mercury vapour bulbs catch nearly as many moths. Actinic bulbs catch fewer, whereas Heath traps sample far fewer moths. However, maximizing catch is only one consideration when choosing which moth trap to use. Others include cost, portability, the need for additional equipment (e.g., ballasts, rain-guards), power consumption, neighbourhood disturbance, and the time needed to identify and count samples. For example, mains Heath traps using actinic bulbs are about half the price of Robinson traps using 125 W mercury vapour bulbs and run on a fraction of the power, which means multiple Heath traps can be run for the same cost as one Robinson trap. Where the aim is to obtain a site species inventory, multiple Heath traps placed in different habitats could potentially outperform a single 125 W mercury vapour Robinson trap. Making these value judgements requires access to good information on the relative performance of different trap and bulb types. This document adds considerably to the body of information available to make informed judgements.

Across the world, the types of light bulbs used for domestic, commercial, and municipal use are changing to reduce cost, light pollution, and greenhouse gas emissions (Holker et al., 2010). Recent European Union (EU) regulations (EU, 2009a,b, 2010) have introduced phased performance requirements for various types of light bulb and their associated ballasts. Each regulation pertains to bulbs used for general purpose lighting and not to those used for special purposes, such as for use in moth traps. However, the number of bulbs and specialist electronic ballasts (chokes) used for moth trapping is unlikely to ever warrant the commercial manufacture of these products. The situation is in flux, but these regulations effectively end the sale of certain bulbs for moth trapping, unless manufacturers are able to meet the new performance requirements. Mercury vapour bulbs are particularly inefficient, and their sale for general purpose lighting will be banned by April 2015. Moth trapping enthusiasts are likely to stockpile mercury vapour bulbs ahead of the ban, but eventually the most effective and extensively used bulb will no longer be available for moth trapping. This research provides information on the relative performances of alternative types of bulbs that can be used for moth trapping. This information will be essential for the interpretation of long-term temporal trends in the abundances of trapped moths in the GMS and other datasets that will be affected by the ban.

Acknowledgements

The authors thank the many members of the Garden Moth Scheme, past and present, who have given freely a great deal of time and effort to make the scheme successful. We also thank Anne Ankcorn for the preparation of the figures, The Institution of Lighting Professionals for information on EU lighting regulations, and two anonymous referees who have greatly improved the quality of this document. This research is part of the OPAL (Open Air Laboratories) project, which is funded by The National Lottery (UK) through the Big Lottery Fund.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1 The 'core' list of 195 moth species used in the data analyses.

Data S2 The GMS garden habitat survey form.

Data S3 Variables included in the 95% confidence sets of GLM models for the full dataset (Lat = latitude, Lon = longitude, Alt = altitude, pH = soil pH, Wood = distance to wood, Water = distance to water, Coast = distance to coast, Gre. sp = distance to green space, Urban = urbanisation level, D. field = distance to field, Str. light = distance to street light, G. size = garden size, Micro = number of microhabitats, AICc = Akaike information criterion adjusted for small sample size, w = model weight, the higher the figure the stronger the model).

Data S4 Variables included in the 95% confidence sets of GLM models for the reduced dataset (Lat = latitude, Lon = longitude, pH = soil pH, Wood = distance to wood, Coast = distance to coast, D. field = distance to field, Micro = number of microhabitats, AICc = Akaike information criterion adjusted for small sample size, w = model weight, the higher the figure the stronger the model).

Data S5 Example of a spatial bubble plot of Pearson residuals for the best model for Total abundance using the full dataset. The coloured dots show very little spatial patterning, in both their size and spatial aggregation. This means that the model has successfully incorporated the spatial autocorrelation in the dataset.