Appendix 1

Investigating the impact of changing streetlight types on moth communities

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1. Introduction

Artificial night lighting is undergoing a rapid global expansion in its spatial distribution and intensity (Cinzano, Falchi & Elvidge 2001; Holker *et al.* 2010), with the potential to have a profound effect on ecological systems (Longcore & Rich 2004; Rich & Longcore 2006; Gaston *et al.* 2012). Recent research has demonstrated diverse impacts of anthropogenic light on behaviour, reproduction, community composition and ecosystem function across a range of taxa (e.g. Davies, Bennie & Gaston 2012; Dwyer *et al.* 2012; Stone, Jones & Harris 2012; Dominoni, Quetting & Partecke 2013; Meyer & Sullivan 2013). In addition, changes to lighting policy, predominantly aimed at improving energy efficiency, have initiated a shift towards new lighting technologies (Hölker *et al.* 2010). Whilst this presents an opportunity to promote 'ecologically-friendly' lighting practices, it simultaneously reveals an important research priority. The implications of large-scale street lighting changes for biodiversity are currently unknown, and as such must be carefully monitored to inform about the potential emergence of new threats to already fragile ecosystems (Hölker *et al.* 2010).

Of prominent concern is the increase in spectral heterogeneity that is likely to result from changes to street lighting (Gaston *et al.* 2012; Gaston *et al.* 2013). Different forms of artificial lighting exhibit unique spectral signatures, which characterise the colour and 'quality' of light perceived by the human eye (Elvidge *et al.* 2010). Street lighting in the UK has traditionally been provided using low-pressure sodium (LPS) lamps, which emit an orange hue over a narrow spectrum, although the dominant lamp type varies within and between urban areas. At the landscape scale, this leads to a complex patterning of artificial light sources, which also varies with land-use (Hale *et al.* 2013). Currently dominant lamp types are generally being replaced with brighter and broader spectrum lamps that produce a whiter light, such as high-pressure sodium (HPS), light-emitting diode (LED) and metal halide (MH) types. Species differ in their sensitivity to various parts of the light spectrum (e.g. Briscoe & Chittka 2001). Therefore the intensity of light emitted by a street light at particular wavelengths may play a critical role in determining its biodiversity impact: broad spectrum lamps emit light over more wavelengths, so have the potential to elicit behavioural responses in a large number of species across all taxa (Davies *et al.* 2013). In addition, some broad spectrum lamps also emit UV light, which is also detectable by many species. As such, the current trend towards diverse, broad spectrum street lighting, and the introduction of broad spectrum ultraviolet (UV) emitting technologies in particular, may have far-reaching consequences for biodiversity and ecosystem function (Davies *et al.* 2013).

The possible implications of artificial night lighting for moth diversity have been highlighted as a particular cause for concern (Frank 1988; Eisenbeis 2006). Many moths are strongly attracted to ultraviolet (UV) emissions, as well as those of shorter wavelengths of visible light (van Langevelde *et al.* 2011; Somers-Yeates *et al.* 2013), which are present to varying degrees in the spectra of MH and mercury vapour (MV) bulbs (Elvidge *et al.* 2010). So-called flight-to-light behaviour is common in most moth species, disturbing local foraging, settling activity and longer-distance dispersal movements and can result in high levels of mortality or reduced reproductive success (Frank 1988; Eisenbeis 2006). As such, artificial night lighting has been highlighted as a potentially key contributor to recently reported large-scale declines in British macro-moth populations (Conrad *et al.* 2006; Fox 2012; Fox *et al.* 2013; Bates *et al.* 2014). Therefore, the consequences of rapid changes in lighting policy and infrastructure currently underway in many UK cities (e.g. Birmingham and Leicester) require urgent investigation.

To investigate the consequences of current shifts to new lighting technologies we examined moth community responses to street lamp replacement in suburban Birmingham, UK. First, using a before-after-control-impact design, we investigated moth responses to street lamp changes in two neighbourhoods, compared to a third neighbourhood where no changes have been made. Second, we examined whether macro- and micro-moth community composition was influenced by the differences in street lighting profiles across the three neighbourhoods that have resulted from the Birmingham City Council lamp replacement programme.

2. Methods

2.1 Study sites

Birmingham City Council embarked upon a 25-year highway infrastructure improvement and maintenance program in 2010, in partnership with public service contractor Amey. Throughout the city, LPS and MV street lights are gradually being replaced by LED lamps in residential areas and HPS lamps on major traffic routes, with city wide increases in bright, broad spectrum street lighting and local shifts in UV emissions. Together with the existence of moth-trapping data pre-dating the changes in lighting, this has made it possible to conduct a 'natural experiment', equivalent to a before-after-control-impact (BACI) study, testing the effects of street lighting replacement on moth communities.

The study was conducted during summer 2013, in three Birmingham neighbourhoods, which were approximately 0.5km^2 in size and at least 1km apart (**Figure 1**), where similar trapping had been conducted in 2011. The neighbourhoods had a similar structural composition in terms of maturity of housing development, road cover and habitat characteristics (**Table 1**), but contrasting street lighting profiles (**Table 2**). As a result of the city-wide lamp replacement program, street lamps within two surveyed neighbourhoods have undergone replacement between the two survey periods (**Figure 1**). HPS lamps have been introduced along the western edge of Edgbaston, replacing the LPS bulbs previously present (36.0% of lamps within 100m buffer of study gardens replaced), and LED lamps have been installed within Selly Park, replacing some of the existing MV lamps (41.6% of lamps within 100m buffer of study gardens). The Moseley survey area is yet to undergo any change (**Table 2**; **Figure 1**).

Within each survey area, six, evenly distributed, gardens were selected for repeated moth sampling in 2013, having been surveyed previously in 2011. Light traps had been deployed within each study garden in August and/or September 2011 to collect baseline macro-moth data prior to street lighting replacement. Each garden was then surveyed again throughout June – September 2013 to provide a representative sample of macro- and micro-moth communities under each lighting regime, allowing both comparison with 2011 and a comprehensive assessment of communities in 2013. Where it became impossible to conduct repeat sampling (across or within years) due to garden access restrictions, sites where replaced by a comparable garden within an average radius of 49.25m (± 3.99 SE) (n = 6).

Table 1 | Habitat characteristics within a 100m radius of all gardens surveyed with each neighbourhood.

	Road cover (%)		Vegetation cover (%)		Tree cover (%)	
	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range
Edgbaston (E)	7.4 ± 1.0	4.5 – 13.1	66.5 ± 2.1	56.1 – 72.2	19.3 ± 1.8	10.3 – 27.3
Selly Park (S)	8.4 ± 0.7	4.9 – 11.5	56.5 ± 1.3	50.5 – 65.2	13.8 ± 0.3	12.5 – 15.0
Moseley (M)	6.0 ± 0.6	4.5 – 8.7	60.7 ± 1.8	52.3 – 69.0	20.1 ± 1.8	12.9 – 26.8

Table 2 | Street lighting characteristics of each neighbourhood surveyed before and after street lamp replacement. Lamp types are given in order of prevalence. The information is summarised for all street lights within a 100m radius of surveyed gardens.

	Before (2011)		After (2013)		
	Lamp types	Spectral profile	Lamp types	Spectral profile	Lighting change
Edgbaston (E)	HPS, LPS	Amber light Low UV	HPS	Amber light Low UV	LPS to HPS: Narrow to broad-spectrum
Selly Park (S)	MV	White light High UV	MV, LED	White light Moderate UV	MV to LED: Reduced UV emission
Moseley (M)	HPS, MV, MH	Amber/white mix High UV	HPS, MV, MH	Amber/white mix High UV	No change

2.2 Moth sampling

Moths were sampled using Skinner traps with 125 Watt MV bulbs run off mains electricity, which were operated during darkness hours. Traps assumed a standardised central position within gardens on repeated visits. Nights with bright moonlight, heavy rain and/or low temperatures were avoided (Eisenbeis 2006). Up to four gardens were sampled per night (mean ± SE: 2011 = 2.14 ± 0.13, 2013 = 3.63 ± 0.08); in 2011 garden visits were grouped temporally, by neighbourhood, but in 2013 visit order was randomised and we aimed to visit each garden at least twice per month to prevent any temporal bias within the sampling regime.

All gardens were surveyed 2 – 3 times on non-consecutive nights in 2011. They were then re-sampled 6 – 8 times over the course of the 2013 survey period (mean ± SE: 6.94 ± 0.19). However, due to the occasionally unsuitable trapping conditions and garden access issues, there was ultimately some disparity in the number of times gardens were sampled within particular months in 2013 (mean no. surveys per garden per month: 1.74 ± 0.05 (SE), range: 0 – 3). Since many moth species have restricted flight periods, this could have affected the representation of the complete moth community in the samples from each neighbourhood. Therefore, the effects of survey effort on moth community measurements were tested and any significant effects accounted for in further analysis (see below).

Macro-moths were counted and identified to species level in 2011; in 2013 all macro- and micro-moths were counted and identified to species level, except for some micro-moths, for which identification was possible only to the genus level in practice. Identification and release took place *in situ* at ca. 0800hrs on the morning after trapping.

Figure 1 | Maps of (a) relative locations of three neighbourhoods surveyed in Birmingham, UK; and positions of individual gardens surveyed in (b) Edgbaston, (c) Selly Park and (d) Moseley. Buffers of radius 50m and 100m were used to measure surrounding lighting and land cover variables over two spatial scales. Orange lines mark areas of street light replacement, see text for details. Contains Ordnance Survey data © Crown copyright and database right (2014).

2.3 Before-after-control-impact (BACI) study

Macro-moth data from two surveys per garden in each year were selected from the full dataset for BACI testing, such that survey effort was consistent in frequency and timing. Survey data were selected according to their date of collection, so as to match the data temporally as closely as possible between years (**Table 3**).

Table 3 | BACI average survey dates in 2011 and 2013.

		2011 average survey date (±SD)		2013 average survey date (±SD)	
Neighbourhood	BACI group	1st survey	2nd survey	1st survey	2nd survey
Edgbaston	+ HPS	5 Aug (±3)	17 Aug (±2)	8 Aug (±2)	25 Aug (±8)
Selly Park	+ LED	26 Aug (±3)	2 Sep (±4)	22 Aug (±4)	4 Sep (±6)
Moseley	No change	15 Sep (±3)	22 Sep (±2)	10 Sep (±6)	23 Sep (±4)

2.4 Street lighting and land-use

Street light position and lamp type data were provided by Birmingham City Council and ground-truthed using field surveys in 2011 and 2013. Aerial night photography (Hale *et al.* 2013) was also used to identify additional lamps such as domestic security lights. ArcGIS 9.2 (ESRI 2006) and Hawth's Analysis Tools (Beyer 2004) were then used to calculate three measures of street lighting variation for all gardens surveyed: (i) proximity to the nearest street lamp, (ii) total street lamp density and (iii) high-UV emitting street lamp density. Lamp densities were calculated at two spatial scales – within radii of 50m and 100m – to capture inter-species flight distance variation and the likely attraction distances of local lighting infrastructure (Eisenbeis 2006; Slade *et al.* 2013). It was not possible to test the effects of larger-scale street lighting variation as data from multiple gardens were no longer independent due to their relative proximity to one another (**Figure 1**).

To control for potentially confounding effects of local habitat on moth communities, the percentage covers of (a) vegetation (b) tree cover > 3m high and (c) road land-cover parcels within 50m and 100m radii of surveyed gardens were extracted using ArcGIS. Vegetation data were generated using colour and near-infrared photography (Bluesky International Limited, 2007) and combined with LIDAR (The Geomatics Group, 2006) to identify tree cover. Roads were identified using Ordnance Survey MasterMap (2008) polygons. As the percentage of tree cover was strongly correlated with vegetation cover at 50m ($r = 0.60$, $p = 0.010$) and 100m-scales ($r = 0.72$, $p < 0.001$), their effects on moth communities could not be tested simultaneously due to issues of collinearity. Since vegetation cover is likely to capture habitat preferences for a wider variety of species, this was selected for inclusion in statistical analyses.

2.5 Statistical analysis

Data from repeated sampling in each garden were combined to generate total and family-specific abundances, observed species richness and Fisher's α diversity index measures per garden and year. For analysis of the BACI data, values were calculated for macro-moths only (n = 36 garden×year samples), but all micro- and macro-moths were included in the analysis of the full 2013 dataset (n = 18 gardens). Individuals not identified to species level were excluded from richness and diversity measures (n = 152, 2013 only). Fisher's α diversity is commonly used to evaluate moth diversity, due to its low sensitivity to under-sampling (Kempton & Taylor 1974; Thomas & Thomas 1994; Fuentes-Montemayor *et al.* 2012).

The data were analysed using generalised linear models to allow appropriate error structures to be fitted. Differences in abundance and species richness were tested using a log link function and either a negative binomial or Poisson error distribution depending on presence of overdispersion, while Fisher's α diversity was fitted using an identity link and Gaussian errors. To test for the impacts of street lamp replacement, macro-moth community variables were fitted as a function of a neighbour × year interaction term within separate models.

To check whether 2013 moth community measures had been affected by variation in survey effort, each response variable was fitted within a separate GLM against the total number of surveys per garden. To capture potential effects of survey effort variation during key moth flight periods, these models were repeated using numbers of surveys per month (June – September) in turn. Species richness and 'other' micro-moth abundance (see **Table 4**) increased significantly with increased total survey effort ($p < 0.010$), whilst Fisher's α and 'other' macro-moth abundance were greater with increased survey numbers in July ($p < 0.033$). Therefore, total or July only survey counts were included as covariates in all analysis of those response variables respectively.

Moth communities may respond to street lighting in a number of different ways. Therefore, we examined variation in total abundance, species richness and Fisher's α-diversity from the 2013 dataset against four measures of street lighting profile variation: (1) neighbourhood [≈ lighting profile], (2) distance to nearest street lamp, (3) total lamp density, (4) high-UV lamp density. An information theoretic analytical approach was used, so that light measures could be fitted within separate models and their relative explanatory power compared directly (Burnham & Anderson 2002). Since moth community differences may also be caused by habitat variation, additional models for each light measure controlling for vegetation and road percentage covers were fitted for comparison, as well as a model for habitat variables only. As such, a candidate set of 10 models, which included an intercept-only null model, were fitted for each moth community measure. These analyses were repeated with lamp densities and habitat variables considered at either a 50m or a 100m scale. Competing models were compared using ΔAICc and Akaike weights (*w*). Models with the lowest AICc value (i.e. top ranked models) were considered to be the most parsimonious, but models with ΔAICc ≤ 2.0 were considered to have a similar level of support from the data (Burnham & Anderson 2002).

To explore the potential for street lighting patterns to explain moth abundance variation further, we fitted negative binomial or Poisson ('other' micro-moths only) regressions of micro- and macro-moth family abundances against each street lighting explanatory variable, controlling for survey effort (number of survey visits as a covariate) where appropriate. A negative binomial error structure was used where abundance data were over-dispersed. See **Table 4** for a list of all families evaluated.

There was no evidence of collinearity between covariates of any models (variance inflation factors ≤ 1.25). Tukey tests were applied for *post-hoc* testing of significant factors. All statistical analyses were conducted in R version 3.0.2 (R Core Team 2013).

3. Results

A total of 513 macro-moths were collected in 2011, representing 33 species. By comparison, there was a 4-fold increase in macro-moth abundance and 2-fold increase species richness in 2013, having matched the data collection by survey location, timing and survey effort (**Table 4**). A total of 8820 individuals, representing 254 species, were collected during the whole 2013 period and used for analysis of the complete moth community composition (**Table 4**). Species richness was highly correlated with total abundance ($r = 0.84$, $p < 0.001$) and Fisher's α diversity ($r = 0.69$, $p = 0.002$) across the 18 sites.

Table 4 | Recorded species numbers and total numbers of individuals collected (*n*) for (i – ii) macro-moths species and total numbers for the BACI study, and (iii) micro- and macro-moth families during 2013 complete moth community sampling. Families with < 50 individuals are combined ('Other' groupings).

	(i) BACI 2011		(ii) BACI 2013		(iii) Complete 2013 moth community	
	Species	*n*	Species	*n*	Species	*n*
Micro-moths:						
Gracillariidae					5	70
Yponomeutidae					10	317
Oecophoridae					5	160
Blastobasidae					1	218
Tortricidae					35	795
Crambidae					16	1297
Other micro-moths [a]					17	72
Macro-moths:						
Geometridae	6	69	27	249	59	1314
Noctuidae	27	444	44	1833	86	4480
Other macro-moths [b]	–	–	4	10	20	97
Totals	33	513	75	2092	254	8820

[a] Other micro-moth families during 2013 survey period, number of individuals in parentheses: Adelidae (1), Tineidae (1), Choreutidae (1), Lyonetiidae (5), Coleophoridae (6), Gelechiidae (3), Momphidae (1), Alucitidae (1), Pyralidae (27), Pterophoridae (19).

[b] Other macro-moth families during 2013 survey period, number of individuals in parentheses: Thyatiridae (23), Sphingidae (30), Notodontidae (8), Lymantriidae (4), Arctiidae (31), Nolidae (1).

3.1 BACI: Effects of street lighting replacement on macro-moths

Macro-moth total abundance, family-specific abundances, species richness and Fisher's α diversity were strongly influenced by year, with all measures significantly higher in 2013 (**Table 5**). This probably reflects the substantial improvement in weather conditions experienced in summer 2013 compared to 2011 (Met Office 2013), which resulted in a boost in Lepidoptera numbers through the UK (e.g. BTO 2014). Neighbourhood also had a highly significant effect on macro-moths (**Table 5**), driven by significant reductions in all macro-moth measures at the no change site (Moseley) compared to the other neighbourhoods (*p* < 0.002). However, this finding is confounded by the temporal pattern by which data were collected; lower values in the no change site are likely to reflect the later sampling period (when the main flight period for the majority of species was at or coming to at end) rather than a 'true' difference in the moth community (see **Table 3**). These strong effects of temporal variation, both within and between years, make it difficult to draw conclusions about the generality of street lighting change effects across neighbourhoods. However, it is still possible to detect impacts of street lighting changes using the neighbourhood × year interaction term.

Streetlamp replacement did not have a significant effect on total abundance or species richness compared to the no change survey area (**Table 5**). However, exchanging LPS for HPS bulbs in Edgbaston resulted in a significant increase in Fisher's α diversity (*post-hoc* t = 5.72, *p* < 0.001; **Table 45**; **Figure 2**). Furthermore, within the Edgbaston survey area the proportional increase in Fisher's α diversity was significantly correlated with the number of street lamps switched from LPS to HPS bulbs within a 50m (r = 0.86, *p* = 0.030) and 100m radius (r = 0.88, *p* = 0.022; **Figure 3**). Although this only tested on a small number of samples (n = 6) in one area, it does suggest that diversity may have increased where more street lamps had been replaced.

Geometridae abundance also appears to have been influenced by street lamp replacement, with significantly greater numbers of geometrids recorded in Selly Park following the replacement of some MV bulbs with LEDs (*p* = 0.044; **Table 5**; **Figure 2**). However, there was a proportionally larger change in abundance in Moseley, where street lights were not changed; suggesting that inter-annual differences at Selly Park may not be due to street lighting replacement. The proportional increase in Geometridae abundance in gardens within Selly Park was not correlated with the number of lamps replaced in the surrounding area (50m and 100m radii, *p* > 0.05). Streetlamp replacement did not have a significant effect on Noctuidae abundance (**Table 5**).

Table 5 | Results of the BACI study to test the effects of street lamp replacement within two neighbourhoods, compared to a third neighbourhood with no street lighting changes.

	Neighbourhood			Year			Neighbourhood × Year interaction		
Response	χ^2	df	*p*	χ^2	df	*p*	χ^2	df	*p*
Total abundance [a]	36.03	2	< 0.001 ***	103.93	1	< 0.001 ***	0.87	2	0.649
Species richness [b]	43.65	2	< 0.001 ***	76.10	1	< 0.001 ***	1.23	2	0.540
Fisher's α diversity [c]	17.44	2	< 0.001 ***	17.37	1	< 0.001 ***	7.53	2	0.023 *
Geometridae abundance [a]	27.17	2	< 0.001 ***	26.32	1	< 0.001 ***	6.26	2	0.044 *
Noctuidae abundance [a]	33.51	2	< 0.001 ***	120.15	1	< 0.001 ***	2.63	2	0.268

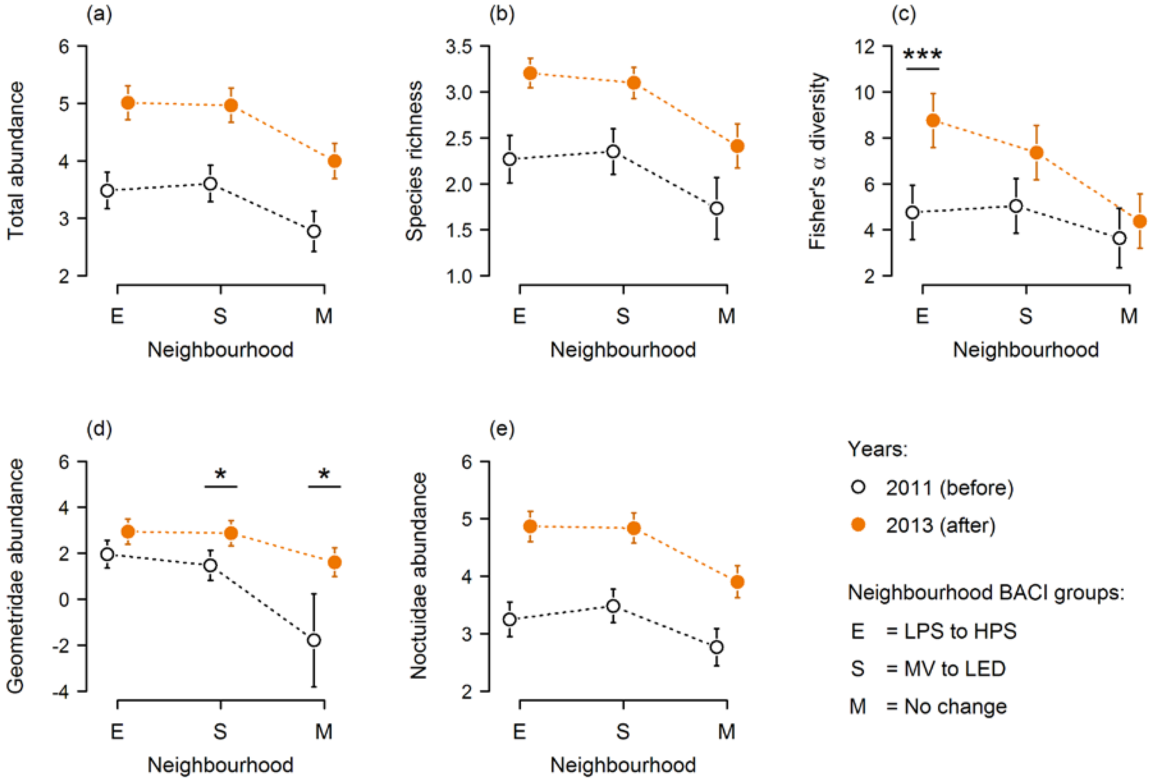

Figure 2 | The effect of street light replacement, compared to an area of no lighting change, on macro-moth community measures: (a) total abundance, (b) species richness, (c) Fisher's α diversity, (d) Geometridae abundance and (e) Noctuidae abundance. Points represent parameter estimates for each neighbourhood per year ± 95% confidence intervals, with abundance and species richness values (a, b, d, and e) plotted on the log scale. Neighbourhood abbreviations; E = Edgbaston, S = Selly Park, M = Moseley. Significance of *post-hoc* pairwise comparisons shown, where * = $p \leq 0.05$, ** = $p \leq 0.01$ and *** = $p \leq 0.001$.

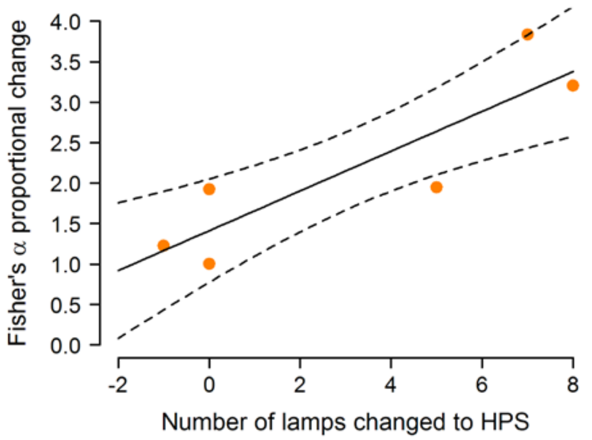

Figure 3 | The quantitative effect of street lamp replacement in Edgbaston (LPS to HPS bulbs) on Fisher's α diversity. Fisher's α proportional change calculated using 2013 diversity / 2011 diversity per site (n = 6). Results shown relate to the 100m-radius density; the pattern for 50m was similar. Best fit line and 95% confidence intervals predicted from the linear model.

3.2 *Effects of street lighting on moth total and family abundances*

Total abundance was not influenced by street lighting or habitat variation within our surveyed gardens, with the null model providing the best fit to the data (**Table 6**). However, models for street lamp distance and densities within a 100m radius fell within 2 ΔAIC of the best-fitting model, whereas models incorporating habitat were considerably poorer. This suggests that street lighting variability may be having a greater impact on moth numbers than effects of habitat variation, although there is no compelling evidence for a strong effect.

Table 6 | The effects of local street lighting differences on moth total abundance in three Birmingham neighbourhoods at two spatial scales (n = 18). Models within 2 ΔAIC of the top model are highlighted.

Model	Rank	Model variables	k^a	Log-likelihood	AICc	ΔAICc^b	w_i^c
Total abundance							
50m	*1*	*Intercept only*	*1*	*-116.9*	*236.0*	*0.000*	*0.419*
	2	Distance	2	-116.4	237.6	1.557	0.193
	3	High-UV	2	-116.8	238.3	2.257	0.136
	4	Density	2	-116.9	238.5	2.477	0.122
	5	Neighbourhood	3	-116.0	239.8	3.740	0.065
	6	%Veg + %Road	3	-116.6	240.9	4.888	0.036
	7	Distance + %Veg + %Road	4	-116.0	243.1	7.074	0.012
	8	High-UV + %Veg + %Road	4	-116.4	243.9	7.841	0.008
	9	Density + %Veg + %Road	4	-116.5	244.1	8.095	0.007
	10	Neighbourhood + %Veg + %Road	5	-115.9	246.9	10.831	0.002
100m	*1*	*Intercept only*	*1*	*-116.9*	*236.0*	*0.000*	*0.419*
	2	Density	2	-116.3	237.4	1.365	0.170
	3	Distance	2	-116.4	237.6	1.557	0.154
	4	High-UV	2	-116.6	238.0	1.920	0.129
	5	%Veg + %Road	3	-115.6	239.0	2.925	0.078
	6	Neighbourhood	3	-116.0	239.8	3.740	0.052
	7	High-UV + %Veg + %Road	4	-114.9	240.8	4.751	0.031
	8	Distance + %Veg + %Road	4	-115.0	241.1	5.045	0.027
	9	Density + %Veg + %Road	4	-115.4	241.8	5.742	0.019
	10	Neighbourhood + %Veg + %Road	5	-115.0	245.0	8.915	0.004

Variable names: Density = Total lamp density (50 or 100m); Distance = Distance to nearest street lamp; High-UV = High-UV emitting lamp density (50 or 100m); Neighbourhood ≈ Street lighting profile; %Road = % Road cover (50 or 100m); %Veg = % Vegetation cover (50 or 100m).

[a] *Number of parameters;* [b] *Difference in AICc compared to the top model;* [c] *Akaike weight for the model.*

To explore the potential of different street lighting metrics (neighbourhood, lamp distance, lamp density [50 or 100m-scale], high-UV lamp density [50 or 100m-scale]) to explain moth abundance patterns further, abundances for each micro- and macro-moth family (see **Table 4**) were fitted separately against each of these factors. Differences between the lighting environments did have a significant effect on two micro-moth families: Moseley had significantly greater numbers of gracillariids compared to Edgbaston ($\chi^2 = 7.42$, df = 2, $p = 0.024$) and blastobasids compared to Selly Park ($\chi^2 = 6.19$, df = 2, $p = 0.045$) (**Figure 4**). Blastobasidae abundance was also significantly positively affected by density of high-UV emitting lamps at 50m ($\chi^2 = 7.70$, df = 1, $p = 0.006$) and 100m scales ($\chi^2 = 4.10$, df = 1, $p = 0.043$), suggesting the between neighbourhood differences may be the result of differential UV emission. Furthermore, abundance of other macro-moths increased where there were a greater number of lamps within a 50m radius ($\chi^2 = 5.87$, df = 1, $p = 0.015$). There were no other significant effects of street lighting on micro- or macro-moth family abundances.

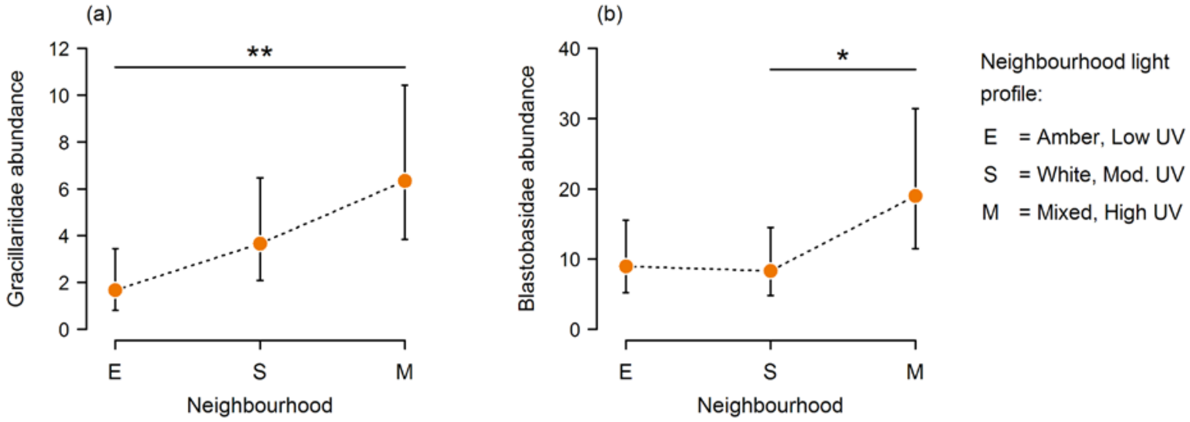

Figure 4 | The effect of different neighbourhood street lighting profiles on abundance of (a) Gracillariids and (b) Blastobasids. Mean ± 95% confidence intervals predicted from models are plotted. Neighbourhood abbreviations; E = Edgbaston, S = Selly Park, M = Moseley. Significance of *post-hoc* pairwise comparisons shown, where * = $p \leq 0.05$, ** = $p \leq 0.01$ and *** = $p \leq 0.001$.

3.3 Effects of street lighting on moth species richness and diversity

There was evidence that both species richness and diversity were influenced by differences in street lighting (**Table 7**). Species richness increased in gardens closer to street lamps, whilst Fisher's α diversity increased in gardens within a greater density of street lamps at a small spatial-scale (**Table 7**; **Figure 5**). Although lamp density at the larger spatial scale also provided a good fit to Fisher's α diversity, this was within 2 ΔAIC of the null model. Model rankings suggest that street lighting measures provide a significant improvement in explaining the variation in species richness and Fisher's α diversity compared to models with habitat variables. The density of high-UV emitting street lights did not have a significant impact on species richness or Fisher's α diversity (**Table 7**).

Table 7 | The effects of local street lighting differences on moth species richness and Fisher's α diversity in three Birmingham neighbourhoods at two spatial scales (n = 18). Survey effort was controlled in all models (see methods). Models within 2 ΔAIC of the top model are highlighted.

Model	Rank	Model variables	k^a	Log-likelihood	AICc	ΔAICc[b]	w_i^c
Species Richness							
50m	1	Distance	3	-68.1	144.0	0.000	0.678
	2	Density	3	-69.9	147.4	3.465	0.120
	3	High-UV	3	-70.0	147.7	3.763	0.103
	4	Neighbourhood	4	-69.5	150.0	6.008	0.034
	5	Distance + %Veg + %Road	5	-67.5	150.1	6.094	0.032
	6	*Intercept only*	*1*	*-74.8*	*151.8*	*7.840*	*0.013*
	7	%Veg + %Road	4	-70.5	152.0	8.056	0.012
	8	Density + %Veg + %Road	5	-69.7	154.3	10.363	0.004
	9	High-UV + %Veg + %Road	5	-69.8	154.6	10.622	0.003
	10	Neighbourhood + %Veg + %Road	6	-68.9	157.4	13.384	0.001
100m	1	Distance	3	-68.1	144.0	0.000	0.685
	2	High-UV	3	-69.9	147.6	3.598	0.113
	3	Density	3	-70.2	148.1	4.097	0.088
	4	Neighbourhood	4	-69.5	150.0	6.008	0.034
	5	Distance + %Veg + %Road	5	-67.6	150.3	6.288	0.030
	6	%Veg + %Road	4	-69.8	150.7	6.747	0.024
	7	*Intercept only*	*1*	*-74.8*	*151.8*	*7.840*	*0.014*
	8	High-UV + %Veg + %Road	5	-69.0	153.0	8.977	0.008
	9	Density + %Veg + %Road	5	-69.7	154.4	10.411	0.004
	10	Neighbourhood + %Veg + %Road	6	-68.9	157.4	13.434	0.001
Fisher's α diversity							
50m	1	Density	4	-44.3	99.7	0.000	0.616
	2	Density + %Veg + %Road	6	-41.5	102.6	2.854	0.148
	3	%Veg + %Road	5	-44.3	103.6	3.852	0.090
	4	*Intercept only*	*2*	*-50.0*	*104.8*	*5.101*	*0.048*
	5	High-UV	4	-47.2	105.4	5.703	0.036
	6	Distance	4	-47.2	105.5	5.766	0.035
	7	Distance + %Veg + %Road	6	-44.1	107.9	8.158	0.010
	8	High-UV + %Veg + %Road	6	-44.2	108.1	8.381	0.009
	9	Neighbourhood	5	-46.8	108.5	8.787	0.008
	10	Neighbourhood + %Veg + %Road	7	-43.9	113.0	13.261	0.001
100m	1	Density	4	-46.2	103.4	0.000	0.288
	2	High-UV	4	-46.3	103.7	0.300	0.248
	3	*Intercept only*	*2*	*-50.0*	*104.8*	*1.382*	*0.144*
	4	%Veg + %Road	5	-45.1	105.1	1.697	0.123
	5	Distance	4	-47.2	105.5	2.047	0.104
	6	Density + %Veg + %Road	6	-43.9	107.5	4.073	0.038
	7	Neighbourhood	5	-46.8	108.5	5.068	0.023
	8	High-UV + %Veg + %Road	6	-44.8	109.2	5.780	0.016
	9	Distance + %Veg + %Road	6	-44.9	109.5	6.080	0.014
	10	Neighbourhood + %Veg + %Road	7	-44.0	113.2	9.778	0.002

Variable names: see Table 5 [a] *Number of parameters;* [b] *Difference in AICc compared to the top model;* [c] *Akaike weight for the model.*

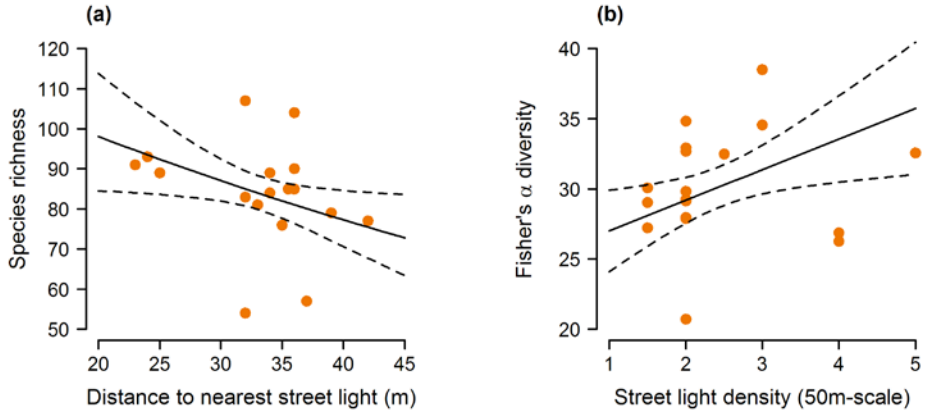

Figure 5 | Significant effects of measures of street lighting variation on moth species richness and Fisher's α diversity. Lines and 95% confidence intervals predicted from minimum models controlling for survey effort.

4. Discussion

The aggregation of moths, and other nocturnal insects, around street lights has been widely documented via both scientific and anecdotal evidence (e.g. Frank 1988). Whilst previous studies have tested the mechanisms driving this attraction using traps housing various bulb types (van Langevelde *et al.* 2011) or suspended from actual street lamps (Eisenbeis 2006; Somers-Yeates *et al.* 2013), here we examine the effects of street lighting composition and spatial characteristics on local moth community composition in suburban gardens, thus facilitating our understanding of exactly how moth communities respond to street lighting variation in an urban context. We show that broad-scale street lighting changes, neighbourhood lighting profiles, street light density and proximity all influence aspects of suburban moth communities in Birmingham.

Of particular relevance to the current shifts in global lighting policy (Hölker *et al.* 2010), our findings point towards the possibility that replacement of low-pressure sodium (LPS) with high-pressure sodium (HPS) lamps can lead to a significant increase in local moth diversity. This could reflect the importance of spectral composition in determining street light attractiveness to nocturnal insects (Eisenbeis 2006; van Langevelde *et al.* 2011; Somers-Yeates *et al.* 2013). Since HPS lamps emit light over a much broader range of the spectrum than LPS lamps, their capacity to elicit visually-guided behaviours in many different insect species is likely to be much greater (Davies *et al.* 2013). Indeed, the attraction of insects to LPS lights in considered to be minimal and at least an order of magnitude lower than that to HPS lights (Eisenbeis 2006). The results are consistent with the newly installed HPS lamps in Edgbaston having stimulated flight-to-light behaviour in a greater range of moth species, thereby drawing a larger diversity of moths into the neighbourhood from surrounding areas. This pattern was most pronounced in gardens where a greater number of the surrounding street lamps had been replaced, as indicated by the significant correlation between number of lamps changed and proportional change in Fisher's α diversity in Edgbaston gardens. This could be an example of the operation of changes to broad-spectrum street lighting as an ecological trap.

Moreover, it would suggest that the increases in moth catches are not an indication that replacement of LPS lighting with HPS causes a recovery in local moth populations.

An ecological trap can arise when an organism chooses poor-quality habitats above better alternatives, with detrimental consequences for their productivity and survival (Schlaepfer, Runge & Sherman 2002; Gilroy & Sutherland 2007). Recent research has suggested that urban areas can act as ecological traps for moths, and vulnerable species in particular, resulting in a general reduction in moth species abundance and richness in more urbanised locations (Bates *et al.* 2014). Bates *et al*. (2014) hypothesise that this is because street lighting provides an unreliable cue about habitat quality, facilitating the dispersal of moths from wide rural areas into urban sink habitats. Indeed, in Germany, eight endangered moth species were attracted to suburban streetlights in areas where their respective host plants were absent (Kolligs 2000). By encouraging moths into unsuitable habitats, street lighting has the potential to result in less foraging opportunities, disruption to dispersal and migration movements, reduced reproduction and ultimately lower survival and declines of certain moth populations (Frank 1988; Frank 2006). Although further research is required to verify this, it is possible that this study has identified a short-term process of lighting impacts while it is in progress. A plausible explanation for our results is that moths are attracted to neighbourhoods with changed lighting regimes and settle there at the end of the night or when they are exhausted, such that they are then available for trapping later. However, the area into which they are attracted may have insufficient resources for survival or reproduction, as well as direct mortality effects from the attraction to light, so acts as a sink. This pattern can only be a short-term term one because supplies of moths to be attracted from nearby are finite, so over time, catches of moths in an area of changed lighting would be expected to diminish as this 'vacuum cleaner effect' progressively damages the integrity of the moth community in the surrounding area. Our results are consistent with the hypothesis that street lighting in suburban areas is acting as an ecological trap, if the sampling captured moth populations in the process of the demographic response. The patterns we have found also emphasise the importance of considering the spatial and temporal scales at which studies like this are undertaken. Broader and long-term impacts on the moth community can be very different from short-term ones and so need to be differentiated with care in interpreting results.

In contrast to the patterns with LPS-to-HPS replacement, replacing mercury vapour (MV) bulbs with light-emitting diode (LED) lights in the Selly Park survey area had little impact on the moth community. MV bulbs emit a white light over a broad range of wavelengths, with significant peaks in the UV (366nm) and blue (403nm) components of the light spectrum (Elvidge *et al.* 2010). By comparison, LED street lights typically emit a white light that covers all parts of the visible light spectrum, with a primary emission peak in the blue region (450-460nm) and a secondary peak in the green and into red components of the spectrum, but no UV (Elvidge *et al.* 2010). The low wavelength emissions of MV bulbs are known to be highly attractive to many moths (Eisenbeis 2006), and since LED lamps do not emit any UV one might have predicted that the replacement of MV bulbs with LEDs would have produced evidence of a reduction in moth attraction to gardens in Selly Park. The comparatively smaller increase in geometrid abundance in Selly Park compared to Moseley, our control survey area, is perhaps a weak indication of this effect, though contradicts previous suggestion that geometrids are not overtly attracted to UV light (Somers-Yeates *et al.* 2013). Perhaps a better explanation of this lack of an effect is that with only 41.6% of lamps having been replaced this may not be enough to reduce the level of attraction created by the remaining MV street lights in the area significantly. Furthermore, although they do not emit UV radiation, insects can still be observed swarming around LED lights (Stone, Jones & Harris 2012). Therefore, any benefits that arise from a reduction in UV emissions might be negated by an increase in emissions in the blue part of the spectrum. Another possibility is that there could be a lag period after lights are switched and before moth community changes become evident, in which case prolonged monitoring may be required to detect significant effects, or indeed, transient, short-term processes of the kind discussed above might already have been completed.

Using a systematic survey encompassing the main flight period for British moth species (June – September), we have identified further possible influences of street lighting on local moth communities. First, we found that apparent effects on moth abundances varied between different taxonomic families and, second, that moth richness and diversity were associated with aspects of street light spatial distribution. Only two micro-moth families, Gracillariidae and Blastobasidae, showed significant differences in abundance between the three surveyed neighbourhoods. Both families were most abundant in Moseley, where the street lighting is provided via a mosaic of HPS, MV and metal halide (MH) lamps and therefore has a diverse spectral composition and a high UV component. Although micro-moths make up the majority of moth species in the UK (Young 1997) and are known to be attracted to light, most surveys exclude them due to difficulties in their identification (Frank 2006). As such, we are not aware of any studies in the literature which have specifically looked at the effects of lighting on micro-moths with which to compare our results, but we believe these findings indicate a high level of attraction of gracillarid and blastobasid micro-moths to UV wavelengths. Indeed Blastobasidae abundance was also positively correlated with the density of UV-emitting lamps. However, there were no such effects for eight other macro- and micro-moth families. It is also important to note that the results are purely correlative: although the neighbourhoods sampled were broadly similar, differences in other environmental factors such as vegetation composition (i.e. larval food plants) could underlie some of the differences observed.

Throughout the three survey areas, gardens closer to street lights had greater species richness, whilst those with more street lights in the immediate vicinity (50m radius) had greater Fisher's α diversity and a higher abundance of the less common macro-moth families ('other' macro-moths, see **Table 3**). These findings are irrespective of street lamp type or spectral output, suggesting that the spatial distribution of street lighting may also be playing an important role in determining its impacts on moth communities. These findings contradict previous suggestions that moth attraction to street lights may be reduced at high lamp densities due to the general overall increase in level of illumination in the surrounding landscape (Eisenbeis 2006). However, they provide further evidence consistent with an ecological trap effect and they highlight the need for further work to explore whether lamp density thresholds exist for flight-to-light behaviour.

In an increasingly urbanised world, where street lighting is expanding globally at an estimated 6% per annum (Hölker *et al.* 2010), these findings provide empirical evidence of the potential impacts changes in street lighting regimes are having on local moth communities. Moths have an important functional role as pollinators, herbivores and prey for a variety of mammalian predators. Therefore, changes to their abundance and diversity resulting from artificial lighting could have significant down-stream effects on ecosystem services provision and at multiple trophic levels. Although the results are based on a single inter-year comparison and use small sample sizes, they include patterns consistent with effects of street lamp replacement. While the results here need to be interpreted with caution, traditional lamps continue to be replaced with newer technologies, such as LEDs. This will offer further ‘natural experiment’ research opportunities which should be taken advantage of in order to improve our understanding of how artificial night lighting is contributing to declines in UK moth populations. Such studies could make use of new, bespoke data collection, or existing citizen science data, such as are collected in the Garden Moth Scheme.

5. Conclusion

Here, we demonstrate that moth community composition in suburban areas is influenced by street lighting in a number of different ways. Furthermore, as broader spectrum lighting technologies increase in prevalence, these findings show that replacing LPS bulbs with HPS bulbs results in a significant increase in moth attraction. These findings support the hypothesis that street lighting can operate as an ecological trap, encouraging moths into urban sink habitats.

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