

Appendix 2

The influence of light type and habitat barriers on moth flight-to-light responses

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Summary

Artificial night lighting is undergoing rapid global expansion in combination with use of new technologies, which have the potential to have a profound effect on ecological systems; recent research has already demonstrated diverse impacts of anthropogenic light across a range of taxa. The extent to which different spectral ranges of street lighting affect the barrier-crossing response within the range of flight-to-light behaviours in moths has yet to be investigated and this aspect is potentially significant in assessing detrimental impacts as well as informing future lighting policy, if the latter is to aim to minimise the impact on moths.

Three barrier scenarios were used to investigate the influence of variation in bulb type upon the barrier-crossing component of flight to light responses in moths. The experiment was conducted in a conifer plantation mosaic where there was no interference from artificial light sources and an abundant moth fauna. LED light arrays were used to mimic three types of street lighting that are in regular use, consisting of O (narrow spectrum - Orange LED representing low pressure sodium), W (broad spectrum - White LED representing high pressure sodium/LED) and UV (broad spectrum with ultra violet - White + UV LED representing metal halide/mercury vapour). The light arrays were used with Skinner moth traps. The three barrier treatments (locations) consisted of open (no barrier), ride (partially closed) and forest (fully closed) habitats. A field experiment was used to sample each location, bulb type and site combination on four occasions (total n=108) between 22nd July and 10th September 2013. Moth movement across the barriers was assessed by extracting the component of the moth community trapped in each location that is associated with open habitats only. The results, therefore, informed about the effects on the permeability of the barrier to open habitat moths of the different bulb types; trapping in open habitats provided a control.

The UV light array consistently attracted the greatest abundance and species richness of moths across all three barrier treatments, whereas the O light array attracted the lowest abundance and species richness of moths in all barrier treatments and the W array was intermediate. The UV array attracted similar, high numbers of moths in the open and ride barrier treatments and considerable numbers in the forest treatment, demonstrating that the UV component exerts a far greater attraction response than W alone, affecting almost all of the local moth community. An interaction between bulb type and barrier treatment showed that W and UV arrays attracted disproportionately greater numbers (marginally significant) and species richness of moths than the O array in the ride location, although there was no such difference in the forest location. Of the individual families examined, the differential response for disproportionately greater attraction in ride locations was found for Noctuidae, and marginally for Geometridae, but not for Crambidae or Hepialidae.

The results suggest that, in addition to previously recognized increased simple attraction of moths to light from the conversion of lighting stocks to new UV-rich of bright white LED bulb types, the new bulb types could exert an influence on animals in habitats that might be thought to be shielded from

their effects by opaque barriers, such as vegetation or buildings. The patterns of response exhibited to the three bulb types tested in this study can be used to inform lighting policy and to provide guidance in the use of appropriate lighting types where impacts on susceptible families or locally important moth communities may occur.

1 Introduction

The spread and diversification of artificial street lighting, occurring in conjunction with urban development, is predicted to have a profound effect on ecological systems (Longcore & Rich 2004; Rich & Longcore 2006; Gaston *et al.* 2012). In particular it is considered to represent a major threat to moth populations, both in the UK and globally (Frank 1988; Eisenbeis 2006). This is because street lighting elicits a ‘flight-to-light’ behaviour in many insects that can disturb foraging and migration movements and so often result in high levels of mortality. As such, the current spread and diversification of artificial street lighting could be having a major impact on moth populations and communities, many of which are in decline in Great Britain, due to factors associated with habitat and climate change (Fox 2012).

Moths are attracted most strongly to ultraviolet (UV) and short wavelength emissions (van Langevelde *et al.* 2011; Somers-Yeates *et al.* 2013), which are present to varying degrees in many common broad-spectrum streetlights such as light-emitting diode (LED), mercury vapour and high pressure sodium bulbs (Elvidge *et al.* 2010). However, few species of moths are sensitive to wavelengths at the red end of the spectrum (van Langevelde *et al.* 2011, Bruce-White & Shardlow 2011), which are also present in many broad-spectrum streetlights and narrow-spectrum bulbs such as low pressure sodium (Elvidge *et al.* 2010).

Moth flight-to-light responses in relation to street lights have been categorised by Bowden (1982) as “near effects”, acting within the zone of attraction, and “far effects”, in relation to night sky glow illumination such as the moon and anthropogenic light sources (Eisenbeis 2006). The “near effects” have been most studied and are thought to result in considerable moth mortality. These behaviours have been classified into three main types of response (Eisenbeis 2006): 1) Fixation - a moth comes into contact with a light and continually flies around or collides with it, 2) Crash barrier – where the intended flight path is interrupted by a light and movement is re-directed along the line of lights and 3) Vacuum cleaner – where moths are directly drawn to the light from the immediate vicinity. This study considers the sum of the effects of all three “near effect” response types, as revealed by attraction to light sources in standard moth traps.

Existing studies show that there is much variation in flight-to-light distances: For a 125 Watt (W) mercury vapour (MV) bulb, distances of 3m (Baker & Sadovy 1978) and 30m (Beck and Linsemair 2006) were noted. However 50-250m has been reported for a 15 W MV bulb (Bowden 1982), while 2-100m was reported for a 2x15 W UV-light tubes (Truxa & Fiedler 2012) and up to 50m for a 6 W Heath-type actinic bulb (Merckx & Slade 2014). The variation in recorded attraction distance derives from studies that examined a small number of species, within few families, rather than entire moth assemblages (Truxa & Fiedler 2012). In addition, the zone of attraction can vary considerably depending upon the type of light source (wavelengths emitted), light intensity, height above ground level, background lighting levels and the attraction response of the species. There is, therefore, a need for studies considering responses at the community level.

The density and configuration of physical structures in the environment are also important in influencing flight-to-light behaviour, because they will affect, first, how far a light source can penetrate and, second, the likelihood of it being encountered by individual moths during nightly movements. To gain a better understanding of how street lighting is affecting moth communities, it is important that these factors are considered together. One approach to doing this is to consider

barrier-crossing: as well as influencing line-of-sight attraction, different light sources could exert different influences on moth movements through, over or past barriers in the physical environment that inhibit light penetration. The effects of different light types on the barrier-crossing response in moths have not been investigated previously.

To investigate the potential for artificial lighting to influence the movement of moths with respect to barrier-crossing, we examined moth attraction to three light types of differing spectral composition, in relation to three different movement barrier contexts, using a field experiment. We tested the hypotheses that (i) elicited community-wide flight to light responses would decrease in strength from a broad spectrum with ultra-violet UV (UV) light, to broad spectrum without UV, to a narrow-spectrum visible light only (Langevelde et al. 2011), (ii) moth attraction would decrease with increasing density of a physical habitat barrier and (iii) that the three bulb types would differ in their propensity of to draw moths across habitat barriers.

2 Methods

2.1 Study sites and experimental design

The experiment was conducted in a forest environment free of competing sources of artificial light and barriers to movement were simulated by positioning light sources in open, partially-closed and fully-closed habitats. This enabled us to examine the flight-to-light responses of open grassland moth species under different movement barrier scenarios.

The study was undertaken in Thetford Forest, Norfolk, England, which is the largest area (185 km²) of lowland plantation forest in southern England. The main tree crop species comprise Corsican (*Pinus nigra*) and Scots Pine (*P. sylvestris*) along with smaller quantities of other coniferous and broad-leaved tree species. The close proximity of Breckland heath and other open habitats makes for a very diverse and abundant moth fauna, including a number of local specialities, contrasting with the proximate, species-poor mature conifer habitat. The absence of street lighting or nightglow from large towns (nearest towns within 8 km: Mundford 1km – population 1,591, Brandon 3.8 km – population 8,749 and Thetford 6.3 km – population 21,588), together with an abundant moth community, provide ideal conditions in which to investigate moth responses to different types of artificial light experimentally.

Three replicate study sites were selected within Thetford Forest (Figure 1). Each “site” comprised an area of plantation forest and grassland mosaic of size 4-5 ha incorporating stands of dense, monoculture trees (age 19 to 27 years), large open areas (8 to 12 ha) containing saplings (age 2-4 years) and grassy rides between forest stands. Barriers to moth flight-to-light responses were provided by the dense stands of conifers in the study areas. The light sources were placed in moth traps in locations as described below such that the plantation structure presented different barriers between open, grass-dominated habitat and the different light sources, as follows:

- (1) Open (No barrier) – moth trap in positioned 30m into open grass area;
- (2) Ride (partially-closed) – moth trap positioned 30m along ride from the open area;
- (3) Forest (fully-closed) – moth trap positioned 18-30m inside forest block adjacent to open area.

“Open” trap locations were situated within areas dominated by grasses and flowering plants (vegetation height between 30cm and 70cm among sites), also including newly planted trees (less than 4 years old, height 50-110 cm; Table 1). Traps were placed 30m from the edge of the area. The location therefore provided ample food resource for a diverse and abundant moth fauna and negligible line-of-sight obstruction between that fauna and the focal moth trap. Partially-closed movement barriers were simulated using “Ride” trap locations (Table 1). These were all located 30m from the edge of the open habitat, within a 2-3m wide track or avenue between tree rows (with substrate vegetation composition less diverse than corresponding open habitat, which is unlikely to support many open habitat moth species), with a direct line of sight to the open habitat. Fully-closed movement barriers were simulated using “Forest” trap locations (Table 1), which were positioned in the dense tree crops (Table 1) that had minimal ground flora (i.e. no potential food resource that might attract non-forest moth species), where the habitat remained uniform for a radius of at least 60m (with the exception of the focal open habitat). This minimized the moth fauna within the forest stand and maximized the contrast with the species-rich, open, grass-dominated habitat that separates the plantation blocks. The forest trapping locations were located at a distance

into a forest block where a 30 cm x 50 cm white board, held at eye level (c. 150 cm), became 50% obscured to a single observer standing at the edge of the block; this was between 18m and 30m from the forest edge (Table 1).

Table 1. Habitat characteristics of study sites and moth trapping locations

Site	Trap location	Tree crop	Crop age (years)	Distance from open edge (m)	Dominant ground cover
1	Open	Eucalyptus	4	30	Grass
	Ride	Scots Pine	84	30	Grass
	Forest	Corsican Pine	27	30	Pine needles
2	Open	Eucalyptus	4	30	Grass
	Ride	Scots Pine	84	30	Grass & Bracken
	Forest	Corsican Pine	21	18	Pine needles
3	Open	Douglas Fir	2	30	Grass
	Ride	Corsican Pine	19	30	Grass & Bracken
	Forest	Corsican Pine	19	18	Grass

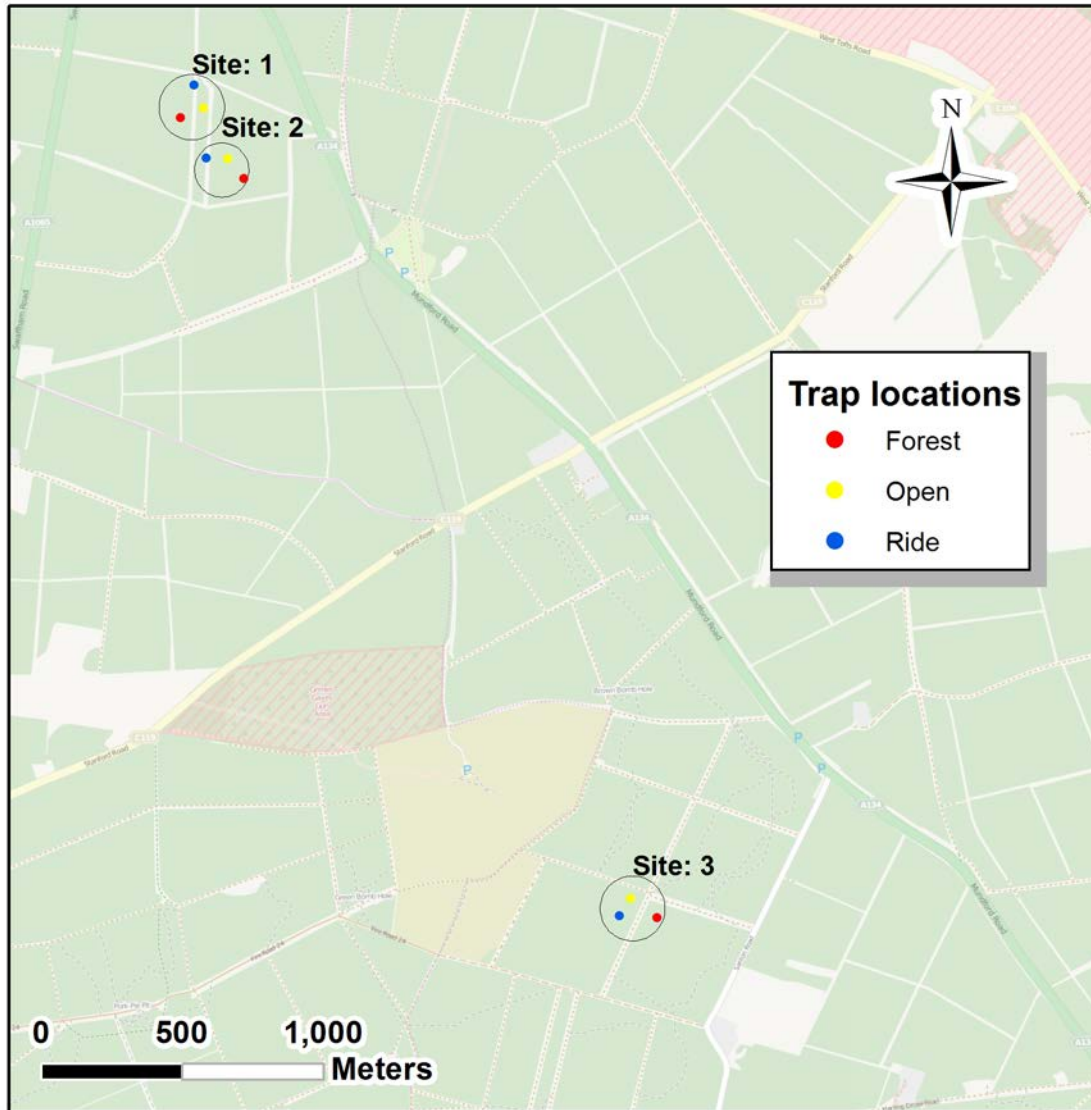


Figure 1 Thetford Forest study sites and moth trapping locations.

Although Open trapping locations for sites 1 and 2 were located in the same habitat block (Figure 1), trapping was never undertaken at both locations on the same night and the locations were separated by 200m. Further, in all instances, the trap locations were set so that there was no direct line of sight to another active trap. Given that Truxa & Fiedler (2012) found no attraction to low-powered traps at distances greater than 80 m, we are confident that they can be considered to be independent sample units.

2.2 Light treatments

The experiment tested three light source treatments that represent the spectral ranges of common streetlights: two broad-spectrum light sources, with ('UV') and without a UV ('W') component, and a narrow-spectrum light source ('O'), thereby mimicking the spectral ranges of existing street lighting technologies. These treatments used using light-emitting diode (LED) bulbs in strips (Figure 2, Table 2), rather than examples of actual street lights, for a number of practical and logistical reasons. A power source was the main limitation, which for low pressure sodium required a mains connection and for mercury vapour or metal halide required a portable generator, which was not practical due

to the potential fire risk and interference from members of the public. Also, the actual types of street lighting bulb differed in both size and light intensity emitted, thus making interpretation of trapping effort and relative attraction problematic. Therefore, we used standardised LED light arrays to minimise variation in trapping effort and light intensity (420 lumens), dimensions (60 bulbs per linear metre) and beam angle (120 degrees), facilitating a direct comparison between the treatments.

The light arrays (Table 2, Figure 3a) were constructed to be as similar as possible in respect of light intensity and size by wrapping the LED light strips (10mm wide by 3mm high) around a 7 cm (external) diameter plastic tube. The O and W arrays (Figure 3a) each measured 15 cm in length, each comprising 3 m LED strip lengths. The UV array (Figure 3a) was composed of a 1m strip of UV LEDs and 2.8 m of White LEDs. Due to the greater total length of strips, the final length of the array was 20 cm; however, to provide the best possible uniformity of UV and White light from the array, the UV LED strip was interlaid with the White LED strip for the middle 10 cm of the array, leaving 5 cm lengths of only White LEDs at either end of the array. As a preliminary investigation to verify the efficacy of our novel light sources, we compared the number and diversity of moths captured using the UV array to that captured using a 15W actinic bulb (a standard bulb type used for moth trapping), with both fitted to a Skinner trap. Both light types attracted a similar number and diversity of moths, thus indicating that our arrays were of sufficient brightness to attract adequate numbers of moths for the purpose of the experiment.

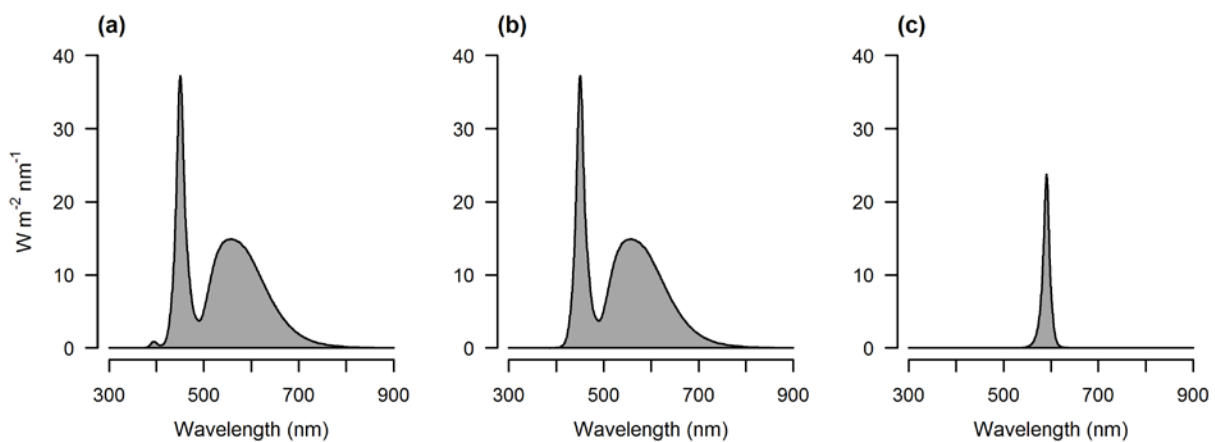


Figure 2. Emission spectra of three LED bulbs used in three light arrays: a) UV, b) W and c) O. Quantified using an Ocean Optics MAYA2000-Pro spectrometer fitted with a CC-3-UV-S cosine corrector.

Table 2. Composition of light treatments using LED strips (Figure 3a) and spectral representation compared to street bulb types (Elvidge *et al.* 2010).

Bulb type	Treatment	LED light strip type and length			Representative of street bulb type
		Bright	Ultra	Orange	

		White	Violet		
UV	broad spectrum with UV	280 cm	100 cm	-	Metal Halide or Mercury Vapour
W	broad spectrum without UV	300 cm	-	-	High Pressure Sodium or LED
O	narrow spectrum	-	-	300 cm	Low Pressure Sodium

2.3 Moth sampling

Moths were sampled using three Skinner traps, modified to house the lighting arrays, which were positioned vertically from a central beam across the top of the trap, and powered by a single 12V battery (Figure 3b). The traps were positioned on 50 cm high tables, so that all light arrays were located 1 m above ground level and not obscured by ground/field layer vegetation. Traps were operated from 2 hours before sunset to 2 hours after sunrise, and never later than 08:00 BST. All electrical components were fitted with waterproof connectors to ensure continued operation during unexpected precipitation events and through condensation. Nights with heavy rain and strong wind were avoided to minimise potential biases in catching rates due to habitat differences (i.e. forest locations sheltered but open locations exposed) between the catching locations.

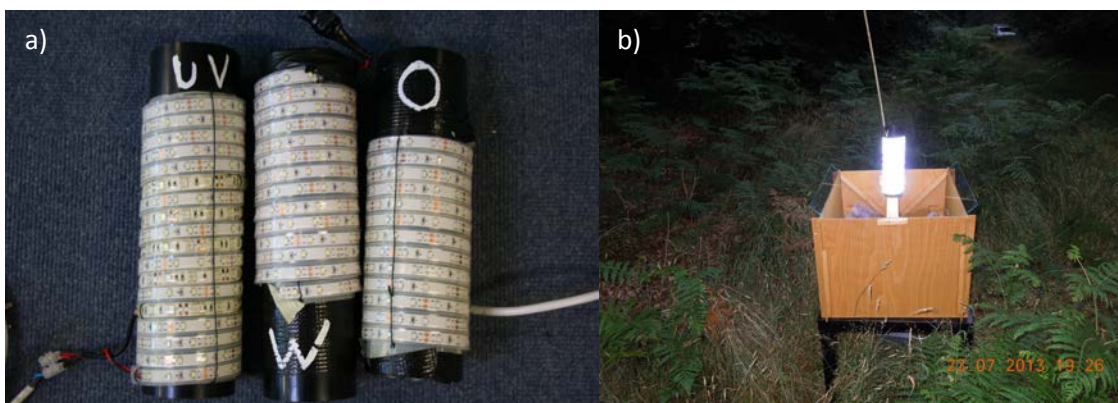


Figure 3. LED light arrays. a) UV, W and O and b) Skinner moth trap fitted with UV light array () during field deployment.

Moth-trapping took place on 36 nights across an eight-week period between 22 July and 10 September 2013. The order of site visits was random (this resulted in some clumping, which was controlled for during modelling by including trapping date), as was the deployment of different bulb types among the different barrier types, which were rotated among the three barrier types over three consecutive nights. Three traps were in used simultaneously at a single site per night.

Trapping on consecutive nights at the same site enabled us to standardize ambient weather conditions and the moth fauna whose flight periods overlapped the sampling period as much as possible. Over the course of the survey, all light-barrier combinations were replicated four times at each site. Temporal variation in the local moth fauna potentially available for trapping was minimized by conducting all of trapping within a single, 45-day period.

A maximum-minimum thermometer was attached to each trap to record external ambient temperature ranges during trap operation periods, typically recording high temperatures in the evening and low ones in the morning (note that temperature was also mediated by the habitat context). Note that the LED lights generated less heat than standard moth trap bulbs and that all bulb type treatments generated similar heat outputs. Trap locations were recorded using a personal GPS device and were marked in the field by upright canes with coloured tape attached to ensure that locations were consistent during repeat trapping sessions.

A complete count of all individuals was made, following a systematic search of the entire inside and outside surfaces of the traps, as well as the outside surfaces of the supporting table. If the initial visit to disconnect lights revealed moths resting on the outside of the trap, or a large visible catch within, then the trap was covered with a large black plastic sheet, to prevent loss of moths, until formal processing of the catch began. All macro- and micro-moths were identified to species level, in the field where possible, using standard guides (Waring & Townsend 2011, Sterling & Parsons 2012); others not identifiable in the field were individually placed in Perspex tubes, removed and identified in the laboratory using the UKMoths (www.ukmoths.org.uk) and NorfolkMoths (www.norfolkmoths.co.uk) on-line resources. All moths taken away for identification were stored in a refrigerator during the day, then released back at the capture site the following evening. Confirmation of identity was provided by local moth experts familiar with species encountered in the study area. Where identification without dissection was not possible, records were attributed to appropriate species pairs or groups (e.g. the 'grey' group of Pyralids). All count and environmental data per trap deployment were recorded on a standard proforma.

2.4 Statistical analysis

To evaluate the effect of the barriers and bulb types, only species that have both larval and adult dependencies upon open habitats or associated vegetation were considered in these analyses. These open habitat species should not occur in the conifer forest habitats, where their food plants were absent, unless attracted by light. The moth species were assigned habitat preferences by reference to Waring & Townsend (2011), Sterling & Parsons (2012) and the UKMoths (www.ukmoths.org.uk) website.

Of the four environmental variables recorded (maximum and minimum temperature (degrees Celsius), and cloud cover (percentage) at the start and end of the night), only maximum temperature was selected as a control in all models, along with site and date (expressed as integer values: 1= 22nd July and included as a quadratic term to allow for curvilinear variation in moth abundance or diversity during the study period). Biologically, temperature has a strong influence upon moth activity and abundance (e.g. McGeachie 1989) and given that there was some variation in this

variable among trapping locations, inclusion was necessary. Cloud cover is also likely to have been important, but varied nightly and its influence will have been balanced across the treatments.

To analyse the variation in moth abundance and species richness (associated with flight-to-light responses) among the different bulb types and barrier scenarios, repeated measures models were fitted, accounting for autocorrelation among repeat samples in sites and locations using Generalized Estimating Equations, within the GENMOD procedure in SAS 9.2. All models used a log link function and negative binomial error distribution, as appropriate for over-dispersed count data, together with an appropriate cluster structure to account for the autocorrelation anticipated for the variable set being tested (i.e. allowing for inter-correlation among all samples within each category being compared in each analysis). The sampling unit was moths per trap (n=108), summarized as both total abundance and species richness. Initial models tested the effect of location and bulb type, separately. Barrier-crossing was then investigated using the interaction term 'location x bulb type', whilst controlling for maximum temperature, site and date. Models including single locations were used to identify the combination of bulb type and location involved where a significant effect was found for the interaction term. Models were conducted for both total abundance and species richness. Further tests were conducted for the four commonest moth families to investigate which drive the patterns of variation observed. The significance of main effect and interaction terms was assessed using score tests.

3 Results

A total of 1,294 moths of 50 open-habitat-occurring species, comprising nine families, were trapped (Figure 4, Table 3,). Open trapping locations attracted the greatest number of moths and richness of species overall, while in forest trapping locations attracted the lowest abundance and species richness (Table 3, Table 4). The highest numbers of moths and greatest species richness were attracted by the UV bulb, with fewest attracted to the O bulb type (Table 4).

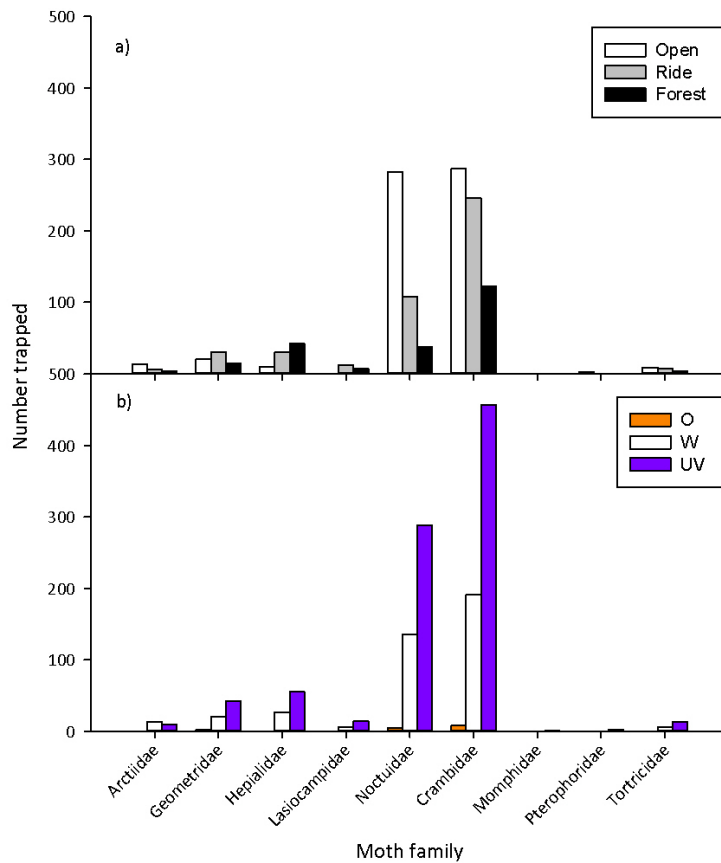


Figure 4. Summary of number of moths trapped, grouped by family, in relation to (a) location (barrier treatment) and (b) bulb type.

Table 3. Summary of families and species and (open-habitat-occurring only) trapped per location.

Family	Species	Location			Total
		Forest	Ride	Open	
Arctiidae	Ruby Tiger	3	6	13	22
	Total	3	6	13	22
Crambidae	Barred Grass-veneer	73	141	182	396
	Beautiful China-mark	0	0	1	1
	Brown China-mark	0	1	0	1
	Chequered Grass-veneer	0	1	0	1
	Common Grass-veneer	7	1	40	48
	Elbow-stripe Grass-veneer	1	7	1	9
	Garden Grass-veneer	0	12	4	16
	Garden Pebble	0	1	0	1
	Golden Pearl	1	0	0	1
	Grass-veneer	0	0	1	1
	Pearl Grass-veneer	1	0	1	2
	Pearl Veneer	8	56	11	75
	Ringed China-mark	1	0	2	3
	Water Veneer	31	24	36	91
	Yellow Satin Veneer	0	2	8	10
Total	123	246	287	656	
Geometridae	Lesser Cream Wave	1	4	2	7
	Oblique Striped	3	1	9	13
	Shaded Broad-bar	9	17	4	30
	Tawny Wave	0	0	3	3
	Toadflax Pug	1	8	2	11
	Total	14	30	20	64
Hepialidae	Orange Swift	42	30	10	82
	Total	42	30	10	82
Lasiocampidae	The Drinker	7	12	1	20
	Total	7	12	1	20
Momphidae	Buff Cosmet	0	1	0	1
	Total	0	1	0	1
Noctuidae	Antler Moth	4	13	73	90
	Archer's Dart	0	7	33	40
	Burnished Brass	0	1	0	1
	Cloaked Minor	0	1	8	9
	Dark Arches	4	2	5	11
	Dusky Sallow	1	0	6	7
	Ear Moth agg.	0	0	5	5
	Feathered Gothic	0	8	10	18
	Flounced Rustic	17	26	100	143
	Hedge Rustic	1	1	9	11
	Least Yellow Underwing	0	1	0	1
	Mere Wainscot	2	7	17	26
	Nutmeg	0	1	0	1
	Rosy Minor	0	0	1	1
	Silver Y	5	27	2	34
	Small Wainscot	1	0	3	4
	Smoky Wainscot	0	4	1	5
	Straw Underwing	0	0	5	5
	True Lover's Knot	0	5	1	6
	White-line Dart	3	4	3	10
Total	38	108	282	428	
Pterophoridae	Triangle Plume	0	0	1	1
	White Plume	0	0	1	1
	Total	0	0	2	2
Tortricidae	Black-headed Conch	0	0	1	1
	Burdock Conch	0	2	0	2
	Hook-marked Straw Moth	1	3	1	5
	Little Conch	2	2	7	11
	Total	3	7	9	19
Grand Total	230	440	624	1294	

Table 4. Number of moths (open-habitat-occurring only) and species trapped per site at each location and bulb type.

Site	Location	Bulb type						Total	
		O		W		UV		Number	Species
		Number	Species	Number	Species	Number	Species		
1	Open	3	3	37	15	78	18	118	18
	Ride	1	1	56	16	115	23	172	24
	Forest	0	0	6	4	26	12	32	10
2	Open	2	2	32	13	47	13	81	17
	Ride	1	1	2	2	70	23	73	24
	Forest	0	0	5	4	11	6	16	7
3	Open	6	6	197	39	222	49	425	35
	Ride	1	1	32	19	162	37	195	20
	Forest	1	1	31	16	150	37	182	19
Totals		15	8	398	33	881	48	1294	50

GLMs examining the individual effects of barrier treatments and bulb type, in separate models, upon moth abundance showed narrowly non-significant relationships with location: X^2 5.371, 2df $P=0.058$ and bulb type: X^2 5.795, 2df $P=0.055$). For species richness, narrowly non-significant relationships with location (X^2 5.84, 2df $P=0.04$) and bulb type (X^2 5.15, 2df $P=0.076$) were also found.

Separate GLMs examining the respective relationships of bulb type and location, within the same model (so controlling for one another), to abundance showed a highly significant differences for bulb type (X^2 13.67, 2df, $P=0.001$) with UV and W bulb types attracting the greatest numbers compared to the O bulb type (Figure 5a). Significant differences were found for location (X^2 12.22, 2df, $P=0.002$), with the greatest numbers of moths attracted in the open and ride locations (Figure 5b).

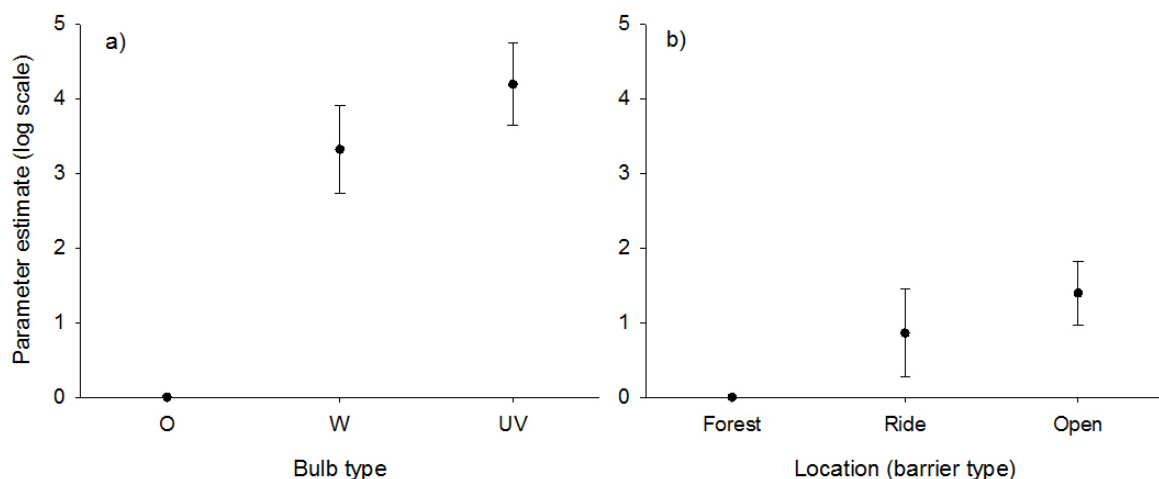


Figure 5. Parameter estimates (log scale), with upper and lower 95% confidence limits, for separate models (GEE model with repeated measures (repeated subject=site×location×bulb type)), examining relative abundance of moths caught per night in relation to a) bulb type and b) location. The O bulb

type and forest location were set to zero and used as the reference category for each bulb type and location, respectively: parameter estimates for the other bulb types and locations, respectively, are relative to these.

For species richness, there were significant differences among bulb types (χ^2 13.85, 2df, $P=0.001$, with UW and W bulb types attracting the greatest numbers compared to the O bulb type (Figure 6a). There were also significant differences among location (χ^2 11.77, 2df, $P=0.003$), where the greatest species richness occurred in the open and ride locations (Figure 6b).

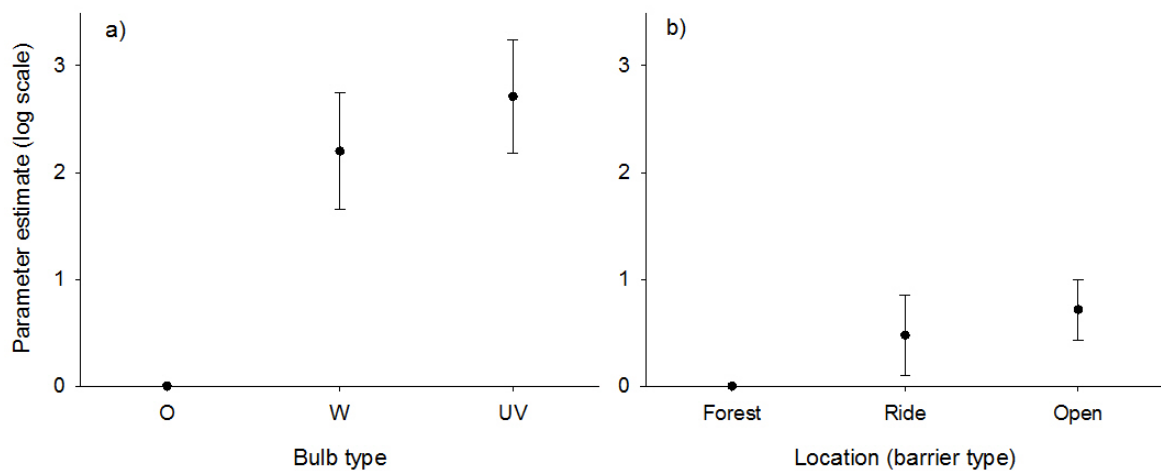


Figure 6. Parameter estimates (log scale), with upper and lower 95% confidence limits, for separate models (GEE model with repeated measures (repeated subject=site×location×bulb type)), examining species richness of moths caught per night in relation to a) bulb type and b) location. The O bulb type and forest location were set to zero and used as the reference category for each bulb type and location, respectively: parameter estimates for the other bulb types and locations, respectively, are relative to these.

To test for differential effects of bulb type and location upon moth abundance and species richness, i.e. whether different bulb types had different effects on barrier crossing, an interaction term between location and bulb type was added to the previous models. This location x bulb type interaction term was marginally significant for abundance (χ^2 9.42, 4df, $P=0.051$) and species richness (χ^2 10.73, 4df, $P=0.030$). The parameter estimates from models examining locations separately (Figure 7) show that the significance derives from additional positive attraction of moths to the UV and W bulb types in the ride location and less attraction of moths to the O bulb type in the open location. The pattern for species richness was similar (Figure 8).

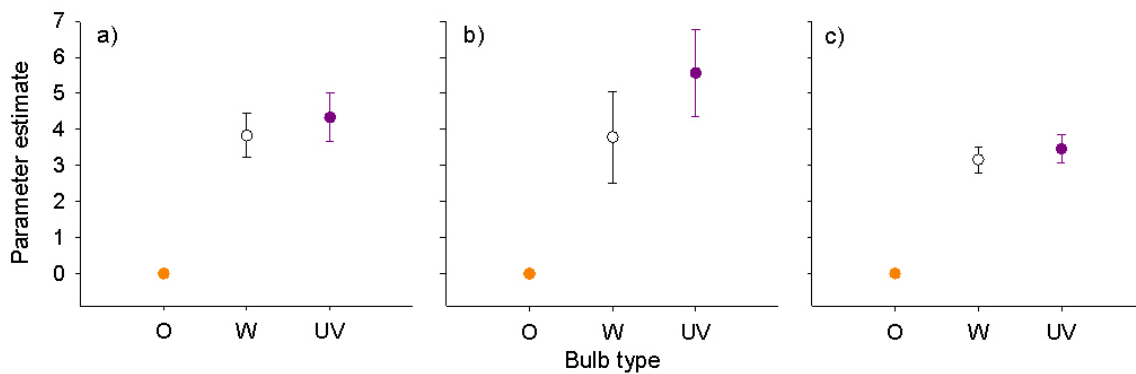


Figure 7. Parameter estimates (log scale), with upper and lower 95% confidence limits, for the effect of location, modelled separately for: a) forest, b) ride and c) open, on abundance of moths caught per night estimated from a GEE model with repeated measures (repeated subject=site×location×bulb type). The O bulb type estimates are set to zero and used as the reference category for each location: parameter estimates for the other bulb types are relative to this for each location shown and values are not comparable between locations.

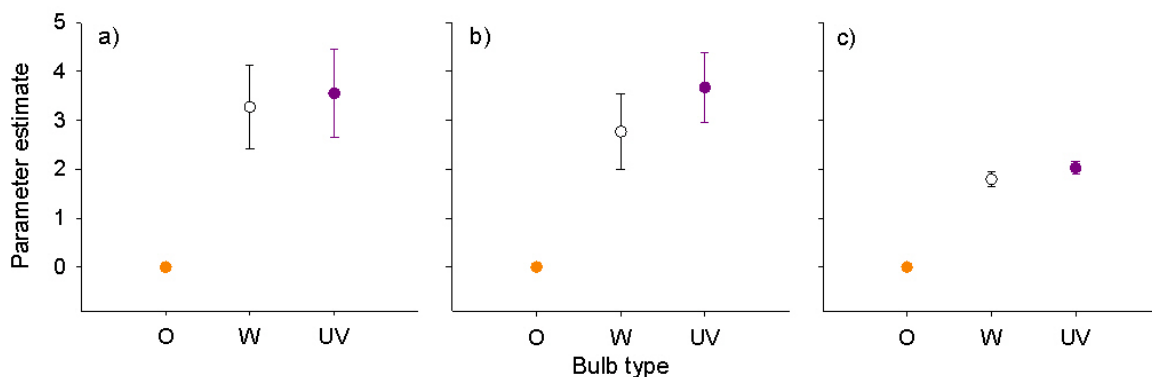


Figure 8. Parameter estimates (log scale), with upper and lower 95% confidence limits, for the effect of location, modelled separately for: a) forest, b) ride and c) open, on species richness of moths caught per night estimated from a GEE model with repeated measures (repeated subject=site×location×bulb type). The O bulb type estimates are set to zero and used as the reference category for each location: parameter estimates for the other bulb types are relative to this for each location shown and values are not comparable between locations.

Moth abundance by family was dominated by Noctuidae for macro moths and Crambidae for micro moths, both of which were least common in the forest location and attracted in greatest numbers to the UV bulb type (Figure 4). GLMs, based on the model from which Figure 5 was derived, examined whether there was a differential relationship for abundance between location and bulb type for the four most numerous families (Geometridae, Hepialidae, Noctuidae and Crambidae; Figure 4). However, only the UV and W bulb types were examined (n=72) as insufficient moths (range: 0 to 8) were trapped by the O bulb type among the four families considered. A significant differential relationship for moth abundance between location and bulb type was found for Noctuidae (X^2 10.18,

2df, P=0.006) and a marginally significant relationship for Geometridae (X^2 5.80, 2df, P=0.055), which shows that moth abundance, compared to the W bulb type, was significantly greater for the UV bulb type in the ride (Table 5). This illustrates that much of the differential effect of the ride location on total moth abundance (Figure 7) was caused by the patterns of attraction of Noctuidae.

Table 5. Test of the interaction term 'location x bulb type' on abundance of open-habitat-occurring moths by family from a GEE model with repeated measures (repeated subject=sitexlocationxbulb type). The W bulb type estimates are set to zero and used as the reference category. Note that the O bulb type was omitted in order for model convergence to be achieved.

Family	Location x bulb type interaction	Description of effects
Crambidae	ns	
Geometridae	P = 0.055	UV > W in open
Hepiladae	ns	
Noctuidae	P = 0.006	UV > W in ride

4 Discussion

The UV component of the emission spectra was demonstrated to exert a far greater attraction response than broad spectrum alone, and affects virtually the entire local open habitat moth community. This demonstrates that the UV component of street lights may act to attract large numbers of moths, in agreement with Eisenbeis (2006) and Somers-Yeates (2013). However, the W bulb type (without UV), as used in this study, also attracted substantial numbers of moths, indicating that this lighting technology may not be as 'insect friendly' as currently perceived (Eisenbeis 2011).

Among the nine families examined, combining data across barrier locations, the pattern of greatest numbers attracted to the UV bulb, compared to the two non-UV bulbs, and was evident in all but one family (Arctiidae) encountered (Figure 4). This demonstrates that the effect is widespread among many families, rather than just Noctuidae, as found by Somers-Yeates (2013). However, Noctuidae, the most numerically abundant family, showed differential responses to bulb type and barrier type, indicating that members of this family are most susceptible to attraction through partially-closed habitat barriers. In turn, this suggests that there could be disproportionate subsequent negative population effects of lighting changes on this family and, therefore, potentially important effects upon other species that preferentially prey on Noctuidae, such as bats (e.g. Rydell 1992, Rydell & Racey 1995) and to a limited extent European Nightjar *Caprimulgus europaeus* (Sharps 2013).

The UV and W bulb types used in this study have been demonstrated to exert a very strong attractive response to moths (more so the former) in previous studies (e.g. Eisenbeis 2006, Eisenbeis 2011 and van Langvelde *et al.* 2011). However, the results of this study area also consistent with disproportionately greater attraction across partially closed habitat barriers. Attraction across completely-closed barriers did not show any significant difference among the O, W or UV bulb types and, although the open location showed disproportionately more moths and higher species richness to be attracted by the O bulb type, this was probably an artefact of the small sample size involved. Therefore, in addition to the previously recognized increased simple attraction of moths to light from the conversion of lighting stocks to new, UV-rich and bright white bulb types, the new bulb types will exert an influence on animals in habitats previously thought to be shielded from their effects by partial barriers, such as vegetation. This raises immediate concern in implying that the impacts of lighting change may include disproportionate effects on moths, and the species that feed on them, in configurations of habitats that are within a direct line-of-sight from street lighting. In an urban context, this could mean, for example, increased attraction of moths from garden habitats that might have been considered to be isolated from lighting impacts by lines of buildings. Further, the scale of the potential impacts could be considerably greater than our experiment indicates, given that the light intensity emitted from our light arrays is likely to be lower than that of actual street lights. Consistent patterns among urban moth communities in neighbourhoods undergoing changes in lighting regimes have recently been found (Plummer *et al. in prep.*).

Once attracted to light, impacts on moths could arise from habitat unsuitability, due to exposure to greater mortality risk through lack of food resources, in addition to consequent mortality from attraction due to the "near effect" described by Eisenbeis (2006). Moths attracted to streetlights may also experience additional mortality as a consequence of bat predation, because bats have been demonstrated to target such aggregations (Rydell 1992, Rydell & Racey 1995).

In all artificially lit environments, but especially in urban situations where housing is dense and green space is minimal, use of broad spectrum streetlights with UV component, and to a slightly lesser but still potentially significant extent, broad spectrum without UV, may have a considerable detrimental effect upon the local moth community. As well as moths found immediately adjacent to the lights, individuals are likely to be attracted from behind partial barriers and potentially over considerable distances. In such circumstances, or in locations where housing is located close to natural or semi-natural habitat where moths of high conservation status may be impacted, narrow spectrum lighting such as low pressure sodium, which exerts a minimal attraction response, ought to be retained rather than replaced with new UV emitting lighting. Alternatively, in sensitive areas, as recommended by Frank (2006) it may be possible to instigate more dark periods where lights are switched off during the night, also coinciding with the period of greatest moth activity. Such sensitive areas would usefully be defined on the basis of moth diversity and abundance, i.e. considering moth conservation *per se* and the value of moth biomass as food for other taxa. In urban areas, the latter could be particularly important because high local species richness, reflecting the presence of rarer species in the community, is more likely to occur in other habitats.

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