The biodiversity impacts of street lighting

Final Report

This work was conducted by Fiona Mathews, Kevin Gaston, John Bennie and Julie Day of The University of Exeter in collaboration with subcontractors Henry Schofield and James Baker of The Vincent Wildlife Trust.

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The impacts of street lighting on biodiversity (WC1011)

EXECUTIVE SUMMARY

Aims and objectives

_Aims_

Defra has committed both nationally and internationally, to halting the overall loss of biodiversity by 2020. In 2009 the Royal Commission on Environmental Pollution (RCEP) published a review of the environmental impacts of artificial light (Royal Commission 2009), which concluded that there was a paucity of information on the ecological impact of artificial lighting and that further studies were needed on the likely impacts of broader wavelength technologies that are being more widely introduced. Defra’s commitment to carry out research in this area was stated in the government response to the RCEP review.

The aim of this project was to assess, through landscape-scale approaches, the impact of alternative road lighting schemes on biodiversity, and to provide evidence to inform policy making.

_Objectives_

(1) Define the linkages between biodiversity and component parts of lighting strategies
(2) Assess the relationships between bat colony viability and lighting strategies
(3) Define accurately the exposure of bats to light, and investigate effectiveness of mitigation strategies for light-sensitive species
(4) Assess experimentally the effects of illuminating water bodies by carriageway lighting
(5) Produce an evidence-base for practitioners and policy makers
Rationale

The amount and intensity of light in the environment is increasing rapidly. A substantial proportion is derived from street lighting (Longcore and Rich 2004, Royal Commission 2009, Gaston et al. 2013). Artificial lighting at night is well known to affect the behaviour of some species, particularly moths (Eisenbeis 2006, van Langevelde et al. 2011), but the wider implications for biodiversity are poorly understood. The spectral composition of street lighting is changing as older energy-inefficient luminaires are replaced with new lighting technologies. Given the variation between species in the perception of different wavelengths, it is likely that there will also be variations in the responsiveness to different types of lighting. It is therefore unclear whether older research based on mercury vapour and low-pressure sodium lamps, both of which are being phased out, is relevant to modern lighting regimes. In addition, little is known about the implications for biodiversity of the partial switch-off of street lighting being implemented by many local authorities in an effort to reduce carbon emissions and costs.

The main taxa studied in this project are bats, amphibians and aquatic invertebrates, following previous research suggesting impacts from artificial lighting. Much of the research focused on bats, which are not only potentially important receptor species, but which also have high legal protection. In the case of greater and lesser horseshoe bats, *Rhinolophus ferrumequinum* and *R. hipposideros*, their listing on Annexe II of the Habitats Directive means that disruption of flightpaths and foraging areas by lighting is a material concern for planning applications. Although it was known at the outset of this study that commuting behaviour close to roosts could be perturbed by artificial lighting (Stone et al. 2009), such locations are rare in the environment. This project therefore focused on evaluating the impacts of lighting on the activity of bats across the wider landscape.

Much of the research used observational techniques, providing field-realistic assessments of the effects of lighting. This approach has the advantage of studying animals habituated to their environment. However, it was also complemented by experimental approaches, which are particularly appropriate where there is little *a priori* evidence about the impact of a stressor.
Methods
The project was conducted as a series of separate studies designed to address different aspects of the potential impacts of lighting on biodiversity. The research focused on bats as bioindicators, but consideration was also given to invertebrates with aquatic life stages and to common frogs. Investigations of bat activity used broad-spectrum real-time detectors automatically triggered to record over a protracted period. In addition, we drew on transect data collected using time-expansion detectors in the National Irish Bat Car Transect survey to complement the data collected during this project. Field experiments of the impacts of lighting used portable Light Emitting Diode (LED) rigs run off 44Ah (Ampere-hour) lead-acid batteries. This approach was selected because LEDs emit only minimal amounts of heat, and could be run at intensities generated by streetlights without the need for a generator. The experiments therefore avoided the potentially confounding effects of noise and heat. LEDs were also used in the randomised laboratory investigations of the effects of lighting on amphibian development and aquatic invertebrate communities, with each experimental tank being individually illuminated. Finally, the project has used recently-developed techniques to model light in the environment, and made use of satellite data as an alternative means of assessing light exposure.

Table Summarising Approaches in relation to Objectives

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**Key Results**

- The project has examined the impacts of lighting on pipistrelle bats using several different approaches and found little evidence of light attraction. The collective conclusion is that under most circumstances they appear to be light averse, or light tolerant, rather than light attracted. Exceptions may occur where there is high tree cover (common pipistrelle only), and feeding activity of this species also appeared higher in areas with livestock present when they were lit. Nevertheless, overall common pipistrelle activity was lower in lit than dark enclosed grassland. This may suggest that pipistrelles respond positively to lighting only when primary productivity of invertebrate prey is high.

- Greater horseshoe bats and lesser horseshoe bats were shown to be light averse throughout their roost sustenance zone.

- There was no evidence across the project of alterations in bat community structure resulting from street lighting.

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1 Improved, semi-improved or unimproved grassland used for grazing or cut for hay or silage
• The lighting of waterways was strongly linked with reduced activity by Daubenton’s bats. In addition, the lighting of water appeared to make the habitat feature repellent to greater horseshoe bats whereas it is attractive in the absence of light.

• Bat activity, and horseshoe bat activity in particular, was low on major roads, regardless of whether or not they were lit, whereas minor roads appeared attractive. Lighting of minor roads was associated with a sharp reduction in bat activity, such that they became comparable with major trunk roads.

• The effect of lighting spectrum on bats remains uncertain. There was some evidence from the transect studies in the UK that high pressure sodium had a greater negative impact on pipistrelle bats (total pipistrelles and common pipistrelle) than low pressure sodium lighting, but no differences according to lighting colour (yellow, orange and white) were found in the Irish transect survey. Experimental reduction of the UV component of lights designed to simulate metal halide street lighting had no influence on common pipistrelle bat activity, though there was some indication that it increased the activity of soprano pipistrelles.

• Part night-lighting strategies are likely to capture only a small percentage of total bat activity, and can therefore be expected to deliver only limited conservation benefits.

• Dark patch connectivity was very high in the landscapes of the South West of Britain used in most of our research. Given that most bat species other than pipistrelles predominantly live in rural or semi-rural landscapes, care should therefore be taken in extrapolating from experiences derived in urban environments. Despite this overall lack of fragmentation, attention needs to focus on the disruption of flight lines close to roosts, and on the potential impacts of joining up existing light patches in the landscape through urbanisation and/or infrastructure development as these could significantly increase the flight distances required of light-sensitive species.

• Satellite data were shown to provide useful information on terrestrial light pollution. At a course spatial scale, roosts of Natterer’s bats (which belong to the generally light-shy genus *Myotis*) were darker than those of pipistrelle bats. However, satellite data are best suited to analyses at broad spatial scale. Light maps based on LiDAR data and streetlight information are more useful at the local spatial scale relevant to local Development Control decisions.
• The growth of common frog tadpoles was reduced by experimental illumination with LED lights at night, and the size differential increased over time. At the end of the experiment (after 83 days) the mean difference in length between tadpoles given light compared with dark nights was more than 10% of body weight. Given that longer periods until metamorphosis and smaller size at metamorphosis are linked with increased predation risk, further work to investigate the conservation implications of night lighting on amphibians is urgently required.

• The impact of lighting on the emergence of flying invertebrates with aquatic life stages was investigated experimentally. The emergence of trichopterans but not chironomids was reduced by LED lighting.

Conclusions
The impacts of artificial night lighting on biodiversity are complex. This project has identified that lighting offers few – if any – benefits to common and widespread species, and is aversive to rare horseshoe bats. Minimisation of the amount and intensity of new carriageway lighting would therefore appear prudent. This may be particularly important on minor roads (‘B’ and ‘unclassified’ roads) as these environments are well-used by greater horseshoe bats when unlit, whereas lit minor roads have minimal activity that is comparable to that on major trunk roads. It is also notable that there is relatively little use of trunk roads, and therefore the ecological impact of additional lighting appears to be small. No evidence for the alteration of community composition by lighting was found in this work, in contrast to research involving plants and invertebrate food webs: although few horseshoe bat passes were recorded in lit areas, light was also generally associated with reduced activity of other bat species. The project has also demonstrated, for the first time in the UK, important impacts of lighting on species dependent on riparian habitats. Given that much lighting in these areas is decorative or the result of light-spill, measures to reduce lighting in these habitats could be considered, for example by the use of appropriate shielding. Where lighting is needed for reasons of public health and safety, care should be taken to ensure that the light is focused on those areas where it can deliver benefits.
SUMMARY AND KEY FINDINGS

To gain an overview of the impacts of lighting on biodiversity, this project used a wide range of approaches. The full reports of the individual studies are given in the appendices. The objectives of the project, the approaches used to address them, and the key findings are summarised below.

Objective 1: Define the linkages between biodiversity and component parts of lighting strategy

1.1 Assess whether artificial lighting alters biodiversity, and potentially ecosystem function, by shifting the ratio of bat species and night-flying insects in a region.

1.2 Identify which aspects of the lighting regime – amount, intensity, spectrum, temporal pattern, or spatial pattern of light and dark patches – are most important to key receptor species.

Approaches

Meeting this fundamental objective has been the primary focus of our research effort. The following studies have been undertaken:

a) A landscape-scale study of bat activity in the sustenance zone of known summer and winter roosts of greater and lesser horseshoe bats (32 roosts in total), including the analysis of activity of non-horseshoe species. Attention was paid to the close matching of ‘light’ and ‘dark’ locations on the basis of habitat to enable the effects of lighting to be separated from those of habitat (Appendices A-C).

b) Modelling the impact of part night-lighting strategies on bats, using data on greater horseshoe bat activity derived from the landscape-scale study of bat activity (Appendix D)

c) Analysis of existing transect survey data of bat activity in areas with varying lighting types (Appendix A).

d) Mapping of lightscapes around the roosts and investigation of thermal and spectral properties of lamps (see below).
e) Experimental study of the effects of lighting on invertebrates with aquatic life-stages (Appendix E. The key findings of this experiment are provided under Objective 2).

f) In addition, and outside the requirements and funding of this project, a transect survey has been conducted in 17 towns in Devon before and after transition to part-night lighting, together with 4 controls that maintained all-night lighting. The data from this project are currently being analysed and will be reported on separately by the University of Exeter.

g) An experimental test of the effect of UV filters in reducing the impacts of lighting on bats (Appendix G. The key findings of this experiment are provided under Objective 3).

Key findings
In analyses of more than 265,000 bat calls from 600 locations, the activity of common and widespread bat species, including soprano pipistrelle (*Pipistrellus pygmaeus*), common pipistrelle (*P. pipistrellus*) and noctule (*Nyctalus noctula*) was shown not to increase in the presence of prevalent street lighting types. We also found no evidence of community composition shifts. Consistent results were obtained from transect surveys (incorporating an analysis of data collected as part of the Irish National Bat Survey) and large-scale deployment of static acoustic detectors in south-west England. Such bats, which are important to ecosystem function, are generally considered ‘light-attracted’ and likely to benefit from the insect congregations that form at lights. The results of this project did not support this assumption, and bat activity was not generally found to increase with commonly-used lighting types. Leisler’s bat (*Nyctalus leisleri*), a species rare in Britain, may be an exception, being more frequent in lit than dark transects. For common pipistrelle bats, lighting is negatively associated with their distribution on a landscape scale, but there may be local increases in habitats with good tree cover. There was some evidence from the transect studies in the UK that high pressure sodium had a greater negative impact on pipistrelle bats (total pipistrelles and common pipistrelle) than low pressure sodium lighting, but no differences according to lighting colour (yellow, orange and white) were found in the Irish transect survey (For further details see Appendix A).
Data from the landscape-scale studies of bat activity around 8 lesser horseshoe (R. hipposideros) roosts showed that dark areas had the highest pass rates of not only lesser horseshoe bats, but also common and soprano pipistrelles. The presence of enclosed grasslands and increased building cover were positively linked with common pipistrelle activity, whilst the presence of and reduced distance to woodland were positively linked with the activity of horseshoe bats. Contrary to previous suggestions, there was no evidence of an inverse relationship between common pipistrelle and lesser horseshoe bat activity: rather there was evidence for a slight positive association between the two species (though habitat was a more important predictor of occurrence). The presence of enclosed grassland was positively associated with the presence of both pipistrelle and horseshoe bats, though these relationships were reversed in the presence of lighting. Feeding activity could be assessed for pipistrelle but not horseshoe bats. Complex relationships appeared to be present, with habitat features that were associated positively with feeding (proximity to woodland, enclosed grassland and presence of grazing animals) becoming even more beneficial in the presence of light (for further details see Appendix B).

Analysis of data collected from the sustenance zones of 8 greater horseshoe roosts showed conclusively for the first time that the species is light averse, and that this aversion exists throughout the landscape, not just at commuting routes close to the roost. Across the sustenance zone, activity was significantly lower at light compared with dark sites. At dark sites, freshwater bodies and minor roads were attractive habitat patches whereas lit major roads were rarely used. However, when lit, these relationships reversed, with the features apparently becoming repellent. These findings have important practical implications. Much attention is currently paid to the impacts of lighting on major infrastructure projects. However, it is probable that these features are rarely used by bats (note the important exception of where bats must cross roads in order to reach roosts or key foraging areas). In contrast, more use is made of minor roads. Although all our samples were drawn from roadside environments, and so we cannot draw comparisons with other habitats away from roads, anecdotal evidence shows that in the south-west of England, small roads with tall hedgerows are frequently used by horseshoe bats (F. Mathews, H Schofield, pers. obs). When lit, activity on these small roads becomes comparable with that on major highways. This suggests that careful attention must be paid by local authorities to schemes that
introduce lighting onto minor roads used by horseshoe bats. Similarly, waterways, particularly those with substantial treelines are frequently used by horseshoe bats for foraging and commuting. Lighting in close proximity to these features has a major impact on their use by horseshoe bats, and should be avoided in important areas for bat conservation (for further details see Appendix C).

Using data collected from the large scale acoustic survey around horseshoe roosts, the potential effects of minimising lighting at certain times were explored. There was a large primary peak in activity 1 hour after sunset, followed by a smaller secondary peak before sunrise. Simulated part-night lighting scenarios reveal that to capture a large proportion of bat activity, streetlights would need to be switched off during the peak of bat activity after sunset. This appears to be incompatible with the aims of part-night lighting strategies, where lighting is maintained during the hours of peak human activity (for further details see Appendix D).

The thermal properties of lamps of different types were measured using an FLIR thermal imaging camera, because of the possibility that temperature variations may explain some of the differences in attractiveness of street lights to invertebrates. Two measurements were made: a spot in the centre of the lamp and also a mean of the temperature within a circle centred on the lamp (see Fig. 1). The data are summarised below.

Fig 1. Measurement of temperature at centre of lamp and within circle.
On the basis of advice from the project steering committee, this aspect of the project was not pursued further as it was considered that the total heat generated by alternative lighting units (as opposed to simply the bulb temperature) were similar across lighting types.

Information on the spectral composition and intensity of lights has been collected from all roads within each of the 24 roost sustenance zones included in our landscape-scale study of horseshoe bats. Unfortunately data extrapolation to other areas and roosts has been hampered by difficulties in obtaining information on the position and type of streetlights. These data are largely held by local authorities. Some have supplied complete or near-complete datasets (Wiltshire, Somerset and Devon) that have been converted into lightscape maps. However, we have had limited success with retrieving the relevant information from many local authorities (not all of which have centralised control of lighting). In the case of many of the sites included in the Welsh Lesser Horseshoe

<table>
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<th>Watts</th>
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<th>Mean temperature across light (circle) (°C)</th>
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<td>5</td>
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Monitoring project the task is particularly complicated because of the large number of small local authorities. We have therefore also pursued alternative approaches, including the use of satellite data (see Objective 2).

Using the data that are available from Devon, it is clear that the majority of lighting is currently low pressure sodium. In addition, we have found that horseshoe roosts are generally located within dark landscapes. Indeed, when identifying sites to include in our landscape-scale project, it proved difficult to identify large lesser horseshoe colonies with sufficient street lighting within the roost sustenance zone to permit the deployment of 25 static detectors separated by at least 100m. In addition, detailed analysis of the structural connectivity of dark patches has shown that even in regions considered at high threat from urbanisation, there is very high connectivity. For example, there is particular concern about the impacts of housing and infrastructure developments on the integrity of flyways used by the greater horseshoe bat colony at Chudleigh Rocks (part of the South Hams Greater Horseshoe Bat SAC). Using ArcGIS, the locations of each streetlight were buffered with a 30m radius (the approximate spread of the light), and were joined to make multipart polygons (Fig.2). Additional fine-scale lighting maps have also been produced which model light more accurately by taking account of light type, intensity, pole height, and the screening potentially provided by surrounding vegetation and buildings (information derived from LiDAR data) (Bennie et al. 2014) (Fig 3). It can be seen that dark patch connectivity is extremely high across the landscape: indeed, at the coarse spatial scale, all of the bat detectors placed in dark locations were within the same dark patch as all of the other detectors. At the finer spatial scale close to the roost, most of the area is again dark, and the precise location of light areas and dark gaps, some of which may be bat-accessible, can be seen. We therefore conclude that although many bats prefer dark environments (see above), most of the landscape around the 24 roosts we studied currently offer suitably dark flightpaths. Care should therefore be taken in extrapolating the results from predominantly urban landscapes e.g. (Hale et al. 2015) to more rural landscapes.

However, there are two circumstances where particular care must be taken: a) close to roosts because the number of possible alternative flightpaths is constrained by physical space; and b) where alternative routes involve considerable deviations or exposure to
additional hazards (such as vehicle collisions). Examples might include coastal towns where the joining of conurbations stretching inwards from the sea would necessitate a long detour, or where lighting channels bats towards trunk roads. In the case of Chudleigh, as illustrated in Fig. 3, there is very little lit environment within 500m of the roost, but expansion of lighting to infill the area outlined in orange on Fig. 2 (a distance of 1.5km, and which already includes a major trunk road and development proposals) would add a minimum of 4km to the journey of any bat needing to travel northwards from the roost (shown by the triangle symbol). Formal analysis of least-cost pathways, accounting for the configuration of habitat within the landscape should now be undertaken. Such landscape lighting maps would provide a valuable resource to competent authorities in identifying ‘pinch-points’ where lighting could materially impact on the integrity of a SAC site.
Fig. 2. A) Example of dark patch connectivity in the 4km radius sustenance zone around the roost (indicated by black triangle) at Chudleigh, Devon. Illuminated areas are shown in white, and dark areas in grey. The locations of bat detectors used in the study are shown as dots. The orange ellipse indicates dark patch where proposed development would interrupt connectivity of dark areas. B) Google Earth satellite image of same area showing urbanised areas, the roost and area proposed for development.
Fig 3. A) Map showing height of vegetation and buildings in a 500m radius around Chudleigh Rocks greater horseshoe bat roost. These data, together with information on the location and type of street lights are used to generate the high resolution map of lighting (B). Colour indicates relative lighting intensity ranging from zero (black) to high (red) (arbitrary units).
Objective 2: Assess the relationships between bat colony viability and lighting strategy

2.0 Assess whether the light profiles in the landscape around maternity roosts of ‘light shy’ and ‘light attracted’ bat species are related to colony size using established datasets.

2.1 Evaluate the impact of lighting profiles in the landscape around maternity roosts on parameters important to the population dynamics of the species.

Approaches

Analyse existing colony count data for lesser horseshoe bats in relation to lighting profiles determined from satellite imagery and, where possible, streetlights.

Key findings

Data on light pollution around roosts of different species were extracted using recently developed techniques (Bennie et al. 2014) to calibrate data from satellite images. These were combined with long term datasets on bat roost locations and population sizes from the Bat Conservation Trust’s National Bat Monitoring Programme. Data were extracted for seven species monitored from 1997-2012; lesser horseshoe bat (*Rhinolophus hipposideros*), greater horseshoe bat (*R. ferrumequinum*), Natterer’s bat (*Myotis nattereri*), brown long-eared bat (*Plecotus auritus*), common pipistrelle (*Pipistrellus pipistrellus*), soprano pipistrelle (*P. pygmaeus*) and serotine bat (*Eptesicus serotinus*). Colony distribution was compared with lighting data collected from two different satellite resources (DMSP-OLS and Suomi-NPP data) and also compared with street lighting data (for counties Wiltshire, Somerset and Devon, where data were made available to us). A total of 1,690 unique roosts were included in the analysis with DMSP-OLS satellite data and 719 with Suomi-NPP satellite data. Comparison with streetlight data showed that satellite data, which measures upward light spill, could provide a useful index of light pollution at a broad spatial scale. Natterer’s bats had consistently lower levels of light pollution within the roost sustenance zone than did soprano pipistrelles, and similar patterns were also seen for the comparison with common pipistrelles. The significance of other between-species comparisons varied according to which lighting dataset was used: lesser horseshoe roost sustenance zones were darker than
those of common pipistrelles using the DMSP-OLS dataset, but not the SUOMI-NPP dataset. However, the marginal $R^2$ values from all the models were very low, suggesting that other features (possibly including characteristics associated with lighting such as habitat quality) are more important in determining roost location. In addition, the southern distribution of horseshoe and serotine bats means that to some extent, light intensity as measured by satellites is confounded by species range (see Appendix F for further information). Work is ongoing, outside the scope of this project, to assess the links between remotely-sensed indices of light pollution and colony size and change over time.

**Objective 3: Define accurately the exposure of bats to light, and investigate effectiveness of mitigation strategies for light-sensitive species**

3.1 Produce accurate quantification of the exposure of ‘light-shy’ and ‘light-attracted’ bats to artificial night lighting.

3.2 Assess the effectiveness of mitigation strategies to protect light-sensitive bats from lighting and to evaluate the potential usefulness of lighting as a means of diverting conservation-priority species away from hazards such as roads.

3.3 Review, using existing data sources, the relationships between bat movements in the landscape and the spatial configuration and type of roadside lighting.

**Approaches**

The use of geolocators (designed to record light in order to determine the locations of migratory birds) to assess directly the exposure of bats to light was trialled using bats using the Vincent Wildlife Trust reserve at Bryanston (Obj. 3.1). The manufacturer (Biotrack/Lotek) worked with us to reduce the size of the battery used in the device to bring it within acceptable limits for use with bats. However, technical issues with power-draw meant that the loggers were unable to record data successfully for more than a few seconds. An alternative model was also tested, but whilst this did not suffer the same technical problems, it only recorded the peak light reading obtained within any 5 minute window. Given the speed of bat flight and our observations that the majority of the landscape is dark, this would give an unacceptably high risk of over-estimating light
exposure due to occasional passes by light sources. We suggest that a more promising approach would be to use GPS tags (the size of which is rapidly reducing) together with detailed modelling of light distribution using the methods outlined above.

In addition, existing radio-tracking reports were interrogated for information on animal movements (Obj 3.3). The approach was judged to be unsuitable for several reasons. First, none of the reports examined had provided information on the location of lighting. Second, obtaining historical data from local authorities proved to be extremely difficult (many did not store the information). Third, most reports were from landscapes that are currently dark (e.g. extensive woodlands, National Trust estates) and are likely to have been so at the time of the radiotracking study. Finally, the exact locations of animals at times when they could potentially have encountered light (for example at road crossings and edges of villages) were rarely available. It was therefore difficult to be confident about whether they were exposed to artificial night lighting or not.

Following discussion with stakeholders (Highways Agency and Ecological Consultants), it was decided that alteration of the ultraviolet light component of lighting was one of the most practicable mitigation options for night lighting since this can be achieved through the simple installation of filter screens on luminaires (Obj 3.2). Both metal halide and halogen lamps produce significant radiation in the ultraviolet range. Experimental lighting rigs were used, in which LED lamps were fitted with additional ultra-violet bulbs to produce emissions similar to metal-halide street lights. The effects of this lighting regime was compared to the use of the same system but with a UV filter (which removes 40% of the UV emission), and to darkness (control). Two additional control linear features without any lighting were also monitored throughout the survey period. The two light treatments were used in random order, and each treatment was conducted for at least 3 days at each site. LEDs were chosen as the optimum experimental lighting type since they can be run on 12v batteries, removing the potential confounding effect of generator noise, fumes and heat. Five locations in Devon with hedgerows known to have high levels of bat activity were chosen as experimental sites, and two lighting rigs were erected at each site. We here report the data collected from 30 minutes before sunset until 3 hours after sunset. For common pipistrelles, *P. pipistrellus*, there was no effect of treatment on bat activity. For soprano
pipistrelles, *P. pygmaeus*, activity throughout the site increased on nights with UV-filtered light treatment compared with either control conditions or darkness, rather than an increase occurring specifically at the lighting rigs. The mechanism for this observation is currently unclear. However, bats are known to perceive ultraviolet light, and it is therefore possible that the filter reduced the repellence of soprano pipistrelles, whilst also congregating a better food resource than would be available during dark conditions (for further information see Appendix G).

Some of the findings from other parts of this project may also help to inform mitigation strategies. For example, we have shown that lighting of minor roads substantially reduces their suitability for greater horseshoe bats, whereas the lighting of major carriageways (unless at a critical crossing point) is unlikely to have a substantial impact as relatively little use is made of this habitat (see Objective 1).

**Objective 4: Assess experimentally the effects of illuminating water bodies by carriageway lighting**

4.0 Determine whether the illumination of water bodies by carriageway lighting affects the use of these features by bats for commuting and foraging.

4.1 Determine whether the behaviour of aquatic invertebrates and amphibians is influenced by alternative types of lighting.

**Approaches**

We conducted experiments to test the effect of white Light Emitting Diode (LED) lamps in known Daubenton’s bat (*M. daubentonii*) foraging areas. Four treatments – bright light, moderate light, low light, or no light (control) – were applied at five sites in southwest England. All the lighting treatments used 18W Cree LED lights mounted on poles. Surveys were also conducted on each study night at control sites without any artificial lighting. Automated acoustic detectors were used to record bat activity, and the abundance of emergent insects was surveyed using floating traps.
A randomised controlled experiment was also conducted to assess the impacts of night lighting on amphibian growth. This work was conducted in the laboratory and exposed newly hatched tadpoles of common frog *Rana temporaria* to either daylight simulation conditions with no lighting at night, or to daylight simulation followed by LED lighting at night. The tadpoles were housed in groups of 5 in 20 experimental and 20 control tanks, and were measured on alternate days until day 83 of the experiment when full metamorphosis occurred in some individuals.

**Key findings**

LED lighting markedly reduced both the flight and foraging activity of Daubenton’s bats. Foraging efficiency was also reduced. In contrast, soprano pipistrelle (*Pipistrellus pygmaeus*) and common pipistrelle (*P. pipistrellus*), which also utilise riparian habitat, were unaffected. Lighting also reduced the emergence of trichopterans but not chironomids. In *P. pipistrellus*, but not the other species, emergent trichopteran abundance was linked with bat activity, and this relationship varied according to lighting conditions.

These findings indicate that LED lighting has important impacts on Daubenton’s bats, and these effects appear to be graded with light intensity. In addition, lighting negatively affects the emergence of key invertebrate prey items, and can also alter the relationship between prey item abundance and bat activity. The use of LED lighting along watercourses should therefore be minimised (for further information see Appendix G).

The growth of tadpoles in the laboratory was significantly reduced under artificial night lighting, and this effect increased over time (interaction *p* < 0.005 for all outcomes measured). At day 83, the raw differences equated to more than 10% of body size (mean length per group 14.4% (0.26/1.81); minimum length per group 19.4% (0.28/1.44), maximum length per group 10.1% (0.22/2.17)). Amphibians are most vulnerable to predation during larval stages, and risks are also increased among individuals metamorphosing at small body sizes. Night lighting may therefore have important consequences for amphibian
conservation and these should be investigated as a matter of urgency (for further information see Appendix H).

An additional randomised controlled laboratory experimental investigation of the effects of LED lighting on aquatic community structure, and a randomised controlled field trial of the effects of lighting on stream drift have also been carried out. The data are currently being analysed, but are additional to the remit of this project.

**Objective 5. Produce an evidence base for practitioners and policy makers**

We have produced GIS lighting map layers for local authorities and other stakeholders for the districts used in our research. Our findings and the implications for two key Special Areas of Conservation for Greater Horseshoe Bats (Bath and Bradford on Avon, and South Hams) have also been discussed with relevant stakeholders. Noting that the impacts of artificial night lighting on biodiversity are complex, the results of the studies undertaken in this project lead us to make the following recommendations to practitioners and policy makers for further consideration:

- Further work is needed to investigate the conservation implications of night lighting on amphibians.

- Artificial night lighting is not usually linked with increased feeding or activity of the common and widespread bat species critical to ecosystem function: in most scenarios there is reduced activity. Horseshoe bats also show clear avoidance of light throughout their roost sustenance zone. The impacts on other rare species, including Bechstein’s, barbastelle and grey long-eared bats are yet to be investigated, but negative associations are expected based on known associations for species in the same functional guilds. A precautionary approach that minimises the amount of artificial light entering the environment is therefore justified.

- The use of LED lighting along watercourses should be minimised given the impacts on Daubenton’s bats and their prey. Although not specifically tested in this programme, the precautionary principle would suggest that other types of lighting should also be avoided wherever possible.
Lighting in close proximity to waterways, particularly those with substantial treelines, has a major impact on their use by horseshoe bats, and should be avoided in important areas for the conservation of these species.

Greater horseshoe bats rarely use major roads, even where suitable habitat is available. Carriageway lighting of these roads is therefore likely to have only small effects on this species unless it interrupts an important crossing point. Conversely the lighting of minor roads with good tree and hedgerow boundaries has a profound negative effect and should be minimised.

Lighting has the potential to fragment the roost sustenance zone of sensitive species such as greater horseshoe bats. Lighting maps should be considered by stakeholders when evaluating the likely impacts of future developments on bats. Particularly around roosts, dark flightpaths should be maintained wherever possible.

Satellite data can provide a useful index of light pollution at a broad spatial scale.

Separating out the ecological effects of different light spectra and intensities is complex, and further work is required in this area.

UV filters on lights that emit in the UV-spectrum show some promise in reducing the repellence of soprano pipistrelle bats. However, further experimental work is required to explore this, and other mitigation strategies.


