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Mapping artificial lightscapes for ecological studies

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Summary

1 Artificial illumination of the night is increasing globally. There is growing evidence of a range of ecological impacts of artificial light and awareness of light pollution as a significant environmental issue. In urban and suburban areas, complex spatial patterns of light sources, structures and vegetation create a highly heterogeneous night-time light environment for plants and animals.

2 We developed a method for modelling the night-time light environment at a high spatial resolution in a small urban area for ecological studies. We used the position and height of street lights, and digital terrain and surface models, to predict the direct light intensity at different wavelengths at different heights above the ground surface.

3 Validation against field measurements of night-time light showed that modelled light intensities in the visible and ultraviolet portions of the spectrum were accurate.

4 We show how this model can be used to map biologically relevant lightscapes across an urban landscape. We also illustrate the utility of the model using night-time light maps as resistance surfaces in the software package CIRCUITSCAPE to predict potential movement of model nocturnal species between habitat patches and to identify key corridors and barriers to movement and dispersal.

5 Understanding the ecological effects of artificial light requires knowledge of the light environment experienced by organisms throughout the diurnal and annual cycles, during periods of activity and rest and during different life stages. Our approach to high-resolution mapping of artificial lightscapes can be adapted to the sensitivity to light of different species and to other urban, suburban, rural and industrial landscapes.

Key-words: light pollution, urban ecology, landscape ecology, diurnal, nocturnal, night, light

Introduction

Artificial light at night is a feature of almost every landscape in which humans live in the 21st century (Cinzano, Falchi & Elvidge 2001). Following from concerns about the effects of light pollution on the visibility of the night sky and the effects on scientific astronomy (Reigel 1973), there is a long-standing and growing base of evidence of a range of ecological impacts of artificial light (Longcore & Rich 2004; Hölker *et al.* 2010; Gaston *et al.* 2013). Such impacts may cover large areas as light is scattered in the atmosphere through ‘skyglow’, increasing ambient light levels and obscuring natural rhythms (Kyba *et al.* 2011; Davies *et al.* 2013a,b; Kyba & Hölker 2013), and potentially masking the patterns of starlight used for navigation (Dacke *et al.* 2013). However, notwithstanding these potential large-scale effects, most ecological effects to date are recorded in the close vicinity (<1 km) of light sources and concern the impacts of direct light or illumination of the environment (e.g. Blake *et al.* 1994; Bird, Branch & Miller 2004; Frank 2009; Stone, Jones & Harris 2009; Dwyer *et al.* 2012). Direct artificial light at levels typical of the vicinity of human settlements, industrial areas or transport networks can have a wide range of impacts on organisms, including restricting or disrupting the movement of animals (Frank 1988; Kuijper *et al.* 2008; Stone, Jones & Harris 2009; Riley *et al.* 2012), extending the activity of normally diurnal species into the night (Negro *et al.* 2000; Dwyer *et al.* 2012), causing mortality due to attraction or disorientation (Verheijen 1985; Reed *et al.*, 1985; Frank 1988; Witherington and Bjorndal 1991) or increased predation risk (Svensson & Rydell 1998), disrupting circadian patterns (Kempenaers *et al.* 2010) and reproductive phenology (Cathey & Campbell 1975; Dominoni *et al.* 2014) and altering the species composition of communities (Davies, Bennie & Gaston 2012). Isolated light sources may act to attract or repel animals and create population ‘sinks’ of high mortality due to predation or exhaustion, or create pools of resources that predators may exploit (Rydell 1992; Heiling 1999). Linear lit features, such as roads or footpaths illuminated by street lights, may create barriers to dispersal and migration that animals are unable or reluctant to cross (Eisenbeis 2006; Threlfall, Law & Banks 2013). Street lighting thus creates networks of light that may effectively constrain the movement of animals between habitat and resource patches, either because light-avoiding species are reluctant to enter or because light-attracted species become trapped within lit areas.

Little is known about the light environment experienced by organisms in urban and suburban environments, or the duration, intensity and range of wavelengths of light that wild animals and plants around human settlements are

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exposed to (however, see Dominoni *et al.* 2014). At a coarse resolution, spatial patterns in light are clearly visible from night-time satellite images (Cinzano, Falchi & Elvidge 2001). However, while such images demonstrate the density and intensity of light sources and have been used to estimate regional patterns of skyglow, they are of limited utility in describing the light intensity experienced by an organism at or near the surface, which depends on its proximity to individual light sources as well as complex patterns of shading by buildings, topography and vegetation. From this perspective, light intensity may vary by orders of magnitude over a distance of a few metres. Night-time aerial photography provides the opportunity to map individual light sources at such a resolution (Barducci *et al.* 2003; Kuechly *et al.* 2012; Hale *et al.* 2013). However, remote detection of light sources from above only detects light emitted with an upward vertical component while organisms near the surface are predominantly influenced by downwelling light from above. Light patterns are further complicated as different types of light sources emit at different wavelengths, which may affect the vision systems and physiology of different species in contrasting ways (Davies *et al.* 2013a,b).

Specialist software is available to map patterns of light for planners and lighting engineers. However, although these can provide complex and accurate maps of visible light, they require detailed information, usually including manufacturer's specifications of both bulbs and light housings, and simulate illuminance on a highly simplified 3D landscape (typically a flat road surface or parking lot).

We develop a simplified three-dimensional model to simulate the light environment due to direct illumination by point light sources in a complex urban and suburban environment for ecological studies. We predict the spatial distribution of light within human visible and ultraviolet wavelengths due to street lighting across the town of Falmouth, UK, and assess its accuracy using field measurements. We then demonstrate how the resulting light maps can be used to form predictions of the movement of model light-avoiding nocturnal species between fragmented habitat patches.

Materials and methods

STUDY AREA

Falmouth is a port town in Cornwall, south-west England, with a population of *c.* 22 000. The town contains a variety of areas including town-centre retail, high-density terraced housing, suburban properties with large gardens, industrial areas, urban green spaces and rural outlying villages. The urban area of the town covers *c.* 5 km^2.

DATA SOURCES

A high-resolution digital surface model (DSM) for the town of Falmouth was obtained from the Channel Coast Observatory (http://www.channelcoast.org/; accessed 2012). The DSM is derived from an airborne light detection and radar (LiDAR) and has a horizontal resolution of 1 × 1 m and a nominal vertical accuracy of 0·15 m. A 10-m-resolution digital terrain model (DTM) was obtained from the Ordnance Survey Profile data set (http://digimap.edina.ac.uk/; accessed 2012). Unlike the DSM, the DTM is derived from digitised elevation contours and does not incorporate buildings, man-made structures or vegetation. A vector GIS layer of the outlines of buildings and structures was obtained from the United Kingdom Ordnance Survey VectorMap (http://digimap.edina.ac.uk/; accessed 2012). Three GIS raster surfaces were obtained from these data sources, representing the elevation of the 'terrain' surface, the 'hard' surface including terrain and buildings, and a 'soft' surface representing the height of vegetation and other surfaces that are not entirely opaque to light. First, the DTM was downscaled using a bilinear interpolation to the same 1 m resolution as the LiDAR DSM. Second, the DSM was masked using the buildings vector layer, and the base 'terrain' elevation raster layer was derived as the pixel-by-pixel minimum value of this masked layer and the DTM. The 'soft' surface was calculated as the difference between the masked DSM and the base 'terrain' surface. The 'hard' surface was then calculated by subtracting the 'soft' surface from the original DSM (see Fig. 1). All GIS processing was carried out in

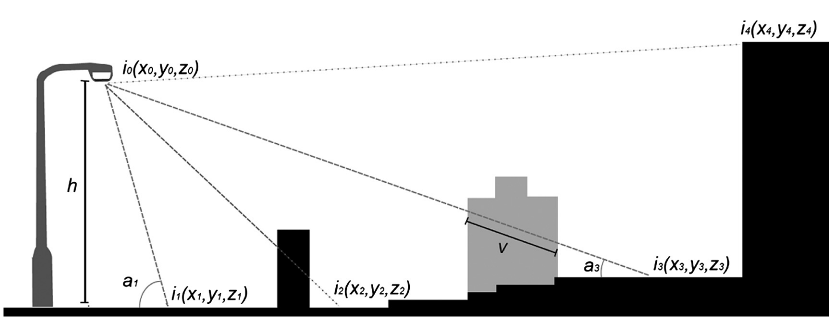

Fig. 1. Two-dimensional representation of the light model. Street lights are represented as point sources with a position in three-dimensional space $i_0(x_0,y_0,z_0)$ at a height h above the digital terrain model. Light intensity at an unshaded point $i_1(x_1,y_1,z_1)$ varies according to the distance between i_0 and i_1 according to the inverse square law. Points that have no direct line of sight to the light source (i_2) have zero light intensity, as do points above the horizontal plane through the street light (i_4). Points for which the line of site passes through objects on the 'soft' surface model, such as vegetation (i_4, vegetation represented in grey), have light attenuated depending on the path length through the object v following the Beer–Lambert law.

QGIS v 1.7.0 using the raster calculator and GDALTOOLS plug in (Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org).

POSITION/TYPE OF STREET LIGHTS

The location (to the nearest metre), height above ground level and bulb type of all street lights within the study area were supplied by the local authority (Cornwall County Council, pers. comm.) in the form of a spreadsheet, which was exported to a text file. Street lighting in the region was recently largely converted from sodium bulbs to 'white' metal halide bulbs (Philips CosmoPolis, Koninklijke Philips NV, Amsterdam, Netherlands), with different bulb ratings (60, 90 and 140 W along different road types). Sample light spectra for each bulb type were measured using a spectrometer (Maya 2000Pro; Ocean Optics, Osfildern, Germany), integrated over the spectral responses of the light sensors used for validation and compared to measurements of light intensity taken at ground level below street lights to calibrate the light output of each bulb type at the range of wavelengths of interest (Fig. 2).

MODEL DESCRIPTION

We used several simplifying assumptions to map light intensity from street lights across the study area. Only direct illumination from street lamps was considered here; light reflected from surfaces, diffuse atmospheric light pollution, moonlight and other artificial light sources were not addressed. Street lights were considered to act as hemispherical isotropic point sources emitting at equal intensity in all directions below the horizontal, although the code is adaptable to allow for more complex non-isotropic emission functions if such data were available for the light sources in a study area. The intensity of light i from a light source was therefore assumed to decline with the distance d from the source according to the inverse-square law:

$$i \propto \frac{1}{d^2}$$

Light from each source was modelled up to 100 m away from that source. 'Hard' surfaces (buildings and terrain) are assumed to be impenetrable to light; therefore, the light intensity at points for which the height of the 'hard' surface exceeds a straight line between the point and the source is zero. 'Soft' surfaces (vegetation) are assumed to absorb light following the Beer–Lambert law, such that

$$i \propto 10^{-\alpha v}$$

where v is the path length through the vegetation and α is the estimated absorbance of the vegetation (given an arbitrary value of 0·5 here, v in metres).

Light intensity was expressed in two ways, to allow for both the cosine-corrected response of the light sensors used in validation, which measure irradiance on a flat surface, and the aim of the model to simulate the light incident on a three-dimensional object (such as an animal or prey item). Irradiance is conventionally defined as a flux density, that is, as the radiant power per unit area. Hence, plane irradiance i_{plane}, the total irradiance incident on a plane at a measurement point, is:

$$i_{\text{plane}} = \sum_{m=1}^{n} \cos(a_m) i_m$$

where i_m is the irradiance from the mth of n lamps within 100 m of the measurement point and a_m is the angle between the path from the source to the measurement point and the normal to the plane. Point irradiance i_{point}, the total irradiance incident on the surface of a sphere at an observation point, is:

$$i_{\text{plane}} = \frac{1}{4} \sum_{m=1}^{n} i_m$$

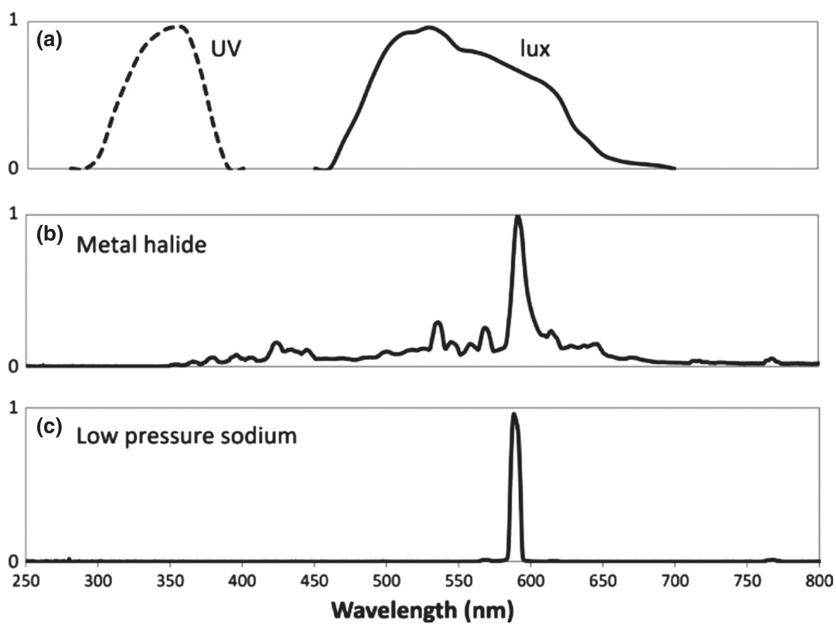

Fig. 2. (a) Relative spectral responses of the ultraviolet (UV; dashed line) and visible (lux; solid line) light sensors used in this study. (b) and (c) Relative spectral power of the two main bulb types of street lighting in the study area.

Plane irradiance is therefore a more useful proxy for the perceived brightness of an illuminated flat surface, while point irradiance is a proxy for the perceived brightness of an illuminated small three-dimensional object.

The method is illustrated graphically in Fig. 1. To map direct light intensity from street lights across the study area, rasters were imported into the R package for statistical computing (R version 2.13.0, R Development Core Team, 2012) and manipulated using the RGDAL and RASTER package (Hijmans 2014). The R code to produce light maps is included in the supplementary material to this paper.

FIELD MEASUREMENTS

Most available sensors used by ecologists for measuring light intensity measure the flux of light intercepted on a two-dimensional plane (in terms of energy, photon count or vision-corrected light intensity per unit area). However, for biological purposes, it is often more relevant to consider the extent to which a three-dimensional object (e.g. a prey item) will be illuminated, independently of the direction of the light source. To calibrate and validate the intensity of different lighting types, we used cosine-corrected sensors on a handheld mounting at 1·5 m above ground level and measured light at the wavelengths visible to human vision (450–650 nm; SKL 310 lux sensor; Skye Instruments, Llandrindod Wells, UK) and in the ultraviolet spectrum (UVA 315–380 nm; SKU 420 UV-A sensor; Skye Instruments). For calibration, five measurements taken directly beneath five lamps of each bulb type were used to calibrate the brightness estimates for each type. To assess the effectiveness of the assumption that street lights approximate point sources, we took measurements at ground level at 2-m intervals along a transect from an isolated street lamp at 8 m height and compared these data to predictions using both a simple inverse-square law prediction and predictions using a more complex commercial simulation model (DIALux 4.11; DIAL GmbH, Lüdenscheid, Germany). Finally, to assess the accuracy of our model predictions, we used cosine-corrected sensors on a handheld mounting at 1·5 m above ground level. Sensors were connected to a datalogger connected to an external GPS unit mounted adjacent to the sensors (Spectrosense 2+; Skye Instruments), and light intensity and position readings were logged at each measurement point. Measurements were taken at 40 points at *c.* 20-m intervals along a 0·8-km transect along a section of street and footpath with overhead street lights with vertical cut-off of four different bulb types (Philips CosmoPolis 60, 90 and 140 W bulbs and an unknown model of low-pressure sodium bulb) and mounting heights (6, 8 and 10 m above street level) . The spacing between street lights was between 25 and 30 m; the spacing between sampling points therefore limited the impact of any individual street light on the validation results. Measurements were taken on the nights of 11 March 2013 and 26 January 2014, under overcast conditions with a less than quarter moon to minimise the effect of moonlight on readings.

APPLICATION OF MODEL TO AN ECOLOGICAL SYSTEM

To demonstrate the application of artificial light mapping to landscape and urban ecology, we used the software CIRUITSCAPE v. 3.5 (Shah & McRae 2008) to illustrate potential flight paths for a hypothetical light-avoiding bat species moving between two foraging patches in a suburban landscape. CIRCUITSCAPE uses circuit theory (McRae *et al.* 2008) to model connectivity and routes of dispersal in landscapes. Landscapes are defined as grids of variable resistance to movement; movement of animals is simulated as analogous to the flow of electric current through a two-dimensional structure with variable electrical resistance. Maps produced by the software represent the flow of current and by analogy can be used to identify dispersal routes and 'pinch points' where connectivity is tenuous and movement is restricted to corridors.

We used maps of point irradiance (in lux) at 2·5 m height to estimate the light intensity within a range visible to mammal species (450–650 nm) experienced by a bat under normal flight conditions. Since certain bat species have been shown to be reluctant to enter illuminated areas, disrupting their patterns of movement between foraging patches (Kuijper *et al.* 2008; Stone *et al.,* 2012), we considered the resistance to movement in the landscape to be proportional to light intensity. Dark areas (with zero modelled light intensity) were given an arbitrary low resistance of 0·01; elsewhere, in the absence of experimental or field data for thresholds or dose–response curves for light avoidance in bats, resistance was taken to be the light intensity in lux. Two focal points, representing resource patches of semi-natural wooded areas alongside water bodies, were defined in the Swanvale suburb of Falmouth, and a current map was produced.

Results

The model is capable of producing complex high-resolution maps of light intensity (Fig. 3), which clearly show the effect of street lighting in forming a network of light at ground level, and is able to identify contrasts between intensively lit regions and relatively dark areas within the urban landscape. Our assessment of the suitability of using a simple inverse-square law approximation suggests that this method can give a good first-order prediction of light intensity under simple conditions, although the street lights are anisotropic emitters, and more complex models predict a wider range of illuminance values depending on the orientation of the luminaire with respect to the observer (Fig. 4a). Our assessment of model accuracy shows good correspondence with measured data in the visible range (Fig. 4b; regression slope = 1·043, $r^2 = 0{\cdot}9619$, RMSE = 3·39 lux). Model performance in the ultraviolet was less accurate (Fig. 4c; regression slope = 0·879, $r^2 = 0{\cdot}6538$, RMSE = 0·228 mW m^{-2}). We attribute this to the lower relative output of the lights below the visible wavelengths (Fig. 2); other sources of ultraviolet light such as moonlight,

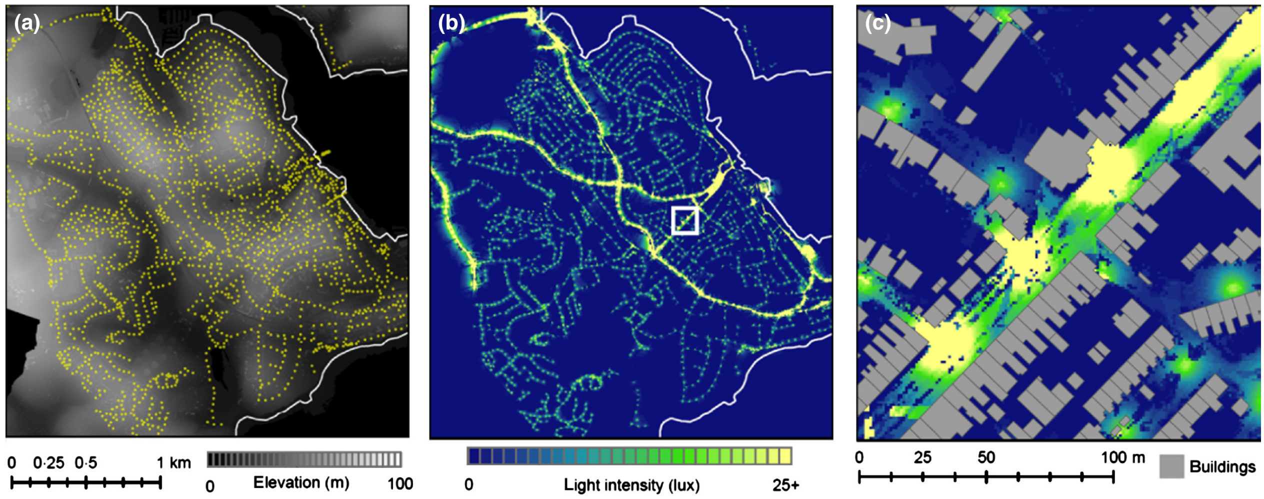

Fig. 3. (a) Shaded elevation model of Falmouth used in the light model with position of street lights marked in yellow. (b) Result of point-intensity visible light mapping at 2·5 m height across the study area. White box marks the area enlarged in (c), showing fine-scale pattern of light along a main street and adjacent side-roads. Building map layer is Crown Copyright/database right 2012. An Ordnance Survey/EDINA supplied service.

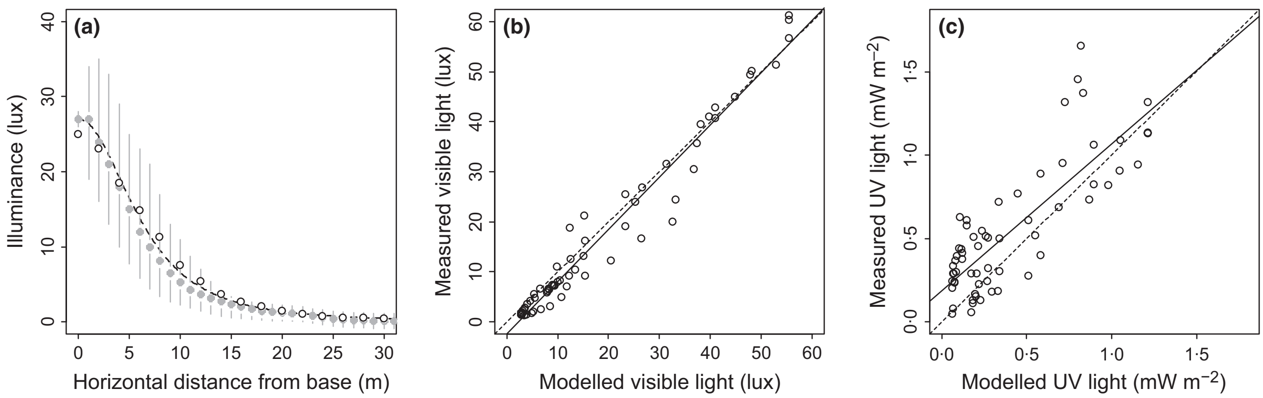

Fig. 4. Calibration and accuracy assessment of light model performance in an open area. In panel (a), the dashed line shows predicted illuminance at ground level along a 30-m transect from the base of a lamp at 8 m height using a simple inverse-square law prediction; filled grey circles show the model predictions at 90° to the orientation of the luminaire using a commercial light design software taking into account a more complex anisotropic distribution of light (DIALUX 4.11; DIAL GmbH) – grey lines show the range of values predicted using this software depending on the orientation of the luminaire. Hollow circles show measurements taken at 90° to the orientation of a luminare. Panels (b) and (c) show light levels predicted using the simple inverse-square law model form compared with data collected at 2-m intervals from (b) visible and (c) ultraviolet light. Measurements of both visible and UV-A light were taken at 1·5 m height above street level at random intervals along a 650-m transect under 18 street lights (of three different bulb types and mounting heights). Dashed lines represent a slope of 1, and solid lines represent a linear fit to the data.

diffuse skyglow and UV-emitting light sources not incorporated in our model (specifically fluorescent illumination of street signs) probably add complexity in the UV environment that is not captured by our model. However, the model was able to characterise the main gradient in light at these wavelengths.

Applying the model output to a landscape ecology context (Fig. 5) demonstrates its applicability to forming testable hypotheses about animal movements within realistic lightscapes. This approach clearly identifies potential dark corridors for movement between habitat or resource patches – in this example, a wooded railway embankment, an area of suburban housing with unlit private roads and suburban gardens with high tree cover are highlighted as likely routes for light-avoiding animals moving between two habitat patches.

Discussion

Municipal street lighting is a major source of artificial light emitted from urban areas, along with industrial and commercial sources (Kuechly *et al.* 2012) and sport and leisure centres (Luginbuhl *et al.* 2009). The impact of street lighting on animal movement is likely to be particularly significant due to its ubiquity and the linear network formed by illuminated road networks, effectively reducing the connectivity of dark habitat and resource patches for species reluctant to cross lit areas (Beier 1995; Kuijper *et al.* 2008; Threlfall, Law & Banks 2013). While many nocturnal species are repelled by artificial light at night, other species are strongly attracted to light, either through disorientation (Verheijen 1958; Frank 1988; Eisenbeis 2006) or as they exploit increased opportunities to hunt or forage in an illuminated environment (Rydell 1992; Negro *et al.*

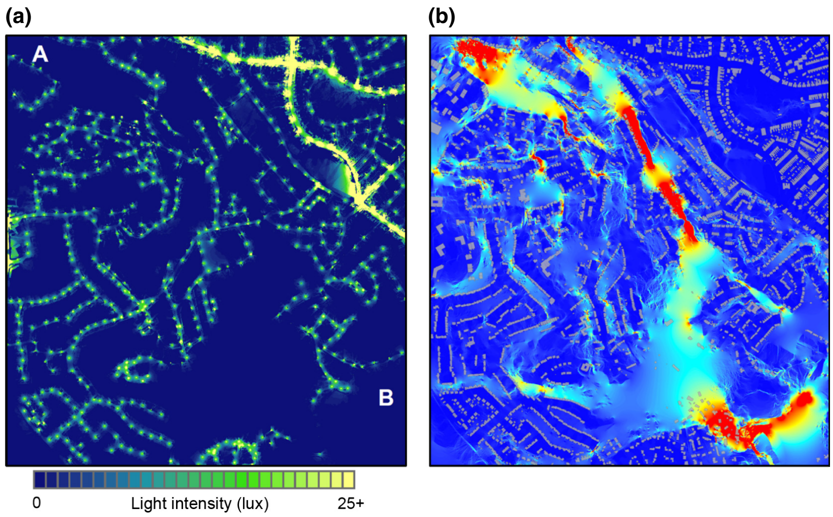

Fig. 5. Application of artificial light mapping to an ecological system. Panel (a) shows the modelled light intensity at 2·5 m height over the Swanvale suburb of Falmouth. Points A and B lie within semi-natural woodland along a river valley, suitable foraging areas for several species of British bat. Panel (b) shows the output of a simulation using CIRCUITSCAPE on the same area in which brightly lit areas in (a) provide 'resistance' to animal movement (as inferred by behavioural studies on bat species; Stone *et al*. 2012). Movement between patches is modelled as electrical current flow between A and B (McRae *et al*. 2008). Red and yellow regions in this map represent 'pinch points' that are predicted to be critical corridors for movement between these patches. The model identifies an area of housing and gardens on unlit private roads (bottom right), and a wooded railway embankment (top centre) as 'dark corridors' that could be utilised for movement between foraging patches.

2000; Frank 2009; Canário *et al*. 2012). By developing a high-resolution model of artificial light from street lights, we are able to identify areas of the urban landscape that may act as 'dark refuges' for nocturnal animals, as well as corridors of darkness for movement through the urban lightscape. This approach could also be used as a tool for quantifying the impact of light within urban environments. While field survey of individual light sources is labour intensive, data bases of the location and type of street lights are increasingly stored in digital form and often publically available, and the increasing availability of high-resolution digital terrain and surface models makes a modelling approach to mapping artificial lightscapes increasingly feasible. Although available satellite images of artificial light at night are increasing in their spatial and spectral resolution (Miller *et al*. 2012), there is still some way to go before they can be used to characterise urban landscapes at a scale relevant to most ecological studies. Aerial surveys can be valuable tools to identify the relative contributions of different lighting and land uses to light emission at the zenith (Kuechly *et al*. 2012; Hale *et al*. 2013); however, a modelling approach is powerful in that it may estimate light emitted in any direction, at the surface or at a height above the surface, and at any wavelength. In addition, the impact of future interventions to reduce the impact of ecological light pollution, such as dimming or switching off lights or changing bulb types, on connectivity within the urban lightscape may be assessed.

While we have deliberately kept the data requirements of this model relatively low, to make it as applicable as possible for ecological studies, there is potential for building on this modelling framework to utilise other data sources where these are available. Lighting inventories could be supplemented by integrating remote sensing, ground survey and field measurements of light levels and spectra to include private lighting sources such as security, industrial and domestic lighting, advertising and sports lighting fixtures. Such an approach will always involve a trade-off between complex models, in which the optical characteristics and orientation of light sources are specified and reflected and diffuse illumination may be considered (which may be critical for, for example, flood lights or spotlights where high-intensity light is emitted over a limited area), and simple approaches appropriate for mapping areas with limited data availability, like the one adopted here where all lamps are treated as point sources, and direct illumination only are modelled. Other remote sensing data, for example full-waveform LiDAR, would give information on the vertical structure of vegetation canopies (Lefsky *et al*. 1999), which here we represent as a single uniform column. Information on the transmissivity of canopies at different wavelengths and during different seasons would allow the varying effects of shading to be quantified. There is thus considerable potential for incorporating both modelling and direct measurements of the spectral and spatial components of urban lightscapes from field survey and/or aerial remote sensing to improve the accuracy of models of ecological lightscapes. Perhaps more pressing, however, is the need for information on the responses and thresholds for both behavioural and physiological responses of organisms to artificial light at night at different wavelengths. By increasing understanding of the levels of light that wildlife is exposed to within urban and suburban environments, and the complexity of their responses, we may start to understand the effects of artificial light on urban ecology, biodiversity and ecosystem function.

Data accessibility

The R script for running the model is included in supplementary material. The LiDAR digital surface model (DSM) for the town of Falmouth was obtained from the Channel Coast Observatory (http://www.channelcoast.org/; accessed 2012). The 10-m-resolution digital terrain model (DTM) was obtained from the Ordnance Survey Profile data, and buildings outline was derived from the Ordnance Survey Vectormap Local data, both accessed under licence from EDINA Digimap Ordnance Survey Service, http://edina.ac.uk/digimap (accessed October 2012).

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Supporting Information

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

Data S1. R code for calculating light intensity maps.