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Research Paper

Evidence for distance and illuminance thresholds in the effects of artificial lighting on bat activity

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ABSTRACT

Light pollution is a major threat to biodiversity worldwide. There is a crucial need to elaborate artificial lighting recommendations to mitigate its impact on wildlife. In the present study, we investigated how streetlight spatial position and light trespass impacted the use of ecological corridors by transiting bats in anthropogenic landscapes. Through a paired, *in situ* experiment, we estimated how streetlight distance of impact and vertical and horizontal illuminance influenced the transiting activity of 6 species and 2 genera of bats. We selected 27 pairs composed of 1 lit site and 1 control unlit site in areas practicing either part-night or full-night lighting. We recorded bat activity at 0, 10, 25, 50 and 100 m, and measured vertical and horizontal light illuminance at the 5 distance steps (range = 0.1–30.2 lx). While streetlight attraction effect was mostly limited to a 10 m radius for *Pipistrellus* sp. and *Nyctalus* sp., streetlight avoidance was detected at up to 25 and 50 m for *Myotis* sp. and *Eptesicus serotinus*, respectively. Streetlight effects on *Myotis* sp. and *Nyctalus* sp. remained after lamps were turned-off. Illuminance had a negative effect on *Myotis* sp. below 1 lx, a mixed effect on *E. serotinus*, and a positive effect on the other species, although a peak of activity was observed between 1 and 5 lx for *P. pipistrellus* and *N. leisleri.* We recommend separating streetlights from ecological corridors by at least 50 m and avoiding vertical light trespass beyond 0.1 lx to ensure their use by light-sensitive bats.

1. Introduction

Considering current levels of urbanization around the world, mitigation its impacts on biodiversity has become a major challenge in sustainable land-use planning strategies (Grimm, Faeth, et al., 2008). Urbanization not only impacts biodiversity through habitat loss and fragmentation, but also due to various sources of pollution, including chemical (Moore & Palmer, 2005), noise (Arroyo-Solís, Castillo, Figueroa, López-Sánchez, & Slabbekoorn, 2013), and light pollution (Hale et al., 2013) which can diffuse beyond urban and suburban landscapes and affect substantial parts of surrounding ecosystems (Grimm, Foster, et al., 2008). Light pollution generated by the use of artificial light at night (ALAN) affects 23% of global land surface, including 88% of Europe, and is spreading annually at 6% worldwide (Falchi et al., 2016; Hölker, Moss, et al., 2010). As a result, major concerns have been raised about the potential impacts of ALAN on biodiversity and ecosystem dynamics (Macgregor, Evans, Fox, & Pocock, 2016; Davies et al., 2017; Hölker, Wolter, Perkin, & Tockner, 2010; Longcore & Rich, 2004).

Light pollution alters the natural light cycle that both diurnal and nocturnal organisms use to synchronize their biological rhythms with their environment (Gaston, Duffy, Gaston, Bennie, & Davies, 2014). This desynchronization has important consequences for individual fitness, sexual selection, and reproductive success (Boldogh, Dobrosi, & Samu, 2007; Nordt & Klenke, 2013; van Geffen et al., 2015). Species response to ALAN is also driven by attraction/repulsion behaviors that can influence species spatial distribution at various spatial and temporal scales (Azam, Le Viol, Julien, Bas, & Kerbiriou, 2016; ffrench-

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Constant et al., 2016; Mathews et al., 2015). As a whole, the effects of light pollution on organisms likely impacts the spatiotemporal dynamics of biological communities and ecosystems (Macgregor et al., 2016; Bennie, Davies, Cruse, Inger, & Gaston, 2015; Davies et al., 2017). Thus, developing outdoor lighting strategies that minimize its negative impacts on biodiversity while meeting social and safety requirements for humans represent a major challenge in land-use planning (Gaston, Davies, Bennie, & Hopkins, 2012).

Current land-use planning policies in Europe tend to restore biodiversity dynamics in human-inhabited landscapes by implementing functional networks of ecological corridors that facilitate the movement of plant and animal populations in fragmented areas (i.e. restoration of landscape connectivity; Ricketts, 2001). Landscape connectivity is crucial to ensure species persistence in a given area as it influences the availability and accessibility of suitable resource patches for organisms, and drives metapopulation dynamics at a landscape scale (Minor & Urban, 2008; Taylor, Fahrig, Henein, & Merriam, 1993). Finally, connectivity also dramatically influences the dispersal success of individuals over large spatial scales with important implications for gene flows (Baguette, Blanchet, Legrand, Stevens, & Turlure, 2013). However, there is currently no recommendation for ALAN management in and around ecological corridors (But see: Bliss-Ketchum, de Rivera, Turner, & Weisbaum, 2016). Considering that 30% of vertebrates and 60% of invertebrates are nocturnal (Hölker, Wolter, et al., 2010), it is likely that ecological corridors are ineffective for a substantial part of biodiversity if not planned concomitantly with the spatial planning of ALAN.

Limiting the impact of light pollution on biodiversity requires managing ALAN through: 1) the spatial arrangement of light sources in the landscape; 2) reducing light trespass (i.e. light spill) into areas that are unintended to be lit by controlling light directionality; 3) limiting the duration of lighting; 4) reducing ALAN illuminance; and, 5) adapting the spectral composition of the lamps to local ecological context (Gaston et al., 2012; Kyba, Hänel, & Hölker, 2014). However, while particular attention has been given to the ecological impacts of lamp spectral composition (Lewanzik & Voigt, 2016; Stone, Wakefield, Harris, & Jones, 2015) and lighting duration (Azam et al., 2015; Day, Baker, Schofield, Mathews, & Gaston, 2015), the impacts of streetlights spatial position and light trespass on biodiversity are unknown.

Because of their nocturnal behavior, bats are directly exposed to ALAN. Bat responses to ALAN vary among species according to their foraging strategies and flight abilities (Jones & Rydell, 1994). Slow-flying species specialized in foraging along or within cluttered vegetation, such as *Rhinolophus* spp., *Myotis* spp., and *Plecotus* spp., avoid illuminated areas due to an intrinsic perception of increased predation risk (Rydell, Entwistle, & Racey, 1996). This avoidance behavior has been detected regardless of the lamp spectrum (Stone, Harris, & Jones, 2015) and even at low level of light illuminance (Lacoeuilhe, Machon, Julien, Le Bocq, & Kerbiriou, 2014). In contrast, fast-flying species that forage for insects in open areas, such as *Pipistrellus* spp. and *Nyctalus* spp., can benefit locally from the increased foraging opportunities provided by streetlights (Lacoeuilhe et al., 2014; Lewanzik & Voigt, 2016), which attract a large portion of the surrounding insect biomass (Perkin, Hölker, & Tockner, 2014). Nevertheless, light pollution negatively affects bat species occurrence at a landscape-scale, regardless of foraging strategy (Azam et al., 2016). Such large-scale negative effect may be partly due to the barrier effect that artificial lighting can induce on individuals' movements and gap-crossings in human-inhabited landscapes (Hale, Fairbrass, Matthews, Davies, & Sadler, 2015; Stone, Jones, & Harris, 2009).

Bats are long-lived insectivorous species with a slow reproductive rate and are thus considered as bio-indicators of biodiversity response to anthropogenic pressures (Jones, Jacobs, Kunz, Willig, & Racey, 2009). In addition, bats deliver important ecosystem services such as pest control and seed dispersal (Lewanzik & Voigt, 2014; Charbonnier, Barbaro, Theillout, & Jactel, 2014). But the persistence of bat species in both urban and rural landscapes is highly reliant on the structural connectivity of such elements as tree lines, hedgerows, and riverbanks that facilitate their movements between foraging patches, and increase landscape connectivity (Hale, Fairbrass, Matthews, & Sadler, 2012; Lintott, Bunnefeld, & Park, 2015).

Considering ALAN's impacts on bats movements, this study aimed at investigating how streetlights spatial position and light trespass impacted the use of ecological corridors by transiting bats. In particular, we first estimated the distance of impact of streetlights on bat activity and the persistence of this effect once streetlights were switched-off. Second, we compared the effects of horizontal and vertical illuminance on bat activity to assess the minimum level of light illuminance that should be respected to avoid light trespass. This study allowed us to elaborate practical ALAN management recommendations to restore landscape connectivity for bats in anthropogenic landscapes.

2. Materials and methods

2.1. Study area

To address our main research question, we sat up an *in situ* paired experiment to investigate how streetlights spatial position and light trespass impacted the use of ecological corridors by bat belonging to 6 species and 2 genera. The field experiment was set up in a protected, 849-km^2 natural park (IUCN Protected Area Category VI). The park is located 60 km south of Paris, France and is comprised of 69 municipalities that average 12 km^2 in size. Part-night lighting schemes have been employed in 56% of municipalities for at least two years. These schemes consist of turning-off all public streetlights from midnight (+/−1 h) to 5 AM. Arable lands represent 58% of the area, and forests comprise 31% (Fig. 1a). Currently, urban areas make up 8% of the park, but the entire region is subject to pressures from urbanization due to its vicinity to the capital. Consequently, the level of artificial brightness of the sky in the area range from 223 to 445 µcd/m^2, which is 1.28 to 2.56 times greater than natural sky brightness (Falchi et al., 2016).

2.2. Sampling design

We selected 27 study locations composed of one lit site and a paired control unlit site, with 19 pairs located in administrations practicing part-night lighting schemes, and 8 located in municipalities with full-night lighting (Fig. 1a). Lit sites were illuminated by 1 high-pressure sodium (HPS) vapor streetlight (average intensity = 16.7 lx; range = 6–42 lx) which is the most commonly used type of streetlight in French rural areas. Unlit control sites were separated from their paired lit site by approximately 250 m and no streetlight was present within a 200 m radius around unlit sites. Both lit and unlit sites were subjected to landscape-scale skyglow. However, as paired sites were located nearby, this exposure was similar between both sites. Thus, our sampling design allowed characterizing the impacts of local outdoor lighting on bat activity.

The two sites of each pair were also located in a similar habitat and set along the same bat commuting route, such as a forest edge or a hedgerow (Walsh & Harris, 1996). The sites were also positioned away from town centers and at similar distances from linear elements, such as roads and streams.

Both lit and unlit sites were composed of five recording stations located at 0, 10, 25, 50 and 100 m from the streetlight (i.e. 10 recording stations per pair; Fig. 1b). We manually measured at each of the five recording stations vertical and horizontal illuminance (lx) which is the luminous flux received by a 1 m^2 vertical (i.e. trees and hedgerows) or horizontal (i.e. ground) surface. We used a luxmeter (Digital Lx Tester YF-1065) fixed at the top of a tripod of 1.20 m height that allowed the device to be held perpendicular or parallel to the ground (Fig. A1). The luxmeter had a resolution of 0.01 lx, but the accuracy of our measurements under real outdoor conditions was estimated to be ± 0.1 lx.