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Guidelines for consideration of bats in lighting projects

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Foreword

Life on Earth has evolved over billions of years under cycles of natural light and darkness that vary diurnally and annually. Artificial light at night (ALAN), and sometimes also at daytime, can cause deviations from these natural patterns of darkness and may thus interfere with natural physiological and ecological rhythms (Longcore & Rich 2004, Hölker *et al.* 2010a, Gaston *et al.* 2013, 2015). In mammals, physiological features such as sleep, food digestion, immune response and body temperature are tightly adjusted to the diurnal light cycle (Arendt 1998). ALAN may disrupt these physiological processes and may further interfere with orientation and navigation, with severe consequences for individual behaviour, local animal populations and whole ecosystems (Rich & Longcore 2006; Gaston *et al.* 2015).

Among vertebrates, bats are almost exclusively nocturnal and extremely sensitive to ALAN, (Hölker *et al.* 2010a, Speakman 1995, Voigt & Lewanzik 2011, Bennie *et al.* 2014a). The information we have on the impact of ALAN on bats is gradually expanding, and helps us formulate management recommendations to mitigate the impact of old and new lighting schemes. The information currently available is a combination of scientific studies, case-reports, and the extensive experience of bat workers. An integration of this information forms the basis of these EUROBATS guidelines. However, it is important to measure the degree of success of the mitigation strategies described in this document, and determine whether they achieve local and landscape-scale benefits for bats. Further, it is important to investigate how these measures can be improved. In addition, quantitative assessments of the effectiveness of mitigation – vital to refine and improve strategies for the future – can only be achieved if structured data are collated from multiple sites.

In these guidelines, we tried to compile available evidence related to the effect of ALAN on bats, a field of research that is very dynamic. Using the current state of knowledge, solutions are formulated on how to avoid, mitigate or compensate the adverse effects which ALAN has on bats in their network of functional habitats, consisting of roosts (maternity, summer, transient, feeding, mating and/or hibernation), ***commuting routes*** and ***migratory*** corridors, ***foraging areas*** and ***swarming sites*** (hereafter, terms highlighted in bold and italics are included in the Glossary).

1 Introduction

All European bat species are protected by several international and European binding treaties, (*e.g.* by the ***EU Habitats Directive***). The Convention on the Conservation of Migratory Species of Wild Animals (also known as CMS or Bonn Convention) aims to conserve terrestrial, aquatic and avian migratory species throughout their range. It is an intergovernmental treaty concluded under the aegis of the United Nations Environment Programme (UNEP). Migratory species threatened with extinction are listed in the Appendix I to the Convention whereas migratory species that need or would significantly benefit from international co-operation (including all European bat species) are listed in the Appendix II. The Agreement on the Conservation of Populations of European Bats (EUROBATS) was set up under the Bonn Convention and aims to protect all European bat populations through legislation, education, conservation measures and international co-operation. According to the fundamental obligations, each EUROBATS Party shall identify important roosting sites and ***feeding areas*** for bats and protect such sites and areas from damage or disturbance such as ALAN.

The Habitats Directive requires that Member States do more than simply prevent the further decline of populations of the listed species. For the priority bat species, included in Annex II, they must also undertake positive conservation measures to ensure that populations are maintained and restored to a favourable conservation status throughout their natural range within the EU. Consequently, responsible authorities in all European countries shall ensure that bat populations are protected also from disturbance caused by light pollution.

A nocturnal lifestyle is inherent to all bats. They usually hide in roosts during the daytime, while fly to ***feeding areas*** or drinking sites using ***commuting routes*** during the night. On the annual scale, bats of the temperate zone aggregate in late summer and autumn for ***swarming*** and later spend the winter in hibernacula. Many bat species move between different roosts and habitats, whereas other perform long-distance ***migrations*** between reproduction and hibernation areas in different parts of Europe (Hutterer *et al.* 2005). In all situations, ALAN may significantly change their natural behaviour (Stone *et al.* 2015a; Rowse *et al.* 2016). A hypothetical case is presented in Figure 1.1. Overlap of illuminated patches with ***foraging areas*** and ***commuting routes*** results in a potential conflict between ALAN and bat conservation. *Plecotus auritus* would stop to use the lit side of the church for emergence; illuminated patches may disrupt flight paths of the bats and affect their foraging areas: tree lines and shores (*Pipistrellus pipistrellus* and *Plecotus auritus*) and waterbodies (*Myotis daubentonii*).

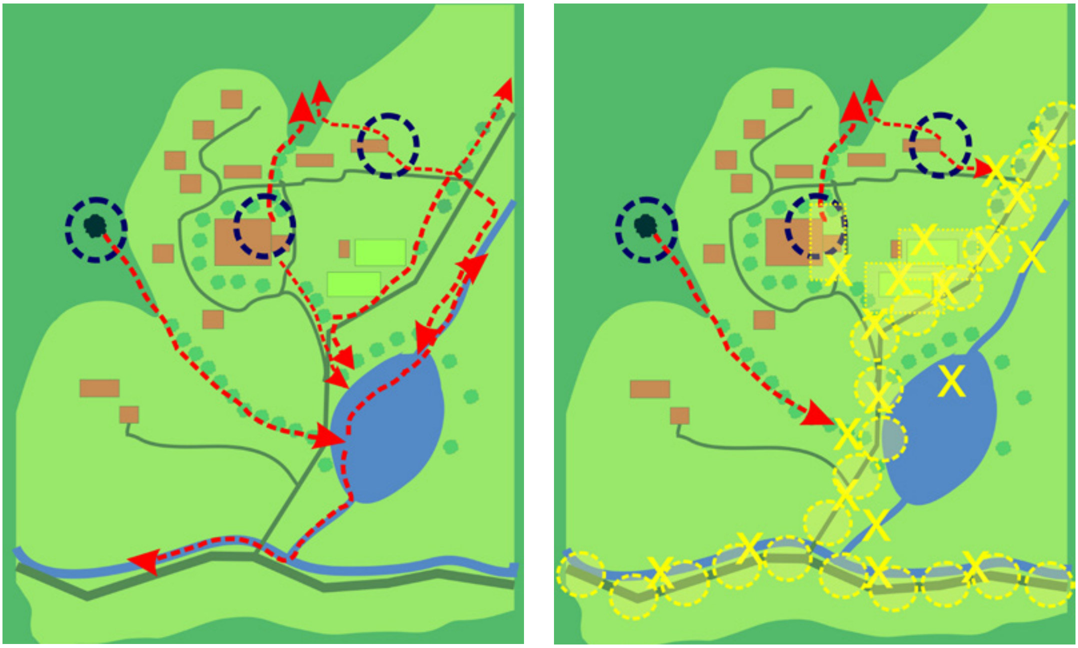

Figure 1.1. Schematic network of roosts, commuting routes and foraging areas of 3 bat species in a situation without ALAN (left picture) and with ALAN (right picture). Red rectangles denote buildings in a village, surrounded by forest (dark green); green circles – individual trees; blue areas – water bodies; grey lines – roads; green rectangles – stadiums. Roosts are encircled by dark blue dashed lines: M. daubentonii *roosting in a tree in the forest, long-eared bats roosting in the church attic (large red rectangle in the village centre) and* P. pipistrellus *roosting in a house. Commuting and foraging areas – red dashed lines with arrows. Illuminated areas are surrounded by yellow dashed lines. Crosses indicate places where the movement through the landscape is blocked by ALAN or the habitat is no longer functional.*

Bats are naturally exposed only to very low lighting levels produced by moonlight, starlight and low intensity twilight (Fig. 1.2). There are rare exceptions of daylight flight activity, such as in *Nyctalus azoreum,* a noctule species from the Azores (Speakman 1995), and in bats at northern latitudes that forage in daylight when nights are shortest (Speakman *et al.* 2000). In general, bat eyes are specialised for low light levels (Shen *et al.* 2010). Light levels as low as typical full moon levels, *i.e.* around 0.1 lx, are known to alter the flight activity of bats. It is important to note that the unit **lux** (symbol lx) is defined according to human spectral sensitivity and determining its relevance for animals with different spectral sensitivities can be problematic. We refer to this unit below, since it may facilitate interdisciplinary communication between biologists, the lighting community and developers.

Any level of artificial light above that of moonlight masks the natural rhythms of lunar sky brightness and, thus, can disrupt patterns of foraging and mating and might, for instance, interfere with entrainment of the circadian system (Fig. 1.3 and 1.4). In

Figure 1.2. Two Plecotus auritus *with rising full moon in the background (© J. Rydell).*

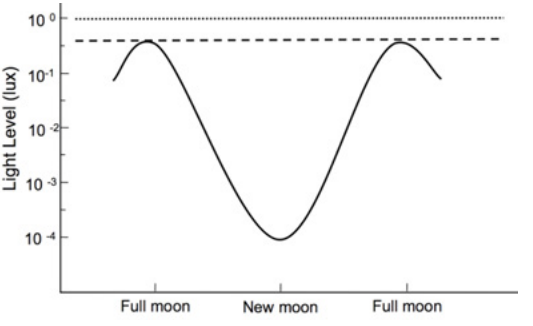

Figure 1.3. Skyglow can mask natural rhythms of lunar sky brightness. The solid line depicts full moon light levels in a temperate habitat without light pollution. The dashed and dotted lines indicate skyglow light levels under clear and cloudy skies respectively, as measured in the centre of Berlin. Figure from Perkin et al. *(2011).*

the lab, even ***illuminance*** as low as 10^{-5} lx was sufficient for the entrainment of circadian rhythm of the Pallas's Mastiff Bat (*Molossus molossus*), the lowest threshold value observed for photic entrainment in vertebrates (Erkert 2004). Consequently, ALAN that may affect bats negatively can be of very low intensity: some bat species are repelled by very low light levels of only 4.5 lx (Lewanzik & Voigt 2016), 3.6 lx (Stone *et al.* 2012), 3.2 lx (Kuijper *et al.* 2008) and 1.9 lx (Lacoeuilhe *et al.* 2014). In comparison, those levels are all lower than the ***illuminance*** level of residential side streets, which is on average about 5 lx at street level, but which often is higher than this (Gaston *et al.* 2012, Azam *et al.* 2015).

Bats possess colour vision (Müller & Peichl 2005), including the ability to perceive UV (Winter *et al.* 2003, Müller *et al.* 2009, Gorresen *et al.* 2015), though UV sensitivity has been lost in some species, including horseshoe bats (Zhao *et al.* 2009). The general sensitivity of bats to light is obvious. Some species adjust their activity in response to the lunar cycle (*e.g.* lunar phobia), a response that is especially pronounced in species that forage over water and in the forest canopy, and live in tropical areas (Saldaña-Vázquez & Munguía-Rosas 2013; Roeleke *et al.* 2018). Polarised light at sunset seems to be important for orientation, *e.g.* for calibrating the magnetic compass of some bats (Greif *et al.* 2014). However, migratory species may represent an exception (Lindecke *et al.* 2015). Bats may also obtain cues from city lights for

Figure 1.4. Skyglow outshining stars and the Milky Way in Cazorla City, Spain (© Jens Rydell).

homing (Tsoar *et al.* 2011) and possess the visual acuity to use information from stars for navigation (Childs & Buchler 1981, Eklöf *et al.* 2014). Bats may demonstrate reduced homing performance, if deprived of visual cues (Davis & Barbour, 1970). Thus, ALAN has the potential to seriously interfere with the vision and behaviour of bats.

ALAN is produced in a variety of ways, for example by street lights, illuminated buildings, lit advertisements, security and domestic lights, lights on vehicles, gas flares and stadiums (Kyba *et al.* 2015, Schoeman 2015; Fig. 1.5). An in-depth remote sensing study of Berlin showed that almost a third of the emitted light came from streets, with considerable amounts of light also originating from industrial areas (16%), public service areas (10%), block buildings (8%), city centre (6%), airfields (4%) and supply and disposal facilities (4%) (Kuechly *et al.* 2012). Direct lighting is affected by physical features of the atmosphere and terrain; it can also be scattered by atmospheric molecules or aerosols, especially under cloudy conditions (Aubé 2015, Kyba *et al.* 2015). Although the scattered artificial light (see ***skyglow***) is relatively dim and homogenous compared with point sources such as street lights, it is still bright compared to natural light sources, such as stars, and spreads over vast areas (Kyba & Hölker 2013, Falchi *et al.* 2016).

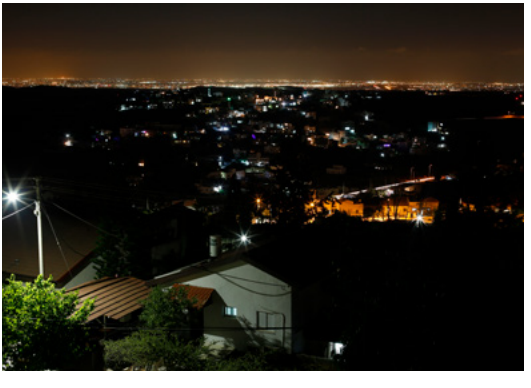

Figure 1.5. Artificial light at night from various sources such as streetlamps, illuminated buildings, lit advertisements, domestic lights, lights from vehicles, resulting in bright skyglow over Israel in the background. The image was captured from the West Bank, which is much darker and with less skyglow (© J. Rydell).

The spectral content of light can differ depending on the source (Fig. 1.6, Table 1.1), and many animals (including bats and insects) are able to perceive wavelengths beyond the range that humans can. For street lights, high-pressure mercury vapour (HPMV) lamps emit what humans recognize as blue-white light containing considerable amounts of UV. Low-pressure sodium (LPS) lamps emit monochromatic orange light, while high-pressure sodium (HPS) lamps emit a broader spectrum of mainly orange-yellow wavelengths. New technologies include light-emitting diodes (LEDs) and metal halide lamps. LEDs are available in 'warm white' and 'cold white' varieties, and typically do not emit UV. Metal halide lights emit UV, similar to HPMV lamps. Domestic lighting traditionally included many tungsten filament lamps that heat up to produce visible light (by incandescence). These lamps are being replaced by compact florescent lamps (that emit some UV), and especially by LEDs. The UV component of lamps seems to be especially important in determining how attractive lamps are to insects: lamps that emit UV attract more insects (Eisenbeis & Eick 2011; Wakefield *et al.* 2016; 2018), and it has been shown that blue wavelengths attracted considerable more moths than lights of longer wavelengths (Verovnik *et al.* 2015). The dense concentrations of insects around these light sources may attract hunting bats of some species (*e.g.* Rydell 1991).

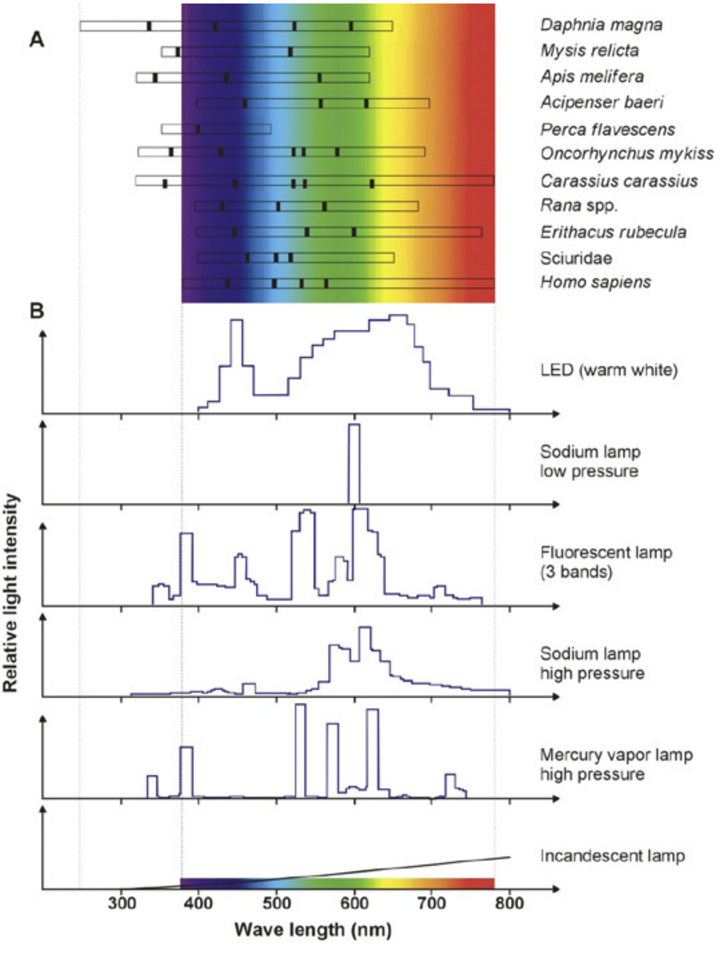

Figure 1.6. (A) The light sensitivities various animals displayed against a background of wavelengths that humans perceive as visible light. The dashed vertical lines cover the range of wavelengths, which the listed animals can perceive. Black marks in bars represent peak sensitivities of visual pigments for small crustaceans: Daphnia magna *and* Mysis relicta*; insect* Apis mellifera *(honeybee); fish* Acipenser baeri *(sturgeon),* Perca flavescens *(perch),* Onchorhychus mykiss *(trout) and* Carassius carassius *(carp); amphibians* Rana spp. *(frogs); bird* Erithacus rubecula (*robin) and mammals* Sciuridae *(squirrels) and* Homo sapience *(human). Figure (B) shows the wavelengths of light emitted from a range of artificial light sources. Some lamps emit light in the UV, and the spectral width varies among lamp types considerably. © Perkin* et al. *(2011).*

Spectrum	Types of lamps	% sales	Colour	UV	CCT	LE	CRI
Narrow	Low Pressure Sodium	37	Orange	0	1807	80-150	NA
Broad	High Pressure Sodium		Orange-yellow	+	2005-2108	45-110	22-80
Broad	High/low Pressure Mercury	27	White	++	2766-5193	25-52	22-43
Broad	Metal Halide	36	White	++	2874-4160	45-150	65-95
Broad	Light Emitting Diode	NA	White	0	1739-8357	160	>90

Table 1.1. Percentage of most common lamps sold in the EU from 2004 to 2007 (European Commission 2011) as well as their physical characteristics extracted from Gaston al. (2012) and from personal data of Georges Zissis. CCT refers to Correlated Colour Temperature (Kelvin); LE refers to Luminous Efficacy (lumens/W); CRI refers to Colour Rendering Index; NA – data are not available.

The growth of the human population and associated processes of urbanisation have resulted in further increases of ALAN at a rate of about 2–6% per year, resulting in ALAN being identified as an important threat to biodiversity (Hölker *et al.* 2010a; Kyba *et al.* 2017). Further, the switch to cost-effectiveness of LEDs has led to a so-called rebound effect, which describes the phenomenon that the increasing use of inexpensive LED outdoor lighting has further accelerated the spread of ALAN worldwide (Kyba *et al.* 2017).

Eighty percent of the world's population now lives under light polluted skies, and the Milky Way is no longer visible to more than a third of humanity (Falchi *et al.* 2016). The rate by which ALAN increases is faster than the rise in human population and economic growth (Hölker *et al.* 2010b). Although European directives have resulted in HPMV lamps being phased out, changes in and implementation of ALAN is unregulated across much of the EU, either generally, or specifically for bats.

Not only the amount of ALAN is increasing, the spectral content of light is changing too. In 2015, HPMV lamps were banned from new lighting installations in the EU in order to reduce costs and CO_2 emissions. In addition, street lighting is rapidly becoming whiter with many sodium lamps being replaced by LEDs, and to some extent by metal halide lamps both of which provide better colour rendition for humans. But, they still include light spectra (UV, blue light) with negative impacts on insects, bats main prey. There are potential benefits to these changes: new technology street lights are programmable from a central control centre, so their light intensity and timing of operation can be modified quickly and over large spatial scales.

In summary, the nightscape is changing as ALAN becomes more prevalent, and it also changes with technological advances that change lighting spectra. The effects of ALAN in general and of specific lighting schemes in particular on biodiversity, including bats, are currently poorly understood. Yet, it is agreed on by all specialists that bats, being nocturnal, are especially affected by ALAN. In the following chapter, we will summarize the state of knowledge with respect to how bats respond to ALAN.

2 Response of bats to artificial light at night

Early observations by *e.g.* Griffin (1958) and Roeder (1967) of bats chasing moths at street lights, which at that time usually were of the light-bulb type, suggests that bats coming near artificial lights to feed is as old as the use of such lights, *i.e.* approximately since the 1920´s. A first quantitative study on the impact of increased levels of natural light on bats was made by Nyholm (1965). He recorded that *Myotis daubentonii* and *M. mystacinus/M. brandtii* consistently avoided their preferred habitats, *i.e.* lakes and forest gaps, in response to the brightness of the Nordic midsummer nights. However, his observations did not include areas illuminated by artificial light, which were still few at that time, but highlighted the relevance of light for the overall activity and habitat use of bats. Soon naturalists and bat biologists observed differences in the way bat species responded to ALAN, and these behavioural differences were most often related to specific flight styles, *i.e.* fast-flying species were found to be more opportunistic to ALAN than slow-flying and hovering species. These differences were explained by the specific capability of species to avoid visually-oriented predators such as birds of prey (Rydell *et al.* 1996). Some bat species were also observed being attracted to ALAN because they feed on insects lured by the artificial light source (Rydell 1991). Following this attraction and avoidance scheme, bat species have been grouped into classes of species which are “sensitive to light” and those which are “tolerant to light” or even “attracted to light”. However, Rowse *et al.* (2016a) recently suggested a reconsideration of this simplistic categorization. For a proper assessment of the impact of ALAN on bats in specific situations, several other factors must be considered.

Bats have evolved in darkness or dim light throughout their history and have become adapted to a nocturnal life over millions of years (Rydell & Speakman 1995; Voigt & Lewanzik 2011). Darkness is the principal protection against predation for bats in most situations. A comprehensive review of predation on bats at roosts and elsewhere was recently provided by Mikula *et al.* (2016). Bats are preyed on by various predators under many different conditions, both inside roosts and in flight. The activity patterns of bats and eventually their survival and reproduction rates are often constrained by predation (Speakman 1991). Emergence and foraging behaviour of individual bats are most likely governed by simple rules of optimality, such as the trade-off between the expected costs, including energetic costs of locomotion and predation risk, and the likely benefits of foraging such as energy intake. Yet, this relationship is far more complex, since it depends on various circumstances. First, the response of a bat to ALAN depends on its nutritional status, which in turn is influenced by *e.g.* reproductive state, sex and age. According to a study on emergence time in three European species, bats emerge relatively early, and hence take higher risks, when being under nutritional stress due to persistent low ambient temperatures, during pregnancy, or when body reserves were low (Duvergé *et al.* 2000). Second, the responses to ALAN also depend on the specific location of bats and the specific motivation of bats for their presence in a habitat, *i.e.* the quality and functional relevance of a habitat. Third, natural or artificial light at any particular location may affect insect availability, as well as the presence of competitors and predators, and these factors influence the presence of bats (Rydell *et al.* 1996). Finally, wavelength, intensity and directionality of the light may be important as well (Mathews *et al.* 2015). In summary, the effect of ALAN on bats depends both on species and context (Fig. 2.1).

ALAN may make a location less attractive for one species, but more attractive for another, supposedly even resulting in competitive exclusion of some light-averse species (Arlettaz *et al.* 2000). On a larger scale, extensive use of ALAN along

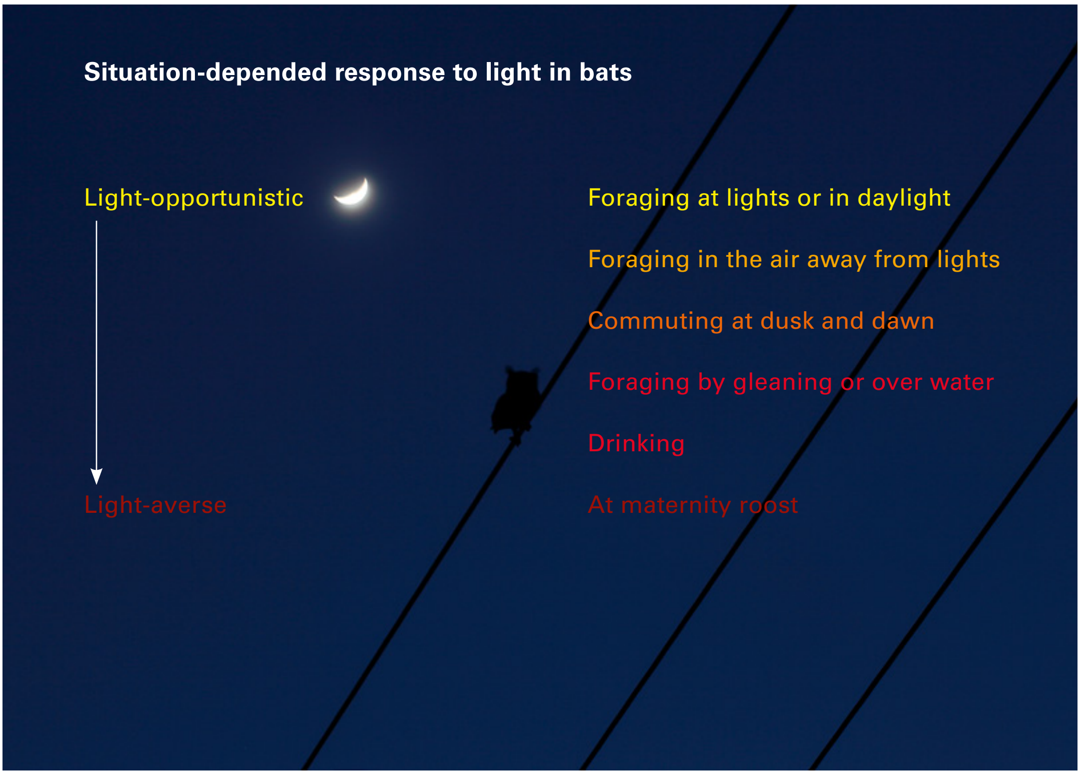

Figure 2.1. A hypothetical example illustrates the context-dependent response of opportunistic and light-averse bats. Note that a single species may display all responses and that these responses may vary seasonally because of factors such as reproduction, migration and hibernation (© J. Rydell).

with urbanisation in general may change bat species composition dramatically over large areas. Consequently, the relatively species-rich communities in unlit areas may be replaced by species-poor communities of opportunistic species that increase in abundance in relation to the intensity of ALAN, resulting in a simplification of the local bat fauna (*e.g.* Gaisler *et al.* 1998; Schoeman 2015; Russo & Ancilotto 2015; Lewanzik & Voigt 2016).

2.1 Impacts of ALAN on insects

European bats in general depend on insects for food and in order to understand the response of bats to ALAN, it is important to know how nocturnal insects respond to ALAN. Most nocturnal insects show phototaxis, that often involves considerable attraction towards and trapping of individuals at artificial light sources (Altermatt *et al.* 2009; Perkin *et al.* 2014; van Grunsven *et al.* 2014; Verovnik *et al.* 2015). Short wavelength emissions in the blue (< 490nm) and UV ranges (< 380nm) are responsible for this "flight-to-light" behaviour because most nocturnal insects have a peak of visual sensitivity in the UV, green and blue portion of the wavelengths spectrum (van Langevelde *et al.* 2011; Somers-Yeates *et al.* 2013; Pawson & Bader 2014). Hence, UV-emitting lamps such as HPMV, metal-halides and compact fluorescent lamps, attract significantly more insects than LED and HPS lamps, which emit less UV (Somers-Yeates *et al.* 2013; van Grunsven *et al.* 2014; Wakefield *et al.* 2016; 2018). Nevertheless, LED and HPS lamps have broad spectrum emissions including wavelengths in the blue range. Blue range has been shown to attract significantly more insects than yellow range light (Verovnik *et al.* 2015). In one study, both "cold" and "warm-white" LEDs attracted significantly more insects than HPS lamps (Pawson & Bader 2014). But, Eisenbeis (2013) found that LEDs attracted fewer insects than HPS and another study (Wakefield *et al.* 2018) reported no difference in the attraction of flying insects to LED and HPS lamps (though LEDs attracted more insect families).

The attraction effect of HPS lamps has been reported to work up to 23m from street lights for moths and 40m for aquatic insects (Perkin *et al.* 2014; Degen *et al.* 2016). Because the typical distance of municipal street lights for roads in the EU ranges between 20 and 45m, it is likely that moths crossing an urban road will be trapped in the zone of street light interference, which causes a further fragmentation of the night habitat, and may reduce landscape connectivity (Degen *et al.* 2016). Overall, ALAN appears to generate an accumulation of insect biomass in illuminated patches and may induce a depletion of insects in dark areas near street lights or other outdoor luminaries, a so called "vacuum cleaner effect of illumination" (Eisenbeis 2006, Verovnik *et al.* 2015). This shift in the spatial distribution of insects induced by ALAN likely triggers cascading impacts on their predators including bats, as it generates high quality foraging patches for opportunistic species, while decreasing the size and quality of dark areas for light-sensitive species (*e.g.* Manfrin *et al.* 2018).

The attraction effect of ALAN to insects likely causes massive mortality as individual insects can be killed directly by the heat of lamps, or they may circle the light until exhaustion, or until being caught by predators (Eisenbeis 2006). In particular, natural as well as artificial light inhibits the evasive flight response of tympanate moths to bat echolocation calls, leading to an increase in the predation success of bats at *e.g.* street lights (Svensson & Rydell 1998; Svensson *et al.* 2003; Wakefield *et al.* 2015).

Additionally, ALAN probably reduces the reproduction success of exposed insect populations as it reduces sex pheromone production and inhibits mating in moths (van Geffen *et al.* 2015a, 2015b). These adverse impacts on moth reproduction occurred regardless of the wavelength spectrum of the lamp, suggesting a negative effect of ***illuminance*** on moth populations (van Geffen *et al.* 2015b). Furthermore, exposure of moth caterpillars to green and white lights probably decreases individual fitness by inducing a lower body mass of caterpillars and pupae and an advance in the date of pupation compared to conspecifics from red light and dark conditions (van Geffen *et al.* 2014).

Finally, many arthropods use celestial cues such as the moon, stars or skyline, for orientation (Dacke *et al.* 2013; Schultheiss *et al.* 2016). Hence, ALAN, including ***skyglow*** above cities, may negatively impact the dispersal movements of populations by masking natural lighting signals at night, with important implications for metapopulation dynamics and gene flow (Baguette *et al.* 2013; Kyba & Hölker 2013). Further, ALAN may also impact the fitness, mortality, and reproduction of insects which may ultimately induce long-term population declines in illuminated areas. Common macromoths in the UK have experienced major declines in recent decades (Conrad *et al.* 2006), and it has been hypothesized that urban areas and their associated ***skyglow*** may act as ecological sinks, depleting the surrounding landscapes of moth species (Bates *et al.* 2014). Thus, the widespread use of ALAN may induce a landscape-scale depletion of insect biomass, which in turn may negatively affect bat population trends by decreasing the amount of foraging resources (Azam *et al.* 2016).

Artificial lights may also inhibit the entire flight activity of nocturnal moths and other insects, because the conditions near the light source may simulate daylight or strong moonlight, both of which normally lead to inactivity in nocturnal moths (Williams 1936). If lit conditions persist continuously in an area, nocturnal insect activity may be expected to decline for this reason alone. In addition, bats prey upon such inactive moths sitting directly in the illuminated building walls (Verovnik *et al.* 2015).

The long-term impact of ALAN on insect populations is largely unknown, however, but recent evidence of dramatic declines in moths and other insects in Western Europe are quite alarming and suggest that the effect is already serious (Conrad *et al.* 2006; Hallman *et al.* 2017). Part of the observed decline can be linked to the increasing use of ALAN because larger moths and other phototactic insects are affected more seriously than others (*e.g.* diurnal or non-phototactic) insects (van Langevelde *et al.* 2018). Ecosystem services such as pollination provided by nocturnal insects are disrupted seriously in lit areas but not in nearby unlit control areas (Macgregor *et al.* 2016) and may even have knock-on consequences for diurnal pollination interactions (Knop *et al.* 2017). In the long run, general decline in insect populations will obviously have negative effects on bats as well as on many other animals and perhaps on entire ecosystems.

2.2 Light averse and opportunistic bat species

Overall, European bats are all well adapted to nocturnal conditions, including a need for protective cover provided by darkness, and it can be expected that ALAN affects them in most situations (Rydell & Speakman 1995).

At the genus level, European bats can roughly be categorized according to the way they respond to ALAN (Table 2.1). This taxonomic simplification seems acceptable, because species of the same genus appear to show a similar response to ALAN, probably owing to similar wing morphology, habitat requirements and life history features. We distinguish between averse, neutral and opportunistic responses. An averse response means that the bat would normally avoid ALAN. A neutral response means that ALAN would not influence the spatial distribution and activity of a bat. An opportunistic response means that the bat turns towards locations with ALAN under certain conditions, for example for feeding, as the expected benefit due to higher insect density near artificial lights may outweigh the potentially increased predation risk. Such species may dominate at illuminated places. We avoid applying the terms "light-tolerant" or "light-exploiting" to bats, because they overlook the fact that the reaction of a species can be different, depending on multiple factors. Even species that readily forage on insect aggregations around street lights might avoid artificial light when commuting (Hale *et al.* 2015) or close to their roost (Downs *et al.* 2003).

Bats of some genera (*Nyctalus*, *Vespertilio*, *Miniopterus* and *Tadarida* spp.) typically feed and commute in the open space above vegetation and buildings and may only sometimes fly under or near street lights or floodlights. We have denoted these bats with n.a. (not applicable), although we acknowledge that they may still exploit insects attracted to ALAN by feeding above lit urban areas or illuminated infrastructure elements, *e.g.* at floodlights on airports, train stations and stadiums (*e.g.* Kronwitter 1988, Rydell 1992, Russo & Papadotou 2014). Hence, they may be considered as "opportunistic", like the pipistrelles and the species of the genus *Eptesicus*, although their behaviour usually is less obvious when observed from the ground. They usually fly at heights above the directly lit zone but within the area influenced by ***skyglow***. Information concerning response to ALAN during long distance ***migrations*** is available only for a few species of the genus *Pipistrellus* (Voigt *et al.* 2017), therefore we did not include migratory behaviour in Table 2.1. We consider maternity roosts, mating roosts and ***swarming*** sites as "roosts", but temporary night roosts used by single or only a few individuals are excluded, since there are no quantitative studies estimating the effect of ALAN at night roosts.

Genera	Daytime Roosts	Commuting	Foraging	Drinking	Hibernacula
Rousettus	Averse	Neutral	Neutral	Averse	Averse
Rhinopoma	Averse	DD	DD	Averse	Averse
Rhinolophus	Averse	Averse	Averse	Averse	Averse
Barbastella	Averse	Averse	Averse	Averse	Averse
Eptesicus	Averse	Averse	Opportunistic	Averse	Averse
Pipistrellus and *Hypsugo*	Averse	Neutral/ opportunistic	Opportunistic	Averse	Averse
Myotis	Averse	Averse	Averse	Averse	Averse
Plecotus	Averse	Averse	Averse	Averse	Averse
Vespertilio	Averse	DD	n.a./opportunistic	Averse	Averse
Nyctalus	Averse	DD	n.a./opportunistic	Averse	Averse
Miniopterus	Averse	DD	n.a./opportunistic	Averse	Averse
Tadarida	Averse	DD	n.a./opportunistic	Averse	Averse

Table 2.1. The likely taxon-specific response of bats to ALAN in relation to specific situations. The table is based on available literature and personal observations of the authors. Note that Nyctalus azoreum, *as well as* Eptesicus nilssonii *in the far north, may fly in broad daylight. N.a. = not applicable, DD = data deficient. Averse, neutral and opportunistic are defined in the text.*

2.3 Two illustrative cases of bat responses to ALAN

The complex response of bats to ALAN may be illustrated by the behaviour of two species that have been studied in detail, the notch-eared bat *Myotis emarginatus* and the northern bat *Eptesicus nilssonii*.

Although *M. emarginatus* belongs to the light-averse group, it occasionally forms maternity colonies in barns and attics that are sometimes brightly illuminated (Fig. 2.2). Nevertheless, when entrances to such maternity roosts are illuminated, notch-eared bats may emerge later than usual (Moermans 2000), which may reduce the total time available for foraging per night. This can lead to a slower growth of the young (Boldogh *et al.* 2007). In the Netherlands, radio-tagged *M. emarginatus* commuted in or above the canopy, thus avoiding lit areas, but can be seen foraging inside both lit and unlit stables (Dekker *et al.* 2013). Presumably, this dualism in response depends on the trade-off between feeding success and either real or perceived predation risk for various habitats. For *M. emarginatus*, the perceived predation risk is probably lower inside than outside stables.

Considered as relatively light-opportunistic, *E. nilssonii* often forages along rows of street lights (patrolling), where individuals sometimes establish and defend feeding territories (Fig. 2.3). However, they only occasionally dive into the light cone in pursuit of an insect. Such dives are short (less than one second) and unpredictable to a

Figure 2.2. Cluster of notch-eared bats Myotis emarginatus *in a maternity roost in the Netherlands, 2016 (© J. Dekker).*

Figure 2.3. The northern bat Eptesicus nilssonii *diving into the light cone of a mercury vapour streetlamp in Sweden (© J. Rydell).*

human observer. While patrolling, northern bats typically fly away from the lights, being very difficult to spot from any direction and hidden from predators. Hence, even this presumably light-opportunistic species may avoid unnecessary exposure to bright illumination (Rydell 1986, 1991).

2.4 Impact of exterior illumination on bat roosts in buildings

Aesthetic illumination of buildings has increased dramatically in Europe over the last 25 years. This is particularly true for churches, monasteries, castles, but also for old bridges, fortresses, towers and monuments (Fig. 2.4). Recently, the lighting of private houses, factories and other buildings has become a widespread practice. Conflicts between the human demand to illuminate such buildings and the protection of bat roosts are already apparent and expected to increase in future.

Numerous studies have reported negative effects of illumination on the persistence of bats inside the roost, on emergence timing, behaviour, foraging activity and on juvenile growth rates have been detected (Boldogh *et al.* 2007; Fuszara & Fuszara 2011; Zagmajster 2014; Kosor 2016; Kotnik 2016; Zeale *et al.* 2016).

Figure 2.4. Illumination of historical buildings repels bats from roosting in large attics. Wroclaw Historical Centre, Poland 2017 (© J. Rydell).

Regardless of bat species, maintenance of dark areas is particularly important around the entrances to maternity roosts, because these places are used consistently by many individuals over the critical periods of pregnancy, parturition and lactation. Maternity roosts are also places where the young learn to fly and where sit-and-wait predators such as owls or cats may pose a serious threat to bats (Downs *et al.* 2003). Therefore, special attention should be given to buildings with maternity roosts.

Short term effects. The effect of illumination on bat roosts has been studied for churches in several countries, ranging from Slovenia to Sweden and from the United Kingdom to Hungary. Although comparable studies for other types of buildings are missing, similar effects can be expected for constructions akin to churches.

Illumination of buildings with roosts exposes bats to increased predation risk, which in turn disrupts their emergence activity and results in deteriorating foraging opportunities. This applies especially to light-averse species such as *Rhinolophus* spp. and *Myotis* spp. (Boldogh *et al.* 2007; Zagmajster 2014; Kosor 2016; Kotnik 2016; Zeale *et al.* 2016), but also to bats of the genus *Pipistrellus* and *Eptesicus* that often feed opportunistically at lights (Downs *et al.* 2003; Fuszara & Fuszara 2011). However, the effects of ALAN on the emergence and activity patterns are also influenced by the presence of surrounding protective trees as well as the intensity, shading, direction and colour of the light close to the roost (Downs *et al.* 2003; Zagmajster 2014; Kosor 2016). When a colony may use several exits, illumination may affect bats differently. Overall, the magnitude of detrimental effects may be weaker when bats could use alternative unlit exits (Zagmajster 2014).

Bright illumination of roosts may cause a sudden decline in the number of emerging bats, as observed in a colony of notch-eared bats in Hungary (Boldogh *et al.* 2007). This decline could indicate that the bats either abandoned the roost or they were entombed inside and, in the latter case, may eventually starve (Zeale *et al.* 2016). Indeed, in several cases artificial illumination forced bat colonies to completely abandon roosts (Boldogh *et al.* 2007).

Long-term effects. Although long-term effects of illumination on bat colonies in buildings can be expected, there is only a single study addressing this topic by comparing colony presence in churches over a period of 25 years. In the 1980s, Rydell (1987) investigated 61 country churches in southern Sweden for the presence of *Pl. auritus*, before any floodlights were installed in this area. The same churches were then surveyed again in summer 2016, when about half of the churches had become illuminated at least partially (Rydell *et al.* 2017; Fig. 2.5). The percentage of churches with bat colonies had decreased by 38% in 2016 and all of the abandoned churches had been fitted with aesthetic lights (floodlights) in the period between the surveys, strongly suggesting that the illumination was causative for the disappearance of bats. Alternative explanations, such as renovations and targeted attempts to exclude bats from roosts, could be ruled out as a reason for colony collapses.

Bats were affected differently if churches were completely or only partly illuminated. For example, *Pl. auritus* were less often observed in churches that were illuminated from all directions, compared to those that were only partly illuminated (Rydell *et al.* 2017). Illumination of buildings from all directions may be particularly detrimental since bats have no dark exits to emerge from, and no dark flyways between the roost and the surrounding areas. In the churches that remained unlit, all colonies of *Pl. auritus* remained in the same place after 25 years, hence showing consistent site fidelity. This study clearly shows that, in the long run, floodlights pointed towards buildings can have a devastating effect on the bats that live in the illuminated building. A smaller decrease in colony numbers was detected when at least part of the building was left dark for the bats' emergence and return. In a three-year study on emergence behaviour of *R. hipposideros* at church roosts, researchers observed differences in the proportion of emerging bats in relation to the level of illumination at roost openings (Zagmajster 2014). A significantly higher proportion of bats exited at the belfry opening closer to the woodland when it was shaded, while when heavily illuminated, a higher proportion of bats used the darker opening directed away from the woodland (Zagmajster 2014).

Disappearance of bats from lit buildings may not be obvious over the short term, as bat colonies are unlikely to abandon favourable roosts quickly. Indeed, *R. hipposideros* and *Pl. auritus* may remain in lit buildings for some time, despite the detrimental effects of ALAN, owing to the bats' extraordinary site fidelity (Zagmajster 2014; Rydell *et al.* 2017). The observation that some of the long-eared bats consistently returned to partly lit churches may be a consequence of the limited number of

Figure 2.5. Three examples of churches in Sweden included in the 2016 survey of Rydell et al. (2017). All had maternity colonies of Plecotus auritus *in the 1980´s.* ***(A)*** *Bats remained in some of the partially illuminated churches, when they could leave from and return to the roost without having to pass through the light cone.* ***(B)*** *Bats disappeared from churches that were illuminated from all sides, without any dark passage left. In this case, lights were also installed inside, where the bat colony lived previously.* ***(C)*** *Bats consistently remained in churches that were not illuminated by flood-light. (© J. Rydell).*

high-quality roosts for this species (Rydell *et al.* 2017). Fidelity of *R. hipposideros* to illuminated roosts has been attributed to a trade-off between the disadvantage of increased predation risk at the lit sites and the advantage of having high-quality feeding grounds unaffected by ALAN in the surrounding environment (Zagmajster 2014).

2.5 Impact of interior illumination on bat roosts in buildings

Lights installed inside lofts or church towers occupied by bats have a detrimental effect on bat colonies, even if these lights are only dim. A colony of *Myotis nattereri* in England did not emerge from the roost inside a church for several days after it was experimentally illuminated. The experiment had to be stopped to avoid starvation of bats and the potential collapse of the colony (Zeale *et al.* 2016). In Sweden, several colonies of *Pl. auritus* disappeared after the installation of light bulbs inside attics and church towers (Rydell *et al.* 2017). In Slovenia, the monitoring of a nursery colony of *R. hipposideros* in a church attic revealed that bats avoided the part of the attic that was illuminated by the sun during the day and by ALAN through a roof window during the night (Kotnik 2016).

2.6 Artificial light in underground roosts

Underground sites, such as caves, mines, drainage pipes and similar subterranean structures are crucial for European bats (Mitchell-Jones *et al.* 2007). Some underground structures such as caves and mines are often open to the public, particularly tourists and therefore are frequently illuminated, but empirical studies on bats using illuminated underground roosts are scarce. *M. bechsteinii* refused to leave the interior of an underground mine after the installation of illumination at the entrance (Kugelschafter pers. comm., in Zeale *et al.* 2016). As a general observation, bats rarely, if ever habituate to artificial lights in underground sites and likely desert illuminated parts of show caves. For instance, commercial use of Fourth Chute Cave in Quebec, Canada, resulted in abandonment of the largest hibernaculum of eastern small-footed Myotis *M. leibii* known at the time in eastern North America (Mohr 1972). High light intensities have the most detrimental effect on the activity of bats, when Mann *et al.* (2002) explored behavioural responses of a maternity colony of 1,000 Cave Myotis *M. velifer* at an underground site by experimentally exposing the colony to cave tours. However, it is usually impossible to disentangle the impact of artificial light in show caves from associated factors, such as noise and changes in temperature and humidity.

Figure 2.6. A root cellar in Latvia regularly used by hibernating brown long-eared bats. (© J. Rydell, 2014).

A special case may be the root cellars traditionally used in northern Europe for storage of potatoes and other root vegetables over winter. These cellars are also used by hibernating bats such as brown long-eared and northern bats (Vintulis & Petersons 2014). Temporary illumination of the interior of such cellars by light bulbs is tolerated by bats, presumably because the light is switched on for only a few minutes at a time (Fig. 2.6), yet long-term or comparative studies on this topic have not yet been undertaken.

2.7 Commuting routes and feeding areas

ALAN may affect the ***commuting routes*** of bats. The effects of light on commuting *M. dasycneme* were experimentally studied by placing a strong lamp (1 kW) along existing ***commuting routes*** (Kuijper *et al.* 2008). The artificial light reduced the percentage of ***feeding buzzes*** by more than 60%, although the abundance of insects tended to increase. Experiments at hedgerows at eight sites in southern Britain indicated that *R. hipposideros* reduced their activity in proximity of light sources (HPS lamps) and delayed the onset of commuting behaviour (Stone *et al.* 2009). The number of commuting bats declined even for bats on the dark side of a hedgerow, indicating that even low levels of light (in average 4.2 lx at 1.75m above the ground) have a negative effect on the commuting behaviour of this species (Stone *et al.* 2009). LED lights also reduced the commuting activity of *R. hipposideros*, even when the lights were dimmed to 3.6 lx at 1.7m above the ground (Stone *et al.* 2012).

Installation of ALAN had a substantial effect on the commuting behaviour of free-flying little brown bats (*M. lucifugus*). Apparently, ALAN prevented bats from flying into the illuminated area and made the flight situation more complex, resulting in a dramatic failure of orientation (McGuire & Fenton 2010). Recent studies revealed that even *P. pipistrellus*, the most common bat species in European cities, avoids highly illuminate areas when commuting even though this species tolerate ALAN when foraging around street lights (Alder 1993; Limpens *et al.* 1997; Verboom & Spoelstra 1999; Hale *et al.* 2015).

Street lights may have two principal effects on bat foraging. The first one is direct, as ALAN may repel light-averse bats from lit areas and restrict their use of commuting or feeding space. Indeed, rows of lights may form barriers which fragment the landscape and constrain flyways and therefore also the use of roosts and feeding grounds (Stone *et al.* 2009, 2015b; Mathews *et al.* 2015; Rowse *et al.* 2016a; Hale *et al.* 2015). Street lamps along roads might also act as fatal traps by increasing bat mortality due to more frequent collision with vehicles, an aspect that awaits investigation (Stone *et al.* 2015a; Fensome & Mathews 2016). The second one is indirect, as street lights may attract insects and thus influences availability and abundance of prey (see Chapter 2.1).

Generally, ALAN may be exploited by bats in diverse ways, depending on the species, as illustrated in Fig. 2.7. The smaller and more manoeuvrable species generally fly lower and closer to the light source, while the larger and faster species usually fly higher and cover wider areas. How the largest and fastest bats such as *Tadarida* spp. exploit urban areas at high altitudes is generally unknown, although there may be considerable activity of bats above city centres.

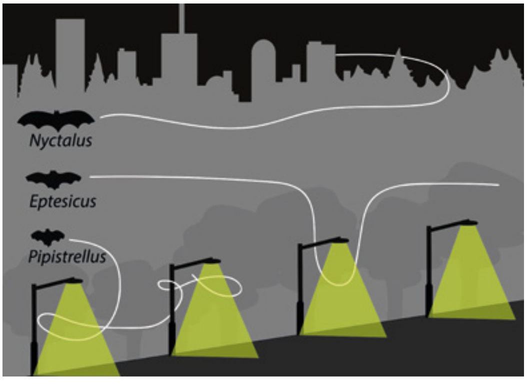

Figure 2.7. A general scheme showing how the size and wing shape relates to the way bats of different genera typically exploit a row of street lights. The smallest bats, e.g. P. pipistrellus, *normally use only one or a few lights at a time and spend some time in each light cone. Bats of the* genus Eptesicus *usually patrol the entire light row and make short and quick dives into the light cone in chase for insects, typically moths. Bats of the genera* Nyctalus *and* Vespertilio *are seldom seen in the light cones of small streetlamps, but occasionally at larger light sources, such as floodlights (© J. Eklöf).*

Stadiums, train stations, harbours and airports are often illuminated with very strong floodlights. There are early observations of bats hunting under floodlights of airports (Gould 1978), later confirmed for flood lights at stadiums (Schoeman 2015). Hunting for insects at such strong lights is observed in free-tailed bats (*Molossidae*) and sheath-tailed bats (*Emballonuridae*), particularly in the tropics. Such behaviour is also shown by other fast-flying species, *e.g.* the *V. murinus* and the *N. noctula* and *N. leisleri*.

Waterways, such as canals, streams and rivers, are important flyways and feeding sites for a diversity of bats. In particular, trawling mouse-eared bats, such as *M. daubentonii*, *M. dasycneme* and *M. capaccinii* are among the most light-averse bat species (Jones & Rydell 1994, Kuijper *et al.* 2008). Lighting of waterways and associated structures, *e.g.* valve bridges and locks, for aesthetic purposes may therefore have serious negative consequences for these species (Kuijper *et al.* 2008).

Drinking sites are important for a variety of bat species, particularly those in Mediterranean, semi-arid and arid areas, and probably for most or all female bats during lactation. Exposing these sites to ALAN has serious negative consequences for bats, almost regardless of species. Russo *et al.* (2017) illuminated ponds in Italy with a strong floodlight and found a negative effect on the drinking activity of all local bats, even on opportunistic species such as *P. kuhlii*. It is likely that bats at drinking sites are also affected when lighting levels are much lower. This applies not only to ponds in arid areas, but also to small bodies of water in forests. The widespread use of artificial lighting along rivers, canals or lake shores may therefore have severe consequences for bats and this fact should be considered whenever illumination of water bodies is planned or installed.

2.8 Effects of ALAN on bat communities

ALAN causes species-specific responses (Rydell 1992; Stone *et al.* 2009; Lewanzik & Voigt 2017), which could cause displacement of species (Polak *et al.* 2011; Stone *et al.* 2015b). For example, a competitive relationship between two bat species that respond differently to ALAN may possibly drive changes in local bat populations (Haffner & Stutz 1984/85; Arlettaz *et al.* 2000). In extensively lit areas, the light-averse species of bats may disappear, at the same time the abundance of opportunistic species may increase when competition is reduced. In the long run, this effect may alter local bat assemblages (Ancilotto *et al.* 2015; Schoeman 2015).

3 General aspects of the planning process

The increase of ALAN affects bats and ecosystems at various scales, reaching from local effects to regional or even global levels. Consequently, protective measures for bats should be integrated into planning and policy processes on all these spatial scales. Particularly, addressing the negative impacts of ALAN on bats (and other protected species) for all functional habitats should be a constituent and explicit part of national planning frameworks. The details of these measures should follow the principles of the mitigation hierarchy – starting with avoidance, then mitigation and lastly compensation (Chapter 5). To achieve this, at the national level the impact of ALAN should be incorporated in the state's ***Strategic Environmental Assessment*** (SEA) to detect environmental conservation problems in plans and programmes. The national implementation of ***SEA*** should then be included into regional and local plans and strategies.

Planning policies at the regional and local level deal with a broad range of issues, including economic development, transport, housing, environment and energy. Consequently, the plans and strategies at this level of governance have potential for adversely affecting the conservation status of protected species. The guidance produced for planning authorities at these levels of governance needs to address how to deal with conflicts between the provisioning of ALAN for humans and the conservation of our natural heritage. By considering possible conservation issues at an early stage in the planning process, conflicts between stakeholders can be avoided or reduced. At the regional or local level this should be achieved through ***Environmental Impact Assessment*** (EIA). GIS-based approaches (Fig. 3.1), *e.g.* the online application available at https://www.lightpollutionmap.info (Fig.3.2) may help to identify areas of potential conflicts. Guidance for carrying out ***EIAs*** around infrastructure construction or other developments should highlight the importance of standardised bat surveys that assess the potential impact of lighting schemes in a methodical manner and oblige developers to employ the mitigation hierarchy (Battersby *et al.* 2010). Where new lighting schemes are unavoidable, it should be mandatory to develop a lighting plan that considers the needs of bats and other wildlife so that a potential negative impact is avoided, or suitable mitigation and post-development monitoring schemes are put in place (Chapter 5).

Impact zone of artificial lighting	**Spatial scale**	**Planning tools for the consideration of lighting schemes**
Migration routes (autumn/spring, long and short distance)	National and regional	• National environmental programmes/regulations; • Regulations/aims of national parks, biosphere reserves, nature parks, Natura 2000 sites • Regulations in national infrastructure projects • Regional conservation plans/landscape plans
Landscape	National and regional	
Commuting route	Regional and local	• Regional conservation plans/landscape plans • Management plans for protected areas (*e.g.* Natura 2000) • Guidelines for ecology assessments surveys • Guidelines for new buildings/developments/ refurbishment • Municipal regulations of o historic buildings o roads o private properties o sport facilities o advertisement o agriculture (*e.g.* greenhouses) o local conservation sites o management plans for caves, parks, green spaces, lakes
Feeding area	Local	
Roost (*e.g.* maternity, hibernation, swarming, mating)	Local	
	Local	

Table 3.1. Summary of spatial scale impacts and planning considerations.

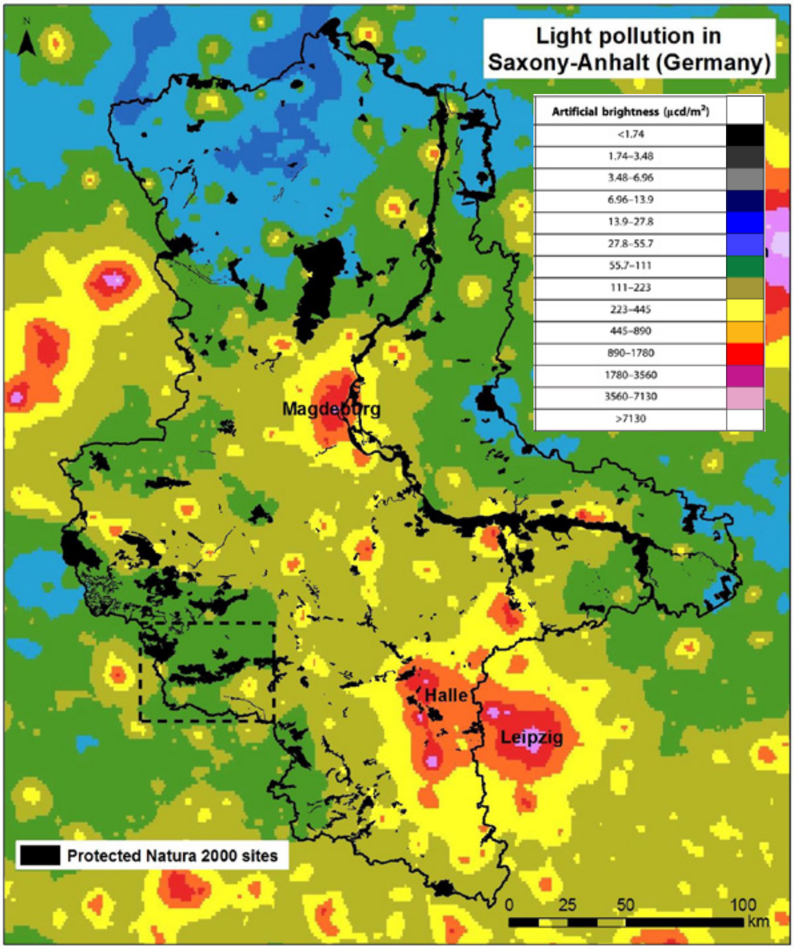

Figure 3.1. GIS map of the German state of Saxony-Anhalt showing Natura 2000 sites and ALAN for identifying zones of potential conflicts between light pollution and protected bat habitats. Dashed line indicates the area of Figure 3.2 (© K. Kuhring & M. Fritze, GIS layer source: F. Falchi et al. *2016).*

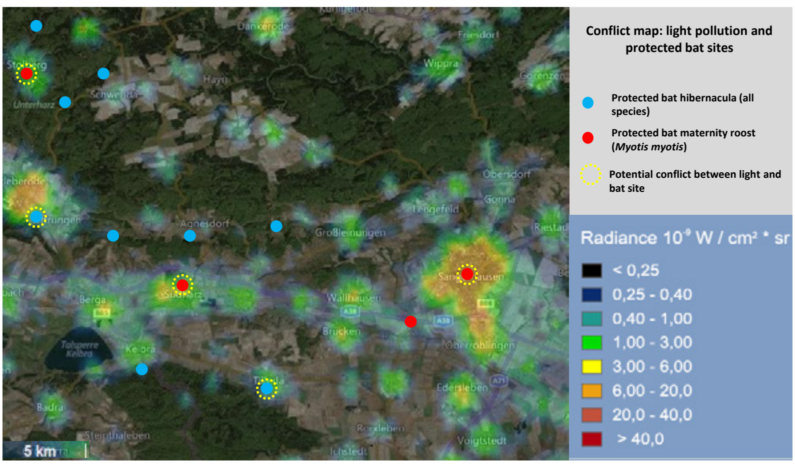

Figure 3.2. A map of the southern Harz in Saxony-Anhalt (local scale) showing protected bat hibernacula and maternity roosts of Myotis myotis *together with ALAN. Mapping may help to identify potential conservation conflicts (© K. Kuhring & M. Fritze, ALAN map source: https://www.lightpollutionmap.info).*

4 Carrying out impact assessments

4.1 General aspects of monitoring and assessment schemes

The most important feature of monitoring schemes, regardless of taxa and context, is a sound research question based in ecological theory, that is tested using a standardised survey technique, with all external factors kept constant (or as close to constant as possible) except for the change in the relevant factor, *i.e.* ALAN. For the assessment of the effects of the impact of a change in lighting, this is typically a before-after treatment assessment, such as counting the number of bats emerging from a roost before and after illumination was installed. A Before-After-Control-Impact approach (abbreviated as BACI) may consider co-varying factors such as the season or the year when multiple factors may change with the light treatment (*e.g.* Rowse *et al.* 2016b, 2018, Lewanzik & Voigt 2017). A standardized survey approach will ensure that other information required for interpreting the results, for example environmental conditions such as lunar cycle, ambient temperature, precipitation, is routinely recorded. More general aspects for surveillance and monitoring of bats can be found in the corresponding EUROBATS guidelines (Battersby *et al.* 2010). In the following, we will focus on specific aspects related to monitoring the impact of ALAN on bats.

4.2 When and where is monitoring important?

Monitoring is needed in all situations where bats are present and an installation or change in artificial light is planned. In some cases, the presence of bats may already be an established fact, especially for large roosts located in buildings, however ***commuting routes*** are usually unknown for these colonies. In most cases exploratory survey will be needed that target the planned change in ALAN. Changes may include the application of mitigation measures, the installation of new illumination, changes in the type of lamps or a modification of the lighting schedule (such as the duration of operation, or seasonal changes in lighting patterns).

Two situations in which the collection of data on the impact of ALAN on bats is particularly important are: 1) changes of ALAN at specific functional bat habitats such as roosts, ***commuting routes*** or ***foraging areas***, and 2) changes of ALAN on the landscape scale that could affect the ability of bats to access ***feeding areas*** and/or alternative roosts. Examples of the second case could include the illumination of river banks and roads.

4.3 Which data should be collected?

The following list provides a general guideline regarding the minimum level of data collection that should be conducted at each site.

General guidelines

- Check whether measures are implemented correctly, in case of the application of mitigation measures;
- Use the same equipment wherever possible, with the same settings, before and after the lighting change;
- Be aware of, and record, additional changes in the vicinity of the location being monitored. For example, habitat alterations which may affect bat activity independent of the effect of lighting.
- Ensure that sufficient data are collected to consider temporal variation in bat activity, *e.g.* from day to day or across seasons. In the case of landscape surveys, automated static bat detectors should be used as these allow efficient data collection over multiple nights;
- The surveys conducted before and after changes to the lighting regime should be performed at the same time of year and in comparable weather;
- When conducting roost surveys, ensure that all exit points are monitored;
- For surveys in the wider landscape away from roosts, conduct surveys over a distance of at least 100 meters, incorporating areas at which the lighting will be changed. Paired control sites where the lighting regime is unchanged should always be included as part of the survey design: this is particularly critical in situations where a before-after comparison is not possible. For a detailed description of how to set up schemes for the monitoring of roosts, see section 3.3 in the EUROBATS guidelines (Battersby *et al.* 2010).
- Surveyors are encouraged to interpret the data they collect to identify patterns of use. For example, peaks of activity at dawn and dusk may indicate proximity to a roost.
- Differences in illumination should be measured and compared with original lighting plans.
- Light meters can be useful, but must be calibrated appropriately, and the same instrument should be used for before- and after-change measurements.
- Another option for quantifying illumination is to use a digital single-lens reflex camera (DSLR) on a tripod. Before and after the change in lighting, photographs should be made from the same spot, with the same DSLR, the same lens, and with the same ISO, image format, aperture, shutter speed and white balance settings (*e.g.* Lamphar *et al.* 2014).

5 Avoidance, mitigation and compensation

As outlined before, ALAN directly affects bats in their activity at night. It is important to keep in mind that ALAN also affects the insects that they feed on. Thus, any consideration of lighting schemes should include both direct and indirect effects, *i.e.* via trophic interactions.

5.1 Avoidance

As a rule, ALAN should be strictly avoided, and artificial lighting should be installed only where and when necessary, *i.e.* when ALAN is needed for safety reasons or to comply with the legal framework. Through careful consideration prior to development of new infrastructure it is often possible to avoid illumination of bat habitats without putting human safety at risk. The protection of dark refuges is essential for bats, particularly in urban areas. Land-use planners and authorities should pay attention to the preservation of dark corridors between roosts and larger unlit, vegetated areas such as urban parks and gardens which might function as the ***feeding areas***. A network of dark corridors would allow bats to commute between roosts and feeding areas without exposure to direct illumination in a landscape that is otherwise fragmented by ALAN (Fig. 5.1). Particularly, in towns where vegetation is scarce and most of the soil is sealed, spatial planning of outdoor lighting and of a 'light-exclusion network', respectively, should be set up concomitantly with the planning of a green infrastructure network. Dark corridors should provide protective vegetation cover, *i.e.* optimally a closed canopy, which helps bats as a leading structure when commuting. Vegetation cover could also provide shade from ***skyglow***. Bright paving materials, that reflects moonlight, help to reduce ALAN since roads and trails are better visible for humans in the twilight. New solar-charged light-emitting materials which could substitute the use of artificial lights at bike paths are being tested (Fig 5.2). Influence of such 'glowing paths' on wildlife has to be evaluated and compared with that of conventional lighting.

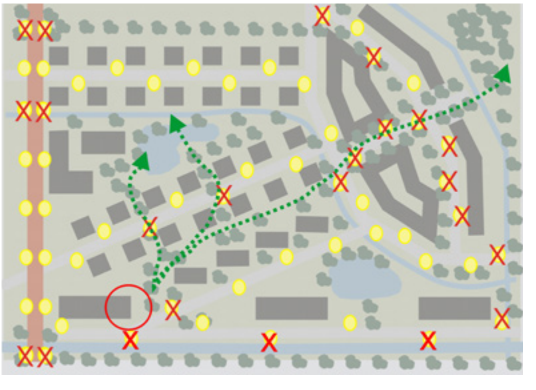

Figure 5.1. Schematic map of a village (dark grey: buildings; light grey: a small road; light blue: water bodies; brown: a large road; green-grey tree silhouettes: locations of trees). Bats emerge from a large building in the lower left corner (red circle) and commute (dashed green lines) along alleys to their foraging areas at a pond and in the forest. It is advised to avoid illumination or shield luminaries at the highlighted areas (red crosses) along treelines, waterbodies/channels and sites where treelines and channels cross the road (© H. Limpens).

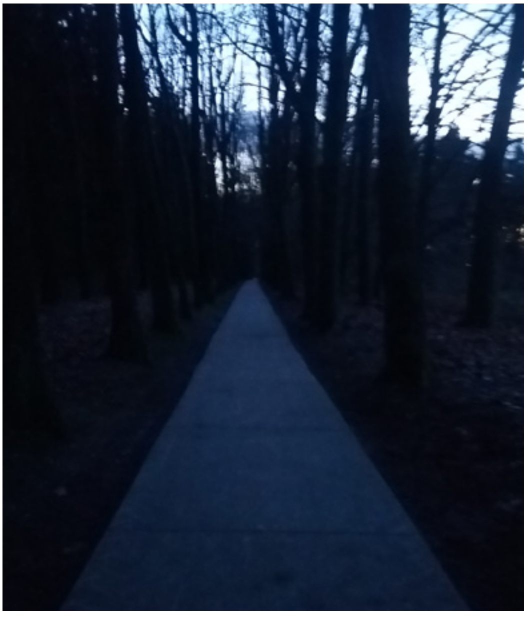

Figure 5.2. *Example of a bicycle trail with a lighter paving material allowing to use it without street lights later in the evening (© H. Limpens).*

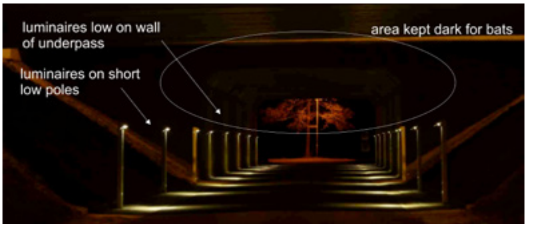

Figure 5.3. Installation of luminaires on short poles for mitigating the effect of ALAN on a commuting route through an underpass in the Netherlands (the same place in daylight and at night). This solution was proven as efficient for P. pipistrellus *but not for the low-flying species* M. daubentonii *(© F. Brekelmans).*

When ALAN is needed for safety reasons, dynamic lighting schemes that are switched on only when needed should be considered. Dynamic lighting schemes are usually triggered via motion sensors by a pedestrian, bicyclist or cars.

Use a minimal number of lighting points and ***luminaires*** on low positions in relation to the ground for minimising ***light trespass*** to adjacent bat habitats or into the sky (Fig. 5.3).

Figure 5.4. Avoidance of light trespass by installing shielded luminaries. Left – conventional luminaire with light spillage into the adjacent forest habitat, right – shielded luminaire that focuses the light cone only on the area where it is needed (© H. Limpens).

Use focused light, *e.g.* by using LED or shielded ***luminaires*** which limit the light flux only to the required areas and prevent ***light trespass*** into adjacent bat habitats (Figs. 5.4 and 5.5).

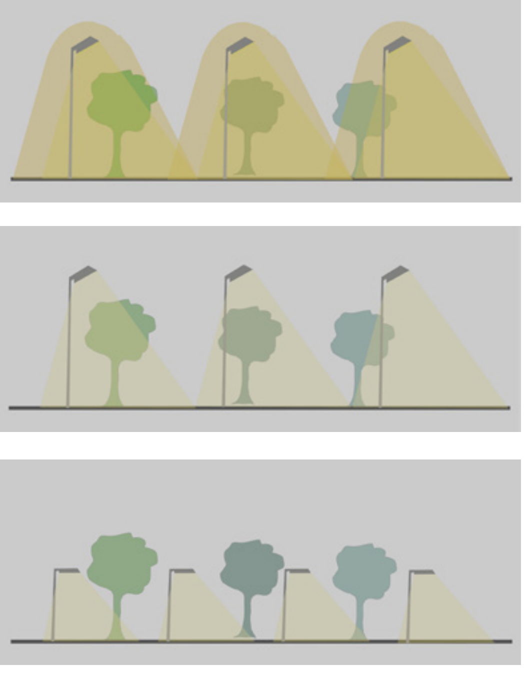

Figure 5.5. Combined effect of shielded luminaires and short poles on reducing light trespass. First picture – unshielded luminaires, second – luminaries with shields. The third picture shows shielded luminaires on short poles which cut-off light trespass and keep adjacent areas dark (© H. Limpens).

Create screens, either by erecting walls or by planting hedgerows or trees, to prevent ***light trespass***, *e.g.* from illuminated roads, to surrounding bat habitats. Screens can reduce the negative effects of ALAN on bats to some degree (Mathews *et al.* 2015; Fig. 5.6, 5.7).

Figure 5.6. In the Netherlands, walls were designed to avoid light trespass from a highway to a wildlife bridge with commuting routes (© H. Limpens).

Figure 5.7. Partially shielded noise screens, installed during the construction of a new motorway in the Netherlands for avoiding light trespass to a compensation area with bat habitats (© V. Loehr).

Exits of bat roosts and a buffer zone around them should be protected from direct or indirect lighting to preserve the natural circadian rhythm of bats. Given that aesthetic light is not required for safety, arguments for such illumination should be reconciled with the need to preserve the nature and nocturnal organisms. Corresponding adjustments to existing artificial lighting should be made.

The following prioritization for areas of conservation concern should be regarded when planning outdoor lighting:

P1: Protected areas (parks, natural monuments) including Natura 2000 sites

- Core zones of protected areas need strict avoidance of any external ALAN, except for inevitable purposes if required by a legal framework (safety). Mitigation measures (Chapter 5.2) must be considered and applied wherever possible.
- In buffer zones around the protected area only long-wavelengths luminaries should be allowed, which do not contribute significantly to ***skyglow***. In buffer zones, light pollution shall be minimised, and further lighting limited (Gaston *et al.* 2015). For unavoidable lighting, mitigation measures must be wherever possible applied. Any light in the buffer zone must be distant enough for ensuring that its ***illuminance*** level at the boundary of the protected area is lower than 0.1 lx, which roughly corresponds to the brightness of a full moon.

P2: Underground and overground roosts

- Strict avoidance of any direct artificial light inside the roost and at its entrances/exits. ***Illuminance*** levels caused by distant lights must be below 0.1 lx at the roost entrances, exits and along the emergence corridors outside the roost (measured by holding a luxmeter in a vertical position at 1.5 m above the ground, measuring perpendicular to the sky, or next to the roost entrance or exit).
- A flyway from the entrances/exits towards nearby unlit hedgerows, treelines or other structures used by bats for commuting must be kept unlit, with light levels below 0.1 lx. If possible, a preferable direction of emerging bats should be investigated beforehand, and the dark corridor accordingly outlined.

P3: Habitats that constitute key feeding areas of light-averse bat species, such as bodies of water (*e.g.* river banks, ponds, canals) and forests

- Strict avoidance of any direct ALAN. ***Illuminance*** levels due to distant lights must be below 0.1 lx.

P4: Habitats that are often used by bats for foraging and commuting, such as urban parks and gardens, the edges of forests, hedgerows and tree lines

- ALAN should be avoided whenever possible. Alternatively, partial lighting or dimming may be used to reduce the negative impact on foraging and commuting bats.

In summary, ALAN should be avoided wherever possible. For any unavoidable artificial lighting at night, adequate mitigation measures (see below) have to be considered and applied wherever possible.

5.2 Mitigation

Careful evaluations of the potential impact of light pollution on bats must be considered prior to any outdoor lighting projects. If artificial light is necessary for social, security or safety reasons, it is of major importance to adopt a "need-based" outdoor lighting planning strategy in order to illuminate only WHEN and WHERE it is actually required (Kyba *et al.* 2014). In this context, limiting the temporal and spatial extent of ALAN is a key issue for mitigating the adverse impacts of light pollution on biodiversity (including bats).

Outdoor lighting planning requires ALAN management through five integrated levels of action that emphasize 1) the spatial arrangement of artificial light sources to enhance connectivity between dark refuges for foraging and roosting in the landscape (see 5.1 Avoidance) and 2) its duration to illuminate only when it is necessary for humans (Kyba *et al.* 2014). Once areas and time periods that actually need to be lit have been defined, outdoor lighting planning should focus on 3) reduction of ***light trespass*** on nearby vegetation through precise directionality of the luminous flux; 4) reduction in the ***illuminance*** of light sources; and 5) adaptation of the spectral composition of the lamps according to the ecological context (Gaston *et al.* 2012; Schroer & Hölker 2016). Outdoor lighting planning recommendations for mitigating the impact of ALAN on ***feeding areas*** and ***commuting routes*** are presented in Table 5.1.

5.2.1 Mitigating the impacts of ALAN on feeding areas and commuting routes

Limiting the duration of night-time lighting (part-night lighting schemes): Public outdoor lighting is responsible for a substantial part of local administration's energy consumption and electricity bills. Following the economic crisis of 2008, many rural administrations across Europe have therefore set up part-night lighting schemes by turning off public outdoor lighting from midnight (± 1 hour) to early morning (05-06 AM). Although these schemes have mostly been set up to reduce local electricity costs, they may effectively mitigate the adverse impacts of ALAN on bats as they allow restoring darkness at a landscape scale for several hours during the night. It may hence give light-sensitive species access to additional ***feeding areas*** and restore landscape connectivity for at least part of the night. However, nocturnal biodiversity is mostly active soon after sunset. Most insect biomass is available at dusk and peak of activity of Microlepidoptera occurs during the first two hours after sunset (Knight *et al.* 1994; Jetz *et al.* 2003). As a consequence, nocturnal insectivores including bats follow the same pattern (Jones & Rydell 1994; Jetz *et al.* 2003). Thus, current part-night lighting schemes appear to fail encompassing the range of activity of most bat species (Azam *et al.* 2015; Day *et al.* 2015). In this context, the dark phase of a lighting scheme must begin within the first 2 hours after sunset to capture more than 50% of nightly bat activity (Fig. 5.8; Day *et al.* 2015). This would be crucial for bats during reproduction and migration. For an entire city or village, such a scheme would likely face resistance from local inhabitants (Gaston *et al.* 2012). However, the emergence of adaptive lighting technologies may open new opportunities for adopting specific part-night lighting schemes at landscape features where bats commute and forage.

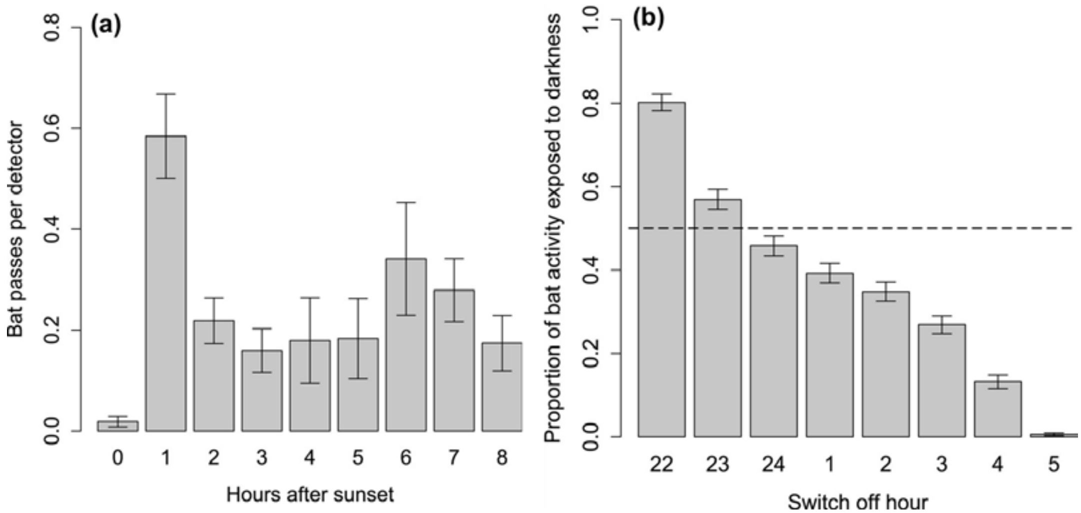

*Figure 5.8. Results of a study in the UK on the activity rhythm of greater horseshoe bats (*Rhinolophus ferrumequinum*) with* ***(a)*** *mean hourly bat passes (±se) across sites and* ***(b)*** *proportion of activity potentially exposed to dark conditions within part-night lighting scenarios. A dashed line represents 50% bat activity in the dark portion of the night (*Day *et al. 2015).*

Dimming illuminance and limiting light trespass: for safety reasons, the European standard EN 13201 recommends illuminating pedestrian pathways and low-traffic roads with a minimum of 7.5 to 10 lx, and commercial areas and access roads with a minimum of 15 to 20 lx. These guidelines conflict with bat conservation as light-sensitive bats avoid areas exposed to even lower ***illuminance*** values (Kuijper *et al.* 2008; Stone *et al.* 2012; Lacoeuilhe *et al.* 2014; Lewanzik & Voigt 2017). Furthermore, many bat species show lunar phobia and reduce foraging and commuting activities during full-moon nights (Saldaña-Vázquez & Munguía-Rosas 2013). In this context, it is important to stress again that exposure to ***illuminance*** as low as full moon (*i.e.* 0.1 lx) may already have a negative impact on bats. Thus, it is probably impossible to define an ***illuminance*** threshold that is compatible with both security standards and conservational requirements. However, the night-time light pollution is often exacerbated by poor lighting designs that emit light in upward and horizontal directions and induce ***light trespass*** (Gaston *et al.* 2012). The trespass may impact significant amounts of natural and semi-natural vegetated patches (Marcantonio *et al.* 2015). Therefore, reducing ***light trespass*** may effectively limit impacts of light pollution on biodiversity, and simultaneously decreasing electricity consumption.

Falchi *et al.* (2011) provide practical recommendations for limiting light pollution in outdoor lighting:

1. Dim light according to actual human usage of a given area to avoid overly illumination. This is particularly relevant for

commercial and industrial areas which are often brightly lit (Hale *et al.* 2013).

2. Use fully shielded ***luminaires*** that have no light emitted above the horizontal.
3. Direct downward light flux only toward the area that needs to be lit. Correcting a luminaire's height can help to focus light and avoid pollution.

These recommendations should help to avoid the vertical illumination of important bat ***commuting routes*** and ***feeding areas*** such as forest edges and hedgerows. Furthermore, controlling luminaires' height could also allow darkness restoration in the upper canopies of trees.

Finally, it is important to note that light reflected from lit surfaces can also induce significant upward light emissions and hence light pollution. For example, in Lombardia, Italy, although 75% of the artificial sky brightness is produced by light escaping directly from fixtures, 25% of it is induced by the reflections off lit surfaces (Falchi *et al.* 2011). Thus, replacing light-reflective surfaces by light-absorbent ones could be an effective way to reduce ***light trespass*** (Gaston *et al.* 2012).

Limiting the short wavelength (UV and blue) content of the light spectrum: In the EU, the most widely used types of light sources for streetlamps are sodium vapour lamps (HPS and LPS), MH and HPMV lamps representing 37, 36, and 27% sales, respectively, for the period 2004-2007 (European Commission 2011). However, since the European Eco-Design Directive (245/2009) became effective, HPMV lamps are being progressively phased out because of their low energetic efficiency (Table 5.1). This change occurs concomitantly with the increased cost-effectiveness of energy-efficient LEDs, representing so far approximately 7% of the European market (Zissis & Bertoldi 2014). HPMV, MH and standard white LED lamps often have broad-spectrum emissions, with an important peak of energy in the blue range and Correlated Colour Temperatures (CCT) > 3000 K.

Short wavelength emissions in the blue and UV ranges are responsible for the "flight-to-light" behaviour of billions of insects (van Langevelde *et al.* 2011) (see Chapter 2.1). During their search for insects, fast-flying aerial-hawking bats such as *Pipistrellus* spp. are therefore more attracted to MH and HPMV than to sodium lamps and white LEDs (Stone *et al.* 2015a; Lewanzik & Voigt 2016). However, although blue and UV emissions may offer foraging benefits for some bat species, they raise environmental concerns as they control melatonin secretions in mammals (Falchi *et al.* 2011, Schroer & Hölker 2016) and likely induce long-term population declines in insect communities (Conrad *et al.* 2006). Furthermore, blue and UV emitting light sources may attract insects from adjacent dark habitats, and thus may lower the quality of these adjacent habitats for bats (Eisenbeis 2006, chapter 3). In this context, it is important to avoid streetlamps emitting "cold-white" light containing wavelengths below 540 nm and with a CCT > 2700 K. It is important to point out that UV light is useless in street lights since it cannot be perceived by humans. Hence, wavelengths in the UV range can be filtered without any decrease in ***illuminance*** level. In contrast to humans, many bats can perceive UV light (Zhao *et al.* 2009, Fujun *et al.* 2012, Gorresen *et al.* 2015). For them, light sources emitting UV waste light presumably appear brighter than light sources with longer wavelength spectra. Consequently, UV-emitting lamps are particularly disturbing for light-averse bats and filtering the UV part of the spectrum may mitigate the effect of ALAN on them.

Nevertheless, it is important to note that slow-flying light-sensitive species such as *Myotis* spp. and *Rhinolophus* spp. avoid illuminated areas regardless of conventional lamp spectra. Negative effects of artificial lighting on their activity have been reported for HPMV (Lewanzik & Voigt 2016), HPS (Stone *et al.* 2009; Azam *et al.* 2015b), and white LEDs (Stone *et al.* 2012). This evidence supports the hypothesis that there are no "bat-friendly" conventional lamp types. Specifically designed light sources can however be an alternative. For example, deterrence of slow-flying bats (*Myotis* spp. and *Plecotus* spp.) and artificial attraction of agile species because of insect attraction (*e.g. Pipistrellus*) in foraging habitat can be avoided by using light with a reduced amount of blue, and an increased amount of red in its spectrum (Spoelstra *et al.* 2017).

Excluding any unwanted effects of any light type or spectrum remains difficult, and it is therefore important to state that darkness is always preferable. However, streetlamps with a pronounced blue content such as "cold-white" LEDs or MH significantly increase light pollution on a landscape scale because blue light is more easily scattered in the atmosphere than green and red lights (Falchi *et al.* 2011). A simulation of a transition from HPS outdoor lighting to white LEDs (4000 K) across Europe revealed a 2.5-fold increase in night sky brightness perceived by a human dark-adapted eye (*i.e.* Falchi *et al.* 2016). Thus, broad spectrum lamps emitting a substantial proportion of their energy in the short wavelength range are likely to exacerbate nightscape fragmentation and induce landscape-scale loss of dark refuges for bats.

New lighting technologies – opportunities and threats: We are currently witnessing an important development in outdoor lighting management as most existing lighting infrastructure is reaching its end-of-life in Europe. In the meantime, the increased cost-effectiveness of LEDs which are highly energy-efficient and have good luminous efficacy, will likely engender an exponential deployment of this technology in outdoor lighting in the coming decade (Zissis & Bertoldi 2014). As with many technological innovations, LEDs not only offer opportunities to limit light pollution, but also potent to increase it (Stanley *et al.* 2015). On the one hand, they can allow light to be directed with unprecedented precision and dimmed, via central management systems, according to human rhythms of activity throughout the night over large scale (Kyba *et al.* 2014). The potential of the adaptability of the spectrum of LEDs can be further explored to reduce impact on natural systems and be used to optimize light for different social contexts. Accordingly, this technology can offer promising options to design outdoor lighting schemes that can limit both the spatial and the temporal extents of ALAN and restore darkness integrity in human-inhabited landscapes. On the other hand, the massive deployment of LEDs in public infrastructure may come with a "rebound effect", characterized by both 1) the introduction of new artificial light sources in previously unlit areas, and 2) the use of brighter and often "cold-white" street lights (Kyba *et al.* 2014, 2017). Therefore, an ecological expertise of outdoor lighting projects will be particularly crucial in the coming decades to ensure that this technological innovation does not increase light pollution (emissions). Additional information on outdoor lighting recommendations can be found on the COST "Loss of the Night Network" website (http://www.cost-lonne.eu/recommendations/).

	Measure	**Recommendations**
Avoidance	*Conserve dark areas*	High priority areas that should remain dark: • protected areas, including roosting and underground hibernation sites • feeding areas (natural areas, vegetation patches) • commuting routes (forest edges, hedgerows, rivers, tree lines)
Only if lighting is necessary, and after an assessment of bat occupancy and patterns of activity within the landscape framework of functional habitats:		
Mitigation	*Part-night lighting*	Turn off public outdoor lighting within **2 hours after sunset** (civil twilight): • Especially during bat reproduction and migration periods • Particular attention within home ranges of maternity colonies
	Dimming	• Adapt dimming strategy to human activities • Keep illuminance levels as low as possible according to EU standards (not going over minimum illuminance required)
	Avoid light trespass	Avoid light trespass over 0.1 lx on surrounding surfaces: • Use fully shielded luminaires • No illumination at or above horizontal • Control street light height, especially along pedestrian pathways and tree lines • Use fewer light sources at points low to the ground • Consider the interaction between light from luminaires and reflecting structures, such as roads and walls
	Adapt lamp spectra	Avoid lamps emitting wavelengths below **540 nm** (blue and UV ranges) and with a correlated colour temperature > 2700 K
Compensation	*Restore dark areas*	No net loss of darkness: • Restore darkness to the same extent as the proportion of dark areas lost • Enhance alternative dark corridors that connect roosts and feeding areas

Table 5.1. Synthesis of the outdoor lighting planning recommendations to limit the impacts of ALAN on bat feeding areas and commuting routes.

5.2.2 Mitigating the impacts of artificial lighting on bat roosting sites

It is paramount to completely avoid artificial illumination at bat roosts. The mitigation measures should be applied only when compelling arguments are present, as absolutely "bat friendly" illumination is impossible (Mohar *et al.* 2014). The proposed mitigation measures should not be regarded as equal alternatives to avoidance, but only as actions with diverse levels of effectiveness for bat conservation. ALAN at bat roosts may originate from sources situated either inside (*e.g.* in caves or church interiors) or outside the roosting structure (*e.g.* external illumination of cultural heritage buildings, or natural rocky walls).

Artificial light outside of bat roosts (see Chapter 2.4): ALAN in front of a roost can affect the evening emergence behaviour and impact ***commuting*** bats (Boldogh *et al.* 2007; Stone *et al.* 2009, 2012). This impact can be reduced by installation of screens or masks that exclude the surfaces with flight openings, and that are directed on the walls of a building to reduce or avoid ***light trespass*** to the environment (Mohar *et al.* 2014). Similarly, light sources illuminating a tree roost exit could be equipped with a shield, which prevents direct illumination of the exit and attributed ***commuting routes***. Wherever exits are already indirectly illuminated, the ***light trespass*** on such surfaces should be stopped. The effectiveness of such measures was studied in a project in Slovenia, on some roosts of *R. hipposideros* (Mohar *et al.* 2014). If a church was illuminated by exaggerated light intensities and light spilled on some flight openings, more bats left the roost from those flight openings that were left dark (Zagmajster 2014). When masks that shaded the illumination of flight opening were installed, bats started to use the shaded flight openings.

Seasonal part-time lighting refers to controlling the illumination according to the season when the roost is occupied by bats. Some churches in Slovenia are lit with external illumination only during the most important religious events, like Christmas and Easter, while during the rest of the year the illumination is switched off. As bats inhabit such churches only during the time of nursery colonies, such a roost can be regarded non-illuminated from the bat perspective (Zagmajster & Hercog, submitted).

Seasonal effects of human impact on bat roosts are more common at places that are visited by tourists throughout specific seasons. For example, the Predjama cave in Slovenia, one of the most important bat hibernation sites in Slovenia (Presetnik *et al.* 2009) is not visited by tourists during the winter. In the case of the Ajdovska jama cave in south east Slovenia, tourist visits and illumination of the cave interior is prohibited in summer, due to the presence of a Mediterranean horseshoe bat (*Rhinolophus euryale)* nursery colony (Presetnik 2004).

The timing of external illumination may also be adjusted on a daily basis. For example, Slovenian guidelines recommend that the illumination should be switched off after 23.00 hours (Mohar *et al.* 2014). This proposal was made mainly to provide enough time for night active moths to leave their resting places near the lights and continue their life cycle, although any effect of this proposed timing on bats was not specifically studied. At least, in case of *R. hipposideros*, *Plecotus macrobullaris* and *Eptesicus serotinus* bats left the roost also under illuminated conditions, but with a delayed emergence time (Zagmajster 2014; Zagmajster, unpublished data). However, switching the lights on later in the night can present a new light barrier when bats return to the roost; especially when mothers return to feed the juveniles. However, there is no empirical evidence that a temporary illumination scheme is less impairing for bats than continuous lighting. Therefore, the regime of part-time lighting should be avoided in favour of total darkness (Boldogh *et al.* 2007) or evaluated before applied on a larger scale.

Artificial light inside bat roosts (see Chapters 2.5, 2.6): Internal illumination of roosts may occur both in buildings (both at the above- and underground level) and natural underground sites (*e.g.* caves). When lights are installed close to bat roosts, *e.g.* in the attics of a church, they are often used only during the visit of maintenance staff. In such cases, if unavoidable, only weak and highly directed light sources should be installed inside buildings or other structures with roosts. It should only provide sufficient light for short term visits by humans, but without trespass to the spaces below the roof and on roost entrances (see also Boldogh *et al.* 2007). Bats may become trapped in the roost in case lights would have accidentally left on (*e.g.* Kugelschafter unpublished, referred to in Zeale *et al.* 2016).

Any internal lighting (including that of hand-held torches and headlamps) as well other as disturbances due to visits shall be avoided at underground sites with either maternity or hibernation roosts. As show caves are sometimes large and complex, tourist trails should guide visitors in a distance from sensitive parts used by bats. Such parts must not be illuminated under any circumstances. A smart lighting design can be applied in show caves, *e.g.* by directing light only at specific cave formations. To avoid ***light trespass*** when illuminating the footpaths, only directional or low path lighting should be used. There are many examples where larger subterranean sites are split into illuminated parts for tourists and dark parts for bats, which show how the conflict between economic interests and conservation requirement can be reconciled. For instance, fortifications in Nietoperek (Poland) and abandoned limestone mines in Mönsted and Daugbjerg (Denmark) have been split into dark and lit parts, with latter ones opened for tourists. Part-time lighting in caves may also represent an effective method to mitigate the effect of interior lights on bats, *i.e.* illumination is only switched on when visitors are present. However, the evidence is lacking whether this scheme might aid bats inside the cave. Further, artificial light in caves can be dimmed to low intensities since the human eye will adjust to these low light levels over time (Mohar *et al.* 2014).

5.2.3 Adjusting light spectra

Little is known about the wavelength-specific response of light receptors in European bats and less so about the light spectra that affect their behaviour most severely.

However, different light spectra can have different effects on the emergence behaviour of bats (Downs *et al.* 2003; Fig. 5.9). Compared to no artificial illumination, red light had the least effect on number of emerging *Pipistrellus pygmaeus* from two roosts while the number dropped significantly when the roost exits were illuminated with blue and white light (Downs *et al.* 2003). Red light was proposed for being used in bat roost checks, supposedly having least effect on bats (Downs *et al.* 2003). A recent study (Spoelstra *et al.* 2017; see Fig. 5.10) showed that reducing the blue and increasing the red part of the spectrum of a light source significantly mitigates its impact on slow-flying *Myotis* and *Plecotus* species in their foraging habitat. Conversely, the absence of blue light reduced the attraction of insects and thereby the attraction of agile, opportunistic species such as *Pipistrellus* spp.

Voigt *et al.* (2018) observed an increase in flight activity for migrating *P. pygmaeus* and a trend for a higher activity for *Pipistrellus nathusii* around red LED lights, which is unrelated to foraging and could be explained by phototaxis. Therefore, response of bats to light spectra modifications may differ during migration season and seems site and species specific.

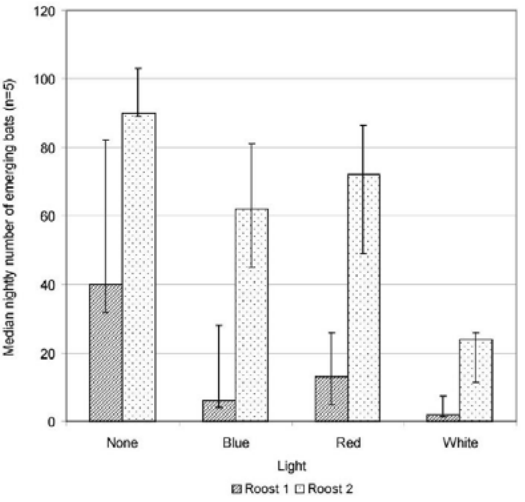

Figure 5.9. The median number of emerging P. pygmaeus *with different light treatments for two roosts (plus IQ range) (Downs et al. 2003: the difference was insignificant between the red-light and no-light treatments).*

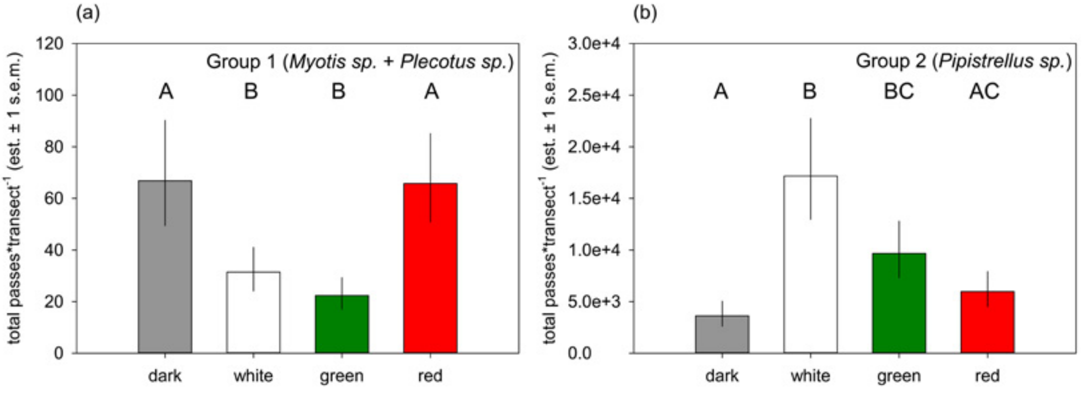

*Figure 5.10. Bat activity under four (permanent) lighting conditions (darkness, white, green, and red light) measured over the course of five years in forest edge habitat (model estimates). Group 1 includes slow-flying light-averse species (*Myotis *and* Plecotus *spp.); Group 2 includes opportunistic, agile* Pipistrellus *species. Capitals identify significant differences between groups in post-hoc tests (figure from Spoelstra et al. 2017).*

	Roosts		
		External illumination of building facades	*Internal illumination of caves and other roosts*
Avoidance	*Conserve dark areas*	Bat roosts should not be illuminated.	Underground roosts (natural or anthropogenic) with hibernating bats and nursery colonies should be kept dark. Tourist visits should be forbidden in such sections.
Only if lighting is considered necessary, and after an assessment of bat occupancy and emergence behaviour:			
Mitigation	*Directional light, avoid light trespass*	Smart lighting onto only specific architectural parts: • surfaces and facades with flight openings must not be illuminated; • luminaires with shades to limit trespass on roost entrances; • directed (controlled) light – no trespass above horizontal.	Smart lighting design only: • low path lighting; • light only on selected speleothems.
	Part-time lighting	Only in season when the roost is not occupied. Evening illumination delayed, or lights switched off after critical time period (when needed for human safety).	Temporary lighting only when tourists are present (*e.g.* for emergency exit signs). Sector lighting of interior, light switched off when tourists not present.
	Dimming	Low intensity (below 0.1 lx)	Low intensity
	Adapt lamp spectra	> 500 nm	> 500 nm
Compensation	*Restore dark areas*	Priority roosts should be strictly protected and not illuminated. Provide alternative roosts nearby.	Provide dark chambers and dark flight tunnels.

Table 5.3. Synthesis of the lighting planning recommendations to limit the impacts of artificial lighting on bats in roosts.

5.2.4 Mitigating indirect effects of ALAN on bats prey

For mitigating the impacts of ALAN on insects, it appears of major importance to limit the amount of blue and UV emissions in outdoor lighting by favouring warm colour temperature lamps (such as low-pressure sodium lamps or amber-LEDs). However, it is important to note that long wavelengths are as attractive as short ones to geometrid moths (Somers-Yeates *et al.* 2013), and that the negative effects of ALAN on moth reproduction was detected regardless of the lamp colour spectrum (van Geffen *et al.* 2015b). Thus, the enhancement of dark corridors and patches in human-inhabited landscapes seems to be a key strategy to effectively limit adverse impacts on biodiversity, including insects (Gaston *et al.* 2012). Outdoor lighting should be separated by at least 25m from vegetated areas, and by at least 40m from riverbanks to limit its effects on insects (Perkin *et al.* 2014; Degen *et al.* 2016). The attraction radius of street lights to moths also suggests that standard inter-street light distances (approximately 20–45m) should be broadened without a concomitant increase in light intensity to allow individual dispersal and increase landscape connectivity (Degen *et al.* 2016). Furthermore, particular attention should be given to dimming and orientating street lights for avoiding ***light trespass.***

Finally, although most dipteran and microlepidopteran activity is highest during the first few hours after sunset (Knight *et al.* 1994; Jetz *et al.* 2003), some taxa of macromoths are active much later at night (*i.e.* peak of activity at midnight; Rydell *et al.* 1996). Because of their large eye size, they appear to be more attracted to ALAN than micromoths, which may result in a size-dependent mortality of moths at street lights (van Langevelde *et al.* 2011). Hence, restoring darkness in human-inhabited landscapes for a part of the night, by turning-off street lights from around midnight to morning hours when traffic and human activities resume (*i.e.* part-night lighting schemes) may effectively limit the adverse impacts of artificial lighting on large moth species, which in turn may positively affect the bats that feed on them (such as *Plecotus* spp.; Azam *et al.* 2015).

5.5 Compensation

Compensating the impacts of ALAN on feeding areas and commuting routes: A "No Net Loss of Darkness" approach should be adopted when planning new outdoor lighting projects. These efforts should be paired with a decrease in light emissions from existing illuminated areas in order to halt the yearly increase in night sky brightness over Europe (Falchi *et al.* 2011; Bennie *et al.* 2014b). The extent of ***feeding areas*** and ***commuting routes*** impacted by ALAN should be quantified for restoring the same amount of dark refuges and corridors in alternative areas. These areas should be located nearby outdoor lighting projects, so that the impacted bat population can benefit from these compensation measures.

Compensating the impacts of ALAN on bat roosting sites: Bats use roosts year after year, and some species do not accept new alternative roosts in the vicinity easily (*e.g.*

Zeale *et al.* 2016). For this reason, it is very difficult to formulate compensation measures for the loss of roosts caused by ALAN. Therefore, the known important roosts in buildings should not be illuminated, or mitigation efforts employed. The same applies to caves and other natural roosts. Alternative dark roosts could be offered, but the effectiveness of these measures should be monitored.

6 Research priorities

We have already collated substantial knowledge about various detrimental effects ALAN has on bats, yet the effects of ALAN are multifaceted and may be long-term. Therefore, we need further research. It is important to collate and analyse reports and single case studies to draw broader conclusions about the effect of ALAN on bats. Here, we propose some directions for future investigations.

6.1 Fitness consequences

Since bats have a low reproductive rate, it is particularly important to understand higher-level responses of bat species to ALAN. Besides a recent study from Sweden on declines in colonies of *Pl. auritus* (Rydell *et al.* 2017), no other long-term studies, covering several decades, have been carried out to determine if any of the observed behavioural changes in response to ALAN have consequences for fitness of bats. Although a potential effect of different illumination schemes on juvenile growth of *R. hipposideros* was studied in Slovenia at three roosts, observed differences could not be unambiguously related to differences in light regimes (Kotnik 2016). Boldogh *et al.* (2007) reported growth rates of juvenile bats in illuminated and dark roosts and interpreted the differences as a result of illumination. However, Kotnik *et al.* (2017) emphasized that multiple factors can influence reproductive success in a complex manner, and attention should be paid to disentangle the effect of illumination from other factors that may affect juvenile growth. Overall, we need to better understand how ALAN affects critical population parameters such as sex ratio, birth rate, dispersal and survival to understand and predict population-level effects.

6.2 Impacts on bat communities

The current literature highlights that ALAN may cause species-specific responses, which could alter the competitive interactions of bat species. For example, decreases in *R. hipposideros* numbers have been linked to increases in *P. pipistrellus* populations in Switzerland. It was suggested that growing, due to the improved food availability at recently installed streetlights, population of *P. pipistrellus* outcompetes and displaces that of *R. hipposideros* (Arlettaz *et al.* 2000). Further studies are needed to address the impact of artificial lighting on bat communities (Davies *et al.* 2013).

6.3 Emerging lighting technologies – spectra

Given the rapid technological advances outdoor lighting, research on how novel light sources may impact bat activity and reproduction are urgently required. Such studies should use sufficient replicates and a controlled design to generate meaningful data. One such example is the "Lichtopnatuur project" in the Netherlands where the effect of white, red and green LED lighting on various taxa is studied on a large spatial scale (Spoelstra *et al.* 2017; see http://www.lichtopnatuur.org).

6.4 Bat vision

To improve our ability to predict the response behaviour of bats, it is key to better understand the spectral sensitivity of bat vision. Determining spectral and intensity thresholds for different species would aid to improve mitigation strategies and conservation initiatives (Gaston *et al.* 2013).

6.5 Efficiency of mitigation

Part-night lighting: some initial research has been performed in this area (see Chapter 5.2), but more studies must be done across a broader geographical range to encompass more species.

Motion detection: the dynamic lighting schemes, *e.g.* via the use of motion detectors, have already been implemented in Portugal, the Netherlands and France, and may have ecological benefits. The lights remain switched off unless needed, and so still provide all the perceived public safety benefits (Royal Commission on Environmental Pollution 2009). However, these fluctuations in lighting levels may also be damaging to bats and should be studied.

Light trespass: Currently, it is largely unknown how bats respond to efforts for minimizing the ***light trespass***.

Dimming: More research needs to be launched to improve our ability to define the optimal light intensities that serve both purposes human safety and nature conservation.

Dark zones: effectiveness of dark areas and corridors for bats should be more thoroughly investigated.

Spectrum adjustment: further studies on the impact of altered spectra are essential, for example at various roost types, ***commuting routes*** and on different bat species.

6.6 Measuring light objectively

Illumination is measured in ***lux***, which is defined as the brightness of a light according to human spectral sensitivities; spectral sensitivities of other taxa are often very different from ours. Since the unit is commonly used by lighting engineers, designers and environmental regulators, migrating from this term may thwart interdisciplinary communication (Longcore & Rich 2004). Although outdoor lighting is usually installed for humans and hence measuring light in ***lux*** is a logical approach, this unit lacks key biological information.

6.7 Migration

Migratory animals are particularly sensitive towards anthropogenic changes because they depend on a serious of intact habitats. Some migratory birds are known to get distracted by ALAN, particularly in the red wavelength spectrum. Indeed, a recent study highlights that migratory *P. nathusii* might as well get disoriented, when exposed to artificial green or red light (Voigt *et al.* 2017, 2018), yet the underlying causes and any potential interference of ALAN with the navigational system of bats are still under debate and require further research.

6.8 Hibernation

The effects of lighting on bat hibernation are currently not known: field observations are contradictory and anecdotal. Given the importance of hibernation for the survival of many temperate species, this is an area which requires urgent attention. Key questions include the impacts of lighting on arousal and overwinter survival.

6.9 Developing a predictive framework at the landscape level

Predicting areas where bats may be most at risk from light pollution will allow planning, avoidance and mitigation on larger scales. Development of methods and techniques for such predictions is crucial for conducting SEAs and EIAs.

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8 Glossary

Commuting routes – flight paths that bats use regularly to fly from a roost to a foraging area (and back) or to move between foraging areas or roosts.

Environmental impact assessment (EIA) – a national procedure for evaluating the likely environmental effects of those public and private projects which may have significant effects on the environment (see for instance Council Directive 85/337/EEC).

Feeding areas – habitat patches where bats perform area-restricted foraging.

Feeding buzzes – stereotypic sequences of echolocation calls indicating an insect hunt.

Illuminance – the total luminous flux per unit area; previously called brightness.

Habitats Directive – Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

Light trespass – artificial light in areas where it is not wanted; spill light.

Luminaire – a lighting unit.

Lux – a measure for the illuminance (lumen per square meter) as perceived by humans, derived from the international system of units (SI).

Migration – regular, usually seasonal, movement of all or part of an animal population to and from a given area.

Mitigation – action taken to mitigate, reduce or minimize any negative environmental impact such as habitat loss, animal fatality or injury where it is not possible to avoid such impacts.

Photic entrainment – adjustment of circadian rhythms by light.

Skyglow – brightness of sky caused by artificial light at night.

Strategic environmental assessment (SEA) – procedure for integration of environmental considerations into the preparation and adoption of plans and programmes with a view to promoting sustainable development (see for instance Directive 2001/42/EC).

Swarming – "autumn swarming" is a behaviour of some temperate bat species (particularly *Myotis*, *Plecotus*, *Eptesicus* spp. and *B. barbastellus*) that occurs from late summer to autumn. *Pl. auritus* performs a "spring swarming" as well. Bats may travel many kilometres to underground "swarming sites", arriving several hours after dusk, flying in and around the site and departing before dawn. Swarming is important part of social interactions, including courtship. Some swarming sites may also be used as hibernacula later in the year. Swarming ("dawn swarming") also refers to the circling flight pattern of some bat species that occurs outside the entrance to a roost (especially maternity roosts) before the bats enter at dawn.

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EUROBATS

Eighty percent of the world's population are currently exposed to light-polluted skies, and the Milky Way is no longer visible to more than a third of humanity. The pace the light pollution is increasing is faster than global population growth and economic development. While environmental conditions at night are being dramatically and rapidly altered, circadian rhythms, behaviour and ecology of plants and animals are imminently influenced. In the same time, effects of artificial lighting, various illumination schemes and spectra on biodiversity, including bats, are currently insufficiently understood, whereas only a vague notion of required mitigation and compensation activities exists among decision-makers and other parties involved in lighting projects. Although the bats are almost exclusively nocturnal and extremely sensitive to multiple effects of light pollution, its negative impact on bats alongside essential measures needed to preserve unfragmented nightscapes for these animals are often disregarded during impact assessments, planning and operation.

In this volume, we tried to compile available evidence related to the effect of artificial light at night on the European bats. Based on the current state of knowledge, solutions are proposed concerning possible ways to avoid, mitigate and compensate the adverse effects which lighting projects may have on bats and their functional habitats. We also outlined research priorities for future studies, required for in-depth understanding of the problem and assessing efficiency of proposed mitigative measures.

These guidelines were developed by the EUROBATS Advisory Committee in collaboration with external experts in pursuance of Resolution 7.13 on Implementation of the Conservation and Management Plan.

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