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Insects, bats and artificial light at night

Measures to reduce the negative effects of light pollution

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Pictures front page (clockwise, starting in above left corner)

Tipulidae, Markus Juvonen, 2013

<http://photoeclecticeffect.blogspot.nl >

Noctua Pronuba, Frans Eggermont, 2011

<http://www.flickr.com/photos/arnoldus1942/6108697808/>

Lampyris noctiluca, Konstantin Korzhavina, 2005

<http://www.zin.ru/animalia/coleoptera/rus/korzhav1.htm>

Rhinolophus hipposideros, Claudia Rieswijk, 2012

PREFACE

Although there is sufficient knowledge of all kinds of pollutants, light pollution remains a phenomenon difficult to identify, let alone to measure. Data on the consequences of artificial light for the biological world are also insufficient, which makes it difficult to develop useful technical and political measures to reduce the possible effects of pollution. Personally, I think the subject of light pollution is very interesting. How come we have used artificial light at night for roughly four century's (including the oil street lamps) and only now we begin to wonder what effect this tremendous change in nightly light intensities could have on the world's biodiversity? Isn't it obvious that a dark night could have countless benefits for many creatures and therefore should be cherished?

This is something I have wondered every time I enjoyed the stars at night or couldn't sleep because my room was too illuminated by light from outside my bedroom. Yet, I never took the time to dig into existing literature to find the proof for my presumptions. In the last ten weeks, I did, and I found lots and lots of information. Still, a lot of questions remain to be answered. But I believe this report presents an up-to-date review of the data that is out there. In addition, I put my own ideas and recommendations in and hereby hope to contribute to the search for darkness. Concerning the question if my ideas were true, you'll find the answer within this report. This literature review is written within the framework of the master's writing thesis for the master programme Environmental Biology at Utrecht University.

I would like to thank my supervisor, Dr. Jos Dekker, for his time and input. I really enjoyed his great patience, involvement in my work and especially his positive and rewarding way of giving feedback.

Claudia Rieswijk

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ABSTRACT

Light largely influences the biological world. It is used by organisms for several purposes. However, the influence of artificial light on species interaction, populations and ecosystems is not well documented. Also, technical and political measures are not used consistently. This study will examine how and to what extend artificial light affects Lepidoptera, Diptera, Coleoptera and insectivorous bat species and also provide for measures to reduce potential negative effects. There are some limitations to the study, since only specific insect and bats species of the European Union are taken into consideration. Also, only measures for the EU are given and long-term effects are not examined.

Insects and bats can see different wavelengths of light. Both bats and insect species use light for partitioning of activity between day and night, dark repair and recovery, circadian clocks and photoperiodism, visual perception and spatial orientation. Artificial light is mainly produced by lamps. The outdoor artificial light is mostly used in urban and western areas in the world. High pressure sodium, low-pressure sodium, high-pressure mercury, metal halide, compact fluorescent, LED, incandescent/Halogen and fluorescent tube lamps are most commonly used outdoor, as street lamps. The effect of those types of lamps varies. For insects and bats, street lamps can have an effect on their daily rhythm and several physiological processes.

Artificial light affects individuals, but it also has an effect on populations and ecosystems. Literature to provide for examples of this phenomenon is very scarce. Artificial light can affect the population itself, by increasing the mortality or reproduction rate, but it can also change the interaction between species of the same family or even predator-prey relationships. For some species with small and fragmented populations, artificial light could cause local extinction. Also, some species that are favoured by artificial light could outcompete another species. Four different scenarios for the effect of artificial light on the predator-prey relationship between bats and insects are considered. However, the possible differences in effect between insect species or bat species is not taken into consideration.

Light pollution can be defined as being *the degradation of the photic habitat by artificial light*. Even though there are still huge gaps in the knowledge about the effect of artificial light at night on these specific species, the knowledge that already has been retrieved is worrying. Light pollution has the potential to disrupt the stability of species and some literature shows that light pollution is already an important factor in the decline of some vulnerable species. There are some studies that have determined limit values for light pollution and some formulas are conducted in the past years. However, these findings have not yet been integrated in EU laws and legislations. When countries individually develop these regulations, this could create economical unequal environments for companies and individuals, thereby undermining the open economy principle of the EU. Since artificial light is a potential problem for the biological world, it is important that further steps are taken concerning guidelines for the use of artificial light in the EU. There are several technological and political measures that are suitable for EU regulations. These measures can be integrated in a plan specifically set up for the species examined in this study. However, other organisms should also be included in these guidelines. Therefore, further research on the effect on other species is needed.

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1. INTRODUCTION

Light largely influences the biological world (Bradshaw & Holzapfel, 2010). The cycle of light intensity, during night and day as well as during a year, has been relatively consistent for a long period of time. Natural light is important for organisms, because it is used as a resource and as a source of information about the environment. Light can be a resource when used for photosynthesis, partitioning of activity between day and night and darkness provides for repair and recovery. Light is used as an information source for visual perception, spatial orientation and circadian clocks and photoperiodism (Gaston *et al.*, 2013).

The spread of artificial light during the night alters the natural daily cycle of light and dark periods, influencing the functioning of plants and animals. Artificial light affects processes including productivity, partitioning of the temporal niche, repair and recovery of physiological function, measurement of time through interference with the detection of circadian, lunar and seasonal cycles, detection of resources and natural enemies and navigation in many species, like jumping spiders (Frank, 2009), insects (Bachleitner *et al.*, 2007; Berger & Gotthard, 2008), reptiles (Perry & Fisher, 2006), birds (Martin, 1990), frogs (Buchanan, 1993), salmon (Riley *et al.*, 2012), mice (Bird *et al.*, 2004), rats (Cos *et al.*, 2006), reindeer (Stokkan *et al.*, 2013), bats (Kuijper *et al.*, 2008) and plants (Johnson, 1979; Nishizawa *et al.*, 2009). Although it is known that artificial light can alter the physiology and behaviour of organisms, the question remains if those alterations could affect populations or ecosystem to a scale at which it forms a serious problem for the persistence of those species. This could be due to changes in mortality, fecundity, community productivity, species composition or trophic interactions. For example, when some species benefit from artificial light at night, where the fitness of others decreases, the balance of species interaction is likely to change, according to Davies *et al.* (2013).

Like many animal species, insects are in many ways influenced by light. For example, when attracted to a streetlight, they might get exhausted, get caught by predators or get killed by flying against the hot glass (Rich and Longcore, 2005). The effects of artificial light can both be beneficial or harmful for species. By causing insect species to increase or decrease in numbers, artificial light at night could have severe implications. From all 1.9 million species that are formally accepted and published worldwide, 72 percent are insects (Chapman, 2009). Various species from this group provide for important ecological services, such as pollination, decomposition and biological control (Kim, 1993). Because insects form such a large part of the worldwide biodiversity, provide for important ecosystem services and are an important food source for many species, this study will mainly focus on the effect of artificial light on this class of invertebrates. To examine how artificial light can influence the balance of species interaction, insectivorous bats (*Chiroptera)* – a group of species that is dependent on insects as a food source - will also be covered in the research in a lesser extent. Only European and insectivorous bat species will be covered, which are five species of horseshoe bats (*Rhinolophidae*), 35 species of evening bats (*Vespertilionidae),* the Schreiber's bat (*Miniopterus schreibersii)* and the European free-tailed bat (*Tadarida teniotis)*. In this report, every time bats are mentioned, it is referring to insectivorous bats. Bats mainly feed on flying insects, and only the three insect families that form the most important food sources will be covered in this study. These three groups of insects are moths and butterflies (*Lepidoptera)*, true flies (*Diptera*) and beetles (*Coleoptera*) will be covered in this study.

In most countries there are few efforts to reduce the impact of light pollution. Especially in the United States and the European Union, artificial light at night is a common and recognized form of pollution (Rich & Longcore, 2005). Here, 99 percent of the population lives in areas where a high level of artificial light at night is always present (Cinzano *et al.*, 2001). This study will therefore be limited to one of those critical areas: the European Union (EU). By choosing a region that is, to a certain degree, homogenous concerning policies and regulations, it is easier to establish suitable conclusions and recommendations in this study. Known examples of laws and other regulations concerning the subject in the EU are found in France (since 2009) and Slovenia (since 2007) (International Year of Astronomy 2009, 2007). Furthermore, only terrestrial and outdoor lights will be considered and, regarding the effects, only short-term effects are examined. So, consequences on population dynamics are taken into account, but not the possible adaptations of a species or other evolutionary changes.

This study will examine how light can alter the physiology and behaviour of insects and – in a lesser extend – their predators. If these changes can form a significant ecological problem will also be determined. Besides, changes in the technology and management of artificial light will be proposed to reduce the negative effect of artificial light at night. The main research question is as follows:

Main research question: How does artificial light at night affect Lepidoptera, Diptera and Coleoptera and their predators -insectivorous bats- , in what extend does this cause significant ecological problems for the viability of these species, and how can the negative effects be reduced by the use of specific regulations and technologies in the EU?

Method

To answer the research question, a literature study will be carried out. The following minor research questions are conducted to reach a main conclusion:

1. How do Lepidoptera, Diptera and Coleoptera use light for their survival, to what extend do they protect themselves from insectivorous bats and how have these predators adapted their hunting techniques to this behaviour?
2. What is the effect of artificial night-time lighting on the spatial, temporal and spectral components of natural light regimes?
3. What are the consequences of the alteration of natural light regimes on the physiology and behaviour of Lepidoptera, Diptera and Coleoptera that use light as a resource or as an information source?
4. To what extent do changes in insect behaviour, caused by artificial light at night, influence the physiology and behaviour of insectivorous bats?
5. To what extent can changes in Lepidoptera, Diptera and Coleoptera, caused by artificial light at night, influence their populations and ecosystems?
6. How can light pollution be defined?
7. Which technological measurements are able to reduce the negative effects of artificial light at night on Lepidoptera, Diptera and Coleoptera and insectivorous bats?
8. Which policy measurements in the EU are able to reduce the negative effects of artificial light at night on Lepidoptera, Diptera and Coleoptera and insectivorous bats?

Thesis outline

This thesis is divided in several chapters. First, a theoretical framework will broadly set out which literature is available on the subject. In the next chapter, basic information about the use of light is explained. The following chapters will explain the characteristics of artificial light at night and how it affects individuals, populations and ecosystems. Then, a full chapter will be devoted to the term 'light pollution' and how this phenomenon can be quantified. The last two chapters will provide for technological and policy measurements and, in the end of the report, the main question and sub-questions will be answered.

2. LIGHT USE BY INSECTS AND INSECTIVOROUS BATS

To understand how artificial light at night impacts the biological world, information is needed about the use of light by organisms. This chapter will discuss the various ways in which Lepidoptera, Diptera and Coleoptera and bat species use light.

What is light?

Light is a form of electromagnetic radiation, expressed in nanometer (nm). It is a stream of photons that can be received by a recipient with the proper visual capabilities. For humans, only light from 380 to 700 nm is visible. Every wavelength of light is seen as a different colour, starting with purple at low wavelengths until red in high wavelengths. For other organisms, light is not necessarily perceived in the same way (Molenaar *et al.*, 1997). Insects can only see light from 300 to 650 nm (Briscoe and Chittka, 2001). For insectivorous bats, visual capabilities differ between species and ranges are not well documented, but for species that are capable of perceiving colours, sensitivity peaks at 500 nm and also at 570. Some species are also sensitive for ultraviolet radiation (390 nm) (Patriarca and Debernardi, 2010).

Not only the wavelength, but also the intensity of the light determines if an organism is able to see the light. The intensity can be too low for organisms to perceive. This intensity, measured in lux (lumens per square meter) depends on the amount of energy transmitted in the light as well as the illuminated surface and the distance from the source. For example: a High Pressure Sodium lamp of 40 Watt can emit 5200 lumens (lm) of light. These lumens are divided over multiple wavelengths, or colours, of light. When measuring the intensity of yellow light: for every lumen of light, 150 µW of yellow light is emitted. So, for this specific lamp, 0.78 W or 101.4 lm of yellow light is emitted. If this light is concentrated over one square meter, it emits 101.4 lux of yellow light. However, if the light is distributed over a larger surface, the amount of lumens per square meters will decrease (Koninklijke Philips Electronics, 2008).

The purpose of light for the biological world

Some studies argue that light is the most important factor for the organization of the biological world (Bradshaw and Holzapfel, 2010). Regardless if that statement is true, it is clear that light is very important for a lot of organisms. The rotation of the earth and formation of the solar system facilitates regular cycles of day and night light regimes as well as seasonal changes and patterns in day and night length. Light is used by organisms in several ways. Gaston *et al.* (2013) developed a mechanistic appraisal to focus on the cross-factoring of the ways in which artificial lighting alters natural light regimes, as well as how artificial light can alter biological systems. They focused on light acting as a resource or as an information source. It is used as a resource when functioning for photosynthesis, partitioning of activity between day and night or when the absence of light provides for repair and recovery. Light can function as an information source when used for circadian clocks and photoperiodism, visual perception or spatial orientation (Gaston *et al.*, 2013). In table 2.1, the use of light in various ways is further explained.

Table 2.1 The use of light by organisms (source: Gaston *et al.*, 2013)

	Function	
Light as a resource	Photosynthesis	Absorption of light by chlorophylls and carotenoids to convert into carbon-based products
	Partitioning of activity between day and night	Organisms are active during specific periods of the day and have adapted their physiological characteristics to the light intensity of these periods. The intensity of light regulates their timing of activity and is therefore the driver for specific patterns of behaviour.
	Dark repair and recovery	The absence of light provides organisms to repair and recover their DNA from damage caused by harmful light, such as solar UV-B radiation.
Light as an information source	Circadian clocks and photoperiodism	The circadian clock refers to the internal physiological system, controlled by cues, which regulates activity and associated physiological patterns in a 24 hour cycle. Photoperiodism is the physiological reaction of organisms to the length of day and night, seasons, as well as the monthly lunar cycle. Organisms use the length of day and night to anticipate their activity patterns on the changing environment, by altering physiological processes like hormonal cycles and the functioning of the immune system. So-called ‘zeitgebers’ are cues that are recognized by organisms and regulate these patterns.
	Visual perception	Organisms use light to perceive their environment. The intensity and wavelengths used by organisms are different among species.
	Spatial orientation and light environment	Light is used by many organisms for directional movement. The moon, for example, is used by many nocturnal organisms as a tool for navigation. Also, light-avoiding movements exist among several species.

Light use by insects

For insects, light functions as a resource as well as an information source, for they use it for partitioning of activity between day and night (Lewis and Taylor, 2009; Fullard and Napoleone, 2001; Molenaar *et al*., 1997; Dreisig, 1886), dark repair and recovery (Koval, 1986), circadian clocks and photoperiodism ((Gaston, 2013), visual perception (Briscoe and Chittka, 2001) and spatial orientation (Jander, 1975). Below, these functions will be further explained.

Partitioning of activity between day and night

Insects are usually active during specific times of the day and have adapted their physiology to this specific period. Time of flight is largely determined by light intensity, while the amplitude of activity is affected by temperature (Lewis and Taylor, 2009). In Lepidoptera, Fullard and Napoleone (2001) found that only butterflies were exclusively diurnal while moths were active in both day and night. This is probably linked to the capability of moths to hear ultrasounds, while butterflies lack the ear structures needed for these abilities (Molenaar *et al.,* 1997). Night-active species generally become active at light intensities below 1.00 to 0.004 lux (dependent on species) (Dreisig, 1986).

Dark repair and recovery

Continuous periods of darkness facilitate certain processes controlling repair and recovery in organisms. During dark repair, holding cells in stasis reverse some of the damage caused by UV light. This is referred to as dark repair or liquid holding recovery. It is a very important process, because damage in cells, especially when DNA is modified, can lead to structural distortions in the physiology of organisms. These processes are found in plants (Vollsnes *et al.*, 2009) but are not well examined in insect species. Studies on this matter on Diptera and Coleoptera species could not be found, but Koval (1986) studied the enhanced survival by liquid holding following UV damage in Lepidoptera. His study concluded that this species group is able to repair UV-induced damage by liquid holding in the dark. It is very well possible that other insect species have similar capabilities.

Circadian clocks and photoperiodism

Light is one of the most important cues for the functioning of the circadian clock. The internal physiological patterns related to this clock are, among others, hormonal cycles and immune responses. Examples of behaviour of insects that reflect those internal processes are migration, transformation from juvenile into adult stage, mating behaviour and hibernation (Gaston, 2013). An example of the functioning of a circadian clock is the reproductive behaviour of *Dioryctria abietella* moths. Fatzinger (1973) found that pheromone responsiveness of males and female production of this sex pheromone were influenced by dial cycles of twelve hours of light followed by twelve hours of darkness.

Visual perception

The insects examined in this study (*Lepidoptera, Diptera* and *Coleoptera*) have visual capabilities and are able to distinguish different types of light (Merry *et al.*, 2006; Mellor and Hamilton, 2003; Ent and Visser, 1991). Light sensitivity of insects differ between species. Diptera are able to see wavelengths between 335 and 530 nm, Coleoptera are sensitive for wavelengths between 348 and 620 nm and Lepidoptera can see light between 380 and 610 nm (Briscoe and Chittka, 2001). Nightly active insects generally become active at light intensities below 1.00 to 0.004 lux (dependent on species) (Dreisig, 1986). Insects use their visual perceptions to examine the environmental conditions around them. Light intensity, quality and wavelength are all factors that determine this ability.

Spatial orientation

Light sources tend to attract multiple insect species, but the reason for this behaviour has not yet been determined (Molenaar *et al.*, 1997). Some studies however claim or hypothesize that light is used for spatial orientation. Only Diptera species are known to sense angular acceleration and angular motion, which is the use of light to stabilize flight position (Jander, 1975). Several moths use light to determine where and when meetings are arranged for reproduction (Molenaar *et al.*, 1997). When migrating, some moths use the moon to orientate their trip. When no moon is present, stars are used for this purpose (Sotthibandu and Baker, 1979). Lepidoptera and Coleoptera, but not Diptera, are able to use the pattern of polarized celestial light in the sky for their orientation (Gaston *et al.*, 2013), while exhibiting a dorsal light orientation during their flight (Jander, 1975).

The species examined in this study are all more or less attracted to light, depending on the spectrum and the characteristics of all light sources combining in the environment. Light with high ultraviolet emission is most attractive (Longcore and Rich, 2004). Langevelde *et al.* (2011)

found that, in moths, the attraction also depended on the size of the individual. Smaller wavelengths are more attractive to larger moth species, possibly because larger insects usually have larger eyes and are therefore more sensitive to light. These findings could also apply to other insect species.

Light use by insectivorous bats

Bats use light for several purposes. Despite the fact that they mostly rely on sonar for their orientation, they use light as well, to determine hibernation length, detect prey and obstacles and to maintain a daily and seasonal rhythm. The sensitivity of light, however, varies between species. Overall, insectivorous species have smaller eyes compared to fruit-and nectar-eating bats (Eklöf and Jones, 2003).

For bats, light functions as a resource as well as an information source, for they use it for partitioning of activity between day and night (Duvergé *et al.,* 2000), dark repair and recovery, circadian clocks and photoperiodism, visual perception and spatial orientation (Patriarca and Debernardi, 2010). Below, these functions will be further explained.

Partitioning of activity between day and night

Light intensity is presumably the most important variable involved in the regulation of activity times. This is supported by several studies (Beer, 1955; Decoursey and Decoursey, 1964; Voûte, 1974). The timing of evening emerge in bats is very important for fitness in bats (Duvergé *et al.,* 2000). As described earlier, species that are more sensitive to light tend to fly out later in the evening. Also fruit – and nectar-eating bats have more visual capabilities compared to insectivorous bats since they rely more on vision to find their food. During the centuries, insectivorous bats have adapted their activity to the daily cycle, choosing to be active at dusk and night. This is shown in many visual adaptations, such as the ability to see at very low light intensities due to the presence of many rods in the bat eye. Consequently, many bats are very vulnerable in conditions with high light intensities (Eklöf and Jones, 2003).

Dark repair and recovery

In bats, some physical processes that are important for the repair and recovery of the organism can only occur in dark conditions. Probably the most important process is the secretion of melatonin, which is suppressed by light. In humans, the suppression already occurs at 420 nm. Melatonin has an important role in all kinds of processes, like skin pigmentation, reproduction, cancer prevention and metabolism (Patriarca and Debernardi, 2010).

Circadian clocks and photoperiodism

Light intensity is presumably the most important variable involved in the regulation of activity times. This is supported by several studies (Beer, 1955; Decoursey and Decoursey, 1964; Voûte, 1974). Light intensity is linked to the emerging time of species. There are some differences in emerging time between species. For example: the Pipistrelle bat tends to fly out early, while the Daubenton bat emerges later in the evening. Light intensity seems to be the cue for emerging time, but the sensitivity to light, availability of prey and the presence of predators are most likely the drivers behind these activity patterns (Fure, 2006; Voûte, 1974).

Bats living in the temperate regions have a hibernation period, in which they become poikilothermic animals (Stones and Wiebers, 1965). They are therefore heterothermic animals, which means that they are able to switch their metabolic strategies from poikilothermic (variable internal temperature) into homeotermic (stable internal temperature). Their state of hibernation does not differ from their natural sleep, it is more of a relatively long period or series of periods when the animals are subjected to low environmental temperatures, become inactive and have a very low metabolic rate correlated with a low body temperature (Beer and Richards, 1956). Their pineal function remains active throughout winter (Ralph *et al.*, 1979), implicating that they are sensitive for light disturbance during their hibernation period. Artificial light in roosting sites has found to suppress the day and night rhythm (Patriarca and Debernardi, 2010). However, other studies found that hibernation is not regulated by light intensity but by temperature (Audet and Fenton, 1987), so this might differ between species.

Visual perception

Bats use their vision regularly (Eklöf and Jones, 2003). Bats see best in dim light (Fure, 2006) because they lack cones and have more rods compared to diurnal mammals. Rods are more sensitive to faint light than cones and they detect basic motion and basic visual information, while cones detect colour. The bat *Myotis myotis,* for example, is 4 to 5 times more efficient in light-gathering compared to humans. Other species, possibly all microbats, do have some cones, enabling them to see at intermediate light levels and distinguish colours. Amongst some of these species, ultraviolet sensitivity has been demonstrated (Patriarca and Debernardi, 2010) but it's not sure which species exactly have this ability. It is very likely that species that are able to see ultraviolet light, are also more vulnerable to these wavelengths. This is due to the fact that they lack an UV-filter in their eyes, which protects them from ultraviolet light and therefore this radiation can disturb their vision and cause damage to their retina (Fure, 2006).

In general, two groups of insectivorous bats can be distinguished. The first group is formed by bats that tend to fly out early in the evening, have smaller wings and fly relatively fast. The second group contains bats that fly out relatively late in the evening, have wide wings and fly relatively slow. While the first group hunts in quite enlightened places, the second group tends to avoid locations with a lot of light (Rydell, 1992). Some studies consider this avoiding behaviour to be predator-avoiding behaviour (Stone *et al.*, 2009) but as explained above, this could as well be explained by a lack of ultraviolet filters in the eyes and/or a reduced tolerance towards light caused by a lack of cones.

Spatial orientation

For orientation, bats use the earth's magnetic field as well as sunset cues. The geomagnetic field is probably used to indicate directions as well as to locate their position. Without the sunset as a calibration, bats are not able to use the magnetic field properly (Holland *et al.*, 2009).

Summary

Insects and bats can see different wavelengths of light. Their visual capabilities are summarized in figure 2.1. For bats, the lower boundaries of their vision has not yet been determined. It is sure they can see somewhat below 400 nm, but it is unsure if they can see below that boundary. For some species, the capability of seeing ultraviolet light has already been found. Both bats and insect species use light for partitioning of activity between day and night, dark repair and recovery, circadian clocks and photoperiodism, visual perception and spatial orientation.

*

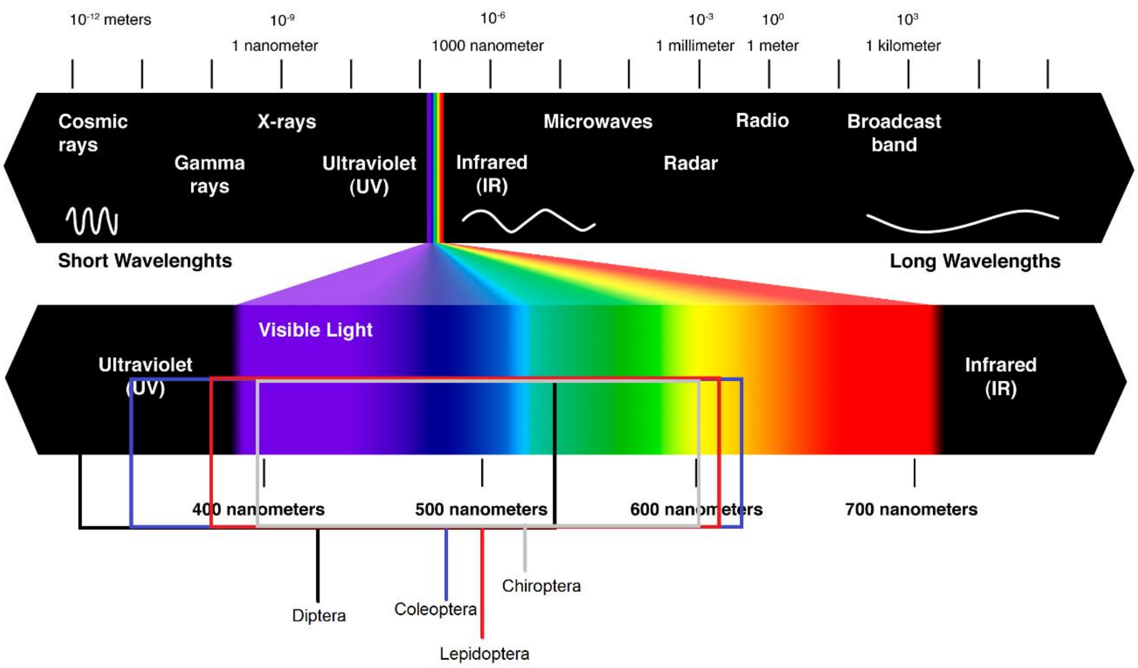

Figure 2.1 visual capabilities of true flies (Diptera), beetles (Coleoptera), butterflies (Lepidoptera) and insectivorous bats (Chiroptera) (source of the light spectrum overview: http://es.paperblog.com/los-pigmentos-fotosinteticos-2056825/)

3. THE EFFECTS OF ARTIFICIAL LIGHT AT NIGHT ON THE PHYSIOLOGY AND BEHAVIOUR OF INSECTS AND INSECTIVOROUS BATS

In the previous chapter, information about the use of light by organisms is examined. In this chapter the effect of artificial light at night on individuals of Diptera, Coleoptera, Lepidoptera and European insectivorous bats will be examined.

About artificial light at night

While natural light is emitted from sun, moon and stars, artificial light is mainly produced by lamps. Natural light is emitted at the whole spectrum, while artificial light usually emits a smaller spectrum, with mainly wavelengths that are visible for the human eye. Outdoor artificial light is mostly used for security and recreational and work purposes. Major sources of outdoor artificial light are sport facilities, commerce, retail, buildings, monuments, mineral extraction, airports, harbours, roads, junctions, pedestrian paths and parking areas. Therefore, there is a concentration of artificial light in urban areas, where a lot of people are active in the evening and night. In figure 3.1, an overview of the amount of artificial light at night is given for the whole world. As described, most artificial light is concentrated in developed countries.

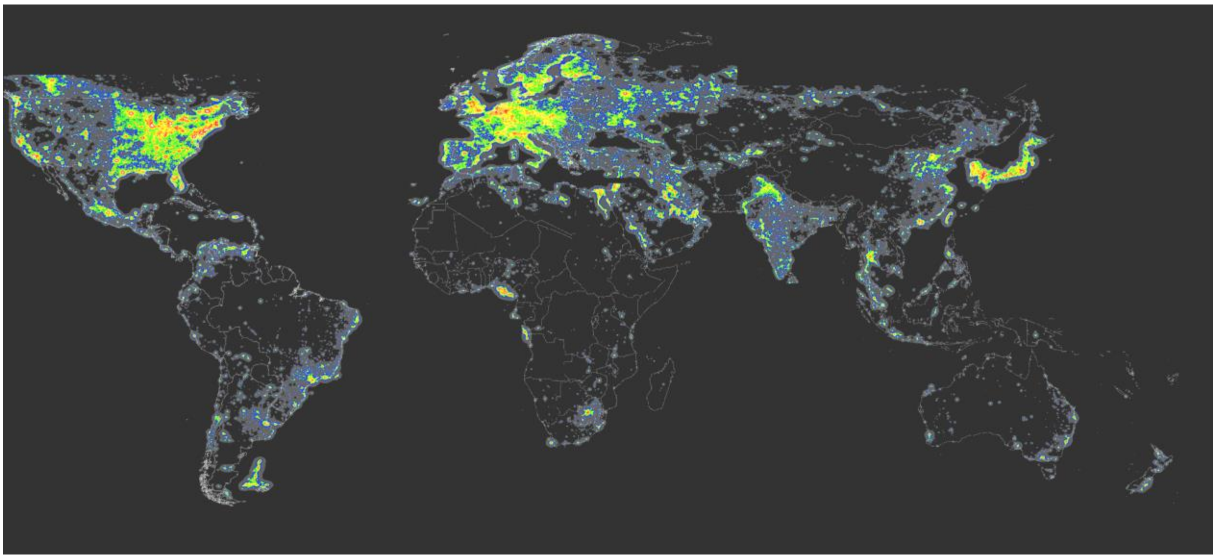

Figure 3.1 Overview of the amount of artificial light at night in the world (source: Cinzano *et al.*, 2001)

In Europe, most outdoor artificial light is generated by street lamps. The types of electric lamps that are commonly used are high-intensity discharge lamps, LED lamps, incandescent lamps and fluorescent lamps (compact or tubes). Incandescent lamps are the most inefficient and the European Union has started in 2009 to phase them out (European Commission, 2011). Street lights are the most common types of artificial light and at the moment, high-intensity discharge lamps, in particular mercury and sodium variants are most commonly used for this purpose in the European Union (European Commission, 2011). In table 3.1, a more detailed overview of the most common used street lamps and their characteristics is shown.

Table 3.1 Overview of street lights used in the EU (source: European Commission, 2011)

Type	Most common variants	Usage in EU	Wavelength (nm)	Max. Efficiency (lm/W)
High-intensity discharge lamps	High pressure sodium (400W)	Banned but still common	460-500 570-600 745	50-130
	Low-pressure sodium lamps	Most common	589	100-203
	High-pressure mercury lamps	Banned but still common	184 253 365-435 546-578	35-60
	Metal halide lamps	Banned but still common	300-800	75-140
Compact fluorescent lamps		Quite rare, only in slow road categories	280-700 > 700	50-85
LED		Rare, but usage is emerging	450-700	Up to 50
Incandescent/Halogen		Banned	300- 900	5-27
Fluorescent tube		Rare	480-570	60-105

Every lamp type has its own advantages. Low-pressure sodium lamps are very efficient, although the emitted wavelength is restricted to one colour. Metal halide lamps, on the other hand, give a clear white illumination but are less efficient. They also have different effects on organisms, as will be discussed in the next paragraphs. As shown in the table, some less efficient lamps are banned following the eco-design requirements or will be banned in 2015 and 2017 (European Commission, 2011).

Effects of artificial light at night on the physiology and behaviour of insects

Adding artificial light to natural light changes the light conditions for organisms. Not only is the intensity of artificial light much higher, also other wavelengths are available for organisms to perceive. Since insects use light for multiple purposes, this can have major effect on the functioning and survival rate of species. The effect of artificial light on all functions of light for insects will be discussed below.

Partitioning of activity between day and night

Insects are usually active during specific times of the day, and have adapted their physiology to these circumstances, due to evolutionary processes. Therefore, artificial light can have influence on their activity patterns. Nightly light intensities above specific values can inhibit the feeding of insects during the night, potentially leading to starvation (Bruce-White and Shardlow, 2011). Light intensities that simulate conditions present at daylight could have a positive effect on the survival rate of daily-active species. It is possible that they remain active during nightly hours and the light enables them to forage more. However, literature to support this theory remains scarce.

Dark repair and recovery

Few data are available on the effect of artificial light on dark repair and recovery. Therefore, it is difficult to say what the possible effects are. However, Gaston *et al.* (2013) found that short pulses of light could already disrupt production of hormones like melatonin. And as described in the previous chapter, there are processes in the insect body able to repair damage caused by light, but only in darkness. Therefore it is expected that the absence of darkness could cause issues concerning the survival rate of individuals. The long-term effect is difficult to predict.

Circadian clocks and photoperiodism

Since light is one of the most important factors to provide for cues, which are used to regulate activity patterns during the day and year, artificial light can have a major impact on the cycle of insects.

One of the major effects of artificial light on insect's photoperiodism is through the hibernation period. In temperate regions, insect species pass through diapause during colder times of the year. Day length, in combination with temperature, determines when an individual starts its diapause. To what extend day length or temperature is the most determining factor varies among species. *Pieris brassicae,* for example, is mainly affected by day length while *Lyceana dispar* is more focused on temperature (Bink, 1992). Therefore, *Pieris brassicae* is expected to shorten its hibernation period due to artificial light, while *Lyceana dispar* is probably not influenced at all.

Another important impact of artificial light concerns the mating behaviour. In some species, light intensity is the determining factor for the timing of mating. In *Heliothis zea*, mating behaviour only occurs at a light intensity of 0.1 lux (about a quarter of the light of a full moon) or lower (Molenaar *et al.,* 1997). So, artificial light is very likely to prevent this species from mating behaviour and consequently will decrease production rates in populations close to artificial light at night. There are several other examples of reproductive behaviour, restricted by artificial light at night. They vary from sperm production limited by too much light to being unable to deposit eggs due to high light intensities (Molenaar *et al.*, 1997). The effects of artificial light on reproduction are thus very likely to be significant for populations in nightly lit areas.

Visual perception

The insects examined in this study are able to see many different wavelengths of light. When an artificial light source is visible for a Diptera, Coleoptera or Diptera species, this species is most likely to be attracted by it. Ultraviolet, green and blue light are most attractive. Moths are known to be attracted to lights up to 500 meters away from them. Insects attracted to a lamp are likely to die due to exhaustion, burning or predation (Bruce-White and Shardlow, 2011). Mercury vapour lamps in particular increase the predation rate, because they interfere with the ability of moths to detect the sound of bats. When flying near a lamp, moths seem to think they are

Figure 3.2 Insects attracted to light (source: Xinhua/Landov/Barcroft Media, 2013

flying in daylight. In daylight time there is little chance to encounter bats, and that is probably the reason that the moths adapted their behaviour. So, when flying in illuminated conditions at night, moths are more vulnerable to predators. Orange Sodium Street lamps do not interfere with insects to the same extend as mercury vapour lamps (Svensson and Rydell, 1998). This is due to the fact that insects cannot perceive all wavelengths like humans do, as described in the previous chapter. Another effect of artificial light is that insects tend to rest near the light sources, where they are not camouflaged well enough to prevent predation. Several species are known to have adapted their hunting techniques and learnt to predate on those insects that are relatively easy to find (Bruce-White and Shardlow, 2011).

Spatial orientation

Artificial light causes disturbed orientation of insects by attracting them, and consequently those individuals are not able to get away from them thus not being able to move to their natural habitat and carry out natural behaviour (Molenaar *et al.*, 1997). Some studies have found evidence that several Lepidoptera and Coleoptera species do use light for migrating. To what extend artificial light can prevent those insects from using light from the sky, has not yet been determined.

Effect of artificial light at night on the physiology and behaviour of insectivorous bats

Since light affects many bat species in their behaviour and physiology, artificial light at night can alter the natural regimes of individuals.

Partitioning of activity between day and night

Bats restrict their activity to twilight and night. However, since light sensitivity varies between species, some species fly out at relatively light conditions while others wait until light intensity is much lower. Naturally, the last group of bats is much more sensitive to artificial light, since it can prevent them from being active (Patriarca and Debernardi, 2010). Artificial light can also have a significant effect on the activity in the bat roost. Non-dark sites are suboptimal for bats, by increasing predation risks. Furthermore, external lighting of roosts, for example when a roost is located in an enlightened monument, can prevent bats from leaving the building. External artificial lighting has shown to delay the onset and sometimes slows down the evening emerge and as a result shortens their feeding time. Even though some species do forage around street lamps, every insectivorous species is sensitive to artificial light at their roost site (Patriarca and Debernardi, 2010).

Even though bats are nocturnal animals, some species have adapted their hunting techniques, now foraging under illuminated conditions. Some bat species can be found predating on insects around street lamps. For these species, artificial light has a positive effect on the amount the amount of prey they catch overnight. Other bat species are not that tolerant at all, avoiding light sources at night. This sensitivity is related to the emerging time of the bat, as well as their feeding habits and wing loading. Species like *Pipistrellus pipistrellus,* for example, are tolerant for light until 15 lux and are very common in rural areas (Swift, 2009). Those light-tolerant species usually also fly relatively fast and have a low wing loading. Species that fly relatively slow, have a larger wing loading and feed on insects that are present later in the evening.

They tend to be light-intolerant and avoid artificial light at night. This could be due to the avoidance of predation, the sensitivity to light (the light intensity is so high it blinds them) or a specialised diet for insect species that emerge later in the evening. Among European bats, species whose wing loading falls between 9.0 and 10.2, which is relatively low (*Barbastella barbastellus, Myotis bechsteinii, Eptesicus nilssonii, Vespertilio murinus* and *Rhinolophus ferrumequinum, Myotis daubentonii*) exhibit similar emergence times (Russo *et al.*, 2007).

Dark repair and recovery

Data on dark repair and recovery in bat species remains scarce. As described earlier, short pulses of light could already disrupt the production of hormones like melatonin (Gaston *et al.*, 2013) and therefore harm bats in their function. Studies on microbats have suggested that melatonin may influence the reproductive activity (Kawamoto, 2003) through sperm storage (Beasley *et al.*, 1984), ovulation (Srivastava and Krishna, 2010a), implantation – which is the stage in which the embryo adheres to the uterus wall - (Haldar and Yadav, 2006) and glucose metabolism during hibernation (Srivastava and Krishna, 2010b). Those studies concluded that artificial light at night simulates long day conditions, which could increase reproduction in bat species. This could lead to a higher mortality rate, since the weather conditions are not always suitable to provide for young bats to survive.

Circadian clocks and photoperiodism

Studies concerning the influence of artificial light on the circadian clock of bats have so far mostly been conducted on species outside of Europe. In general, bats have more rods than cones in their eyes. Therefore, they are probably more sensitive to light compared to other mammals. This hypothesis is confirmed in the microbat *Molossus molussus,* which has the lowest observed illuminance threshold (10^{-5}) for photic entrainment of circadian activity rhythms in vertebrates (Erkert, 2004). A study on an Asiatic species (*Hipposideros speoris)* has found that the constant illumination of a cave-roost suppressed the synchronisation of the rhythm between rest and activity (Marimuthu and Chandrashekaran, 1983).

Visual perception

Bats see best in dim light, and they predominantly rely on vision rather than echolocation when both cues are available. When bats are blinded or fly under dark conditions, fewer collisions (like crashing on to buildings and windows) are seen compared to enlightened conditions (Davis and Barbour, 1965).This indicates that high light intensity levels can cause problems for the visual perception of bats. For some species, this might affect their ability to hunt or find their way back to their roost.

Spatial orientation

Since bats use sunset cues to calibrate the Earth's magnetic field, artificial light can disturb this calibration and therefore make it more difficult for bats to navigate (Holland *et al.*, 2006). Some species avoid lighted areas. Therefore, artificial light can act as barriers, obliging bats to change their flight route or even forcing them to leave the area (Patriarca and Debernardi, 2010). For spatial orientation, this means that migrating is more difficult and therefore more costly.

The effects of different light sources on insect and bat species

In table 3.2, for the species covered in this study, the spectrum of light they can detect is shown.

Table 3.2 The sensitivity of bat and insect species to the wavelengths of light, and the effect of specific street lights on those species, ranging from -- (very negative) to ++ (very positive). The table was creating using own insight, using the literature summed up in this chapter. HPS= High pressure sodium lamp, LPS = Low pressure sodium lamp, HPM= High pressure mercury lamp, MH= Metal halide lamp, CFL= Compact fluoride lamp, LED= Light emitting diode lamp, HAL= Halogen lamp.

	Eye sensitivity (nm)							
		HPS	LPS	HPM	MH	CFL	LED	HAL
Light-avoiding bats (Chiroptera)	400-600(with some species being able to see below 400)	+	+-	+	+	+	*	+
Light-attracted bats (Chiroptera)	400-600(with some species being able to see below 400)	--[1]	+-	--	--	--	+*	--
Beetles (Coleoptera)	348-620	--	+-	--	--	--	*	--
True flies (Diptera)	335-530	--	+-	--	--	--	*	--
Butterflies (Lepidoptera)	380-610	--	+-	--	--	--	*	--

***Depends on the colour of the LED**

Summary

Artificial light is mainly produced by lamps. The outdoor artificial light is mostly used in urban and western areas in the world. High pressure sodium, low-pressure sodium, high-pressure mercury, metal halide, compact fluorescent, LED, incandescent/Halogen and fluorescent tube lamps are most commonly used outdoor, as street lamps. The effect of those types of lamps varies. For insects and bats, street lamps can have an effect on their daily rhythm and several physiological processes. In table 3.2, the effect of street lights on the species examined in this study is summarized.

4. THE EFFECT OF ARTIFICIAL LIGHT ON POPULATIONS AND ECOSYSTEMS

In the previous chapter, the effect of artificial light on individuals is discussed. In this chapter a further step will be taken, by analysing how artificial light could affect whole populations and ecosystems. Naturally, when individuals are affected, this could as well cause the disruption or a blooming period for populations. In the first part, the different effects of artificial light within bat and insect populations and between bat populations and between insect populations will be presented, not taking into account the interaction between the two groups. In the second part, four different scenarios will be presented, showing the possible withdrawal of artificial light on insects and bat populations, looking specifically at the interaction between the species.

The effect of artificial light within insect populations

As described in the previous chapter, artificial light can disorientate or attract insects described in this study, thereby leading to a higher energy consumption and altered behaviour (such as flying against a hot lighbulb), possibly causing a higher predation or death rate by exhaustion or getting burned by a lamp. Also, as described in the previous chapter, lighting can affect insects in their navigation, vision, migration, dispersal, egg-laying, mating, feeding and camouflage. For some species with small, isolated populations, this could lead to local extinction. In Great Britain, light pollution has been identified as being a possible contributor for the decrease in 337 moth species (Fox *et al*., 2006). In other insect families, examples are known from species that declined with artificial light being the direct cause. Mayflies (*Ehpemera*) are attracted to light, because they confuse it with a water surface. They lay their eggs on artificial sources of polarised light, such as cars and road surfaces, while thinking it is a water surface. As a consequence, these eggs will not harvest. This increased mortality rate is likely to affect the population size. In Korea, species of the genus Lethocerus are attracted in large numbers to artificial light sources during night dispersion flights. Consequently, they die due to dehydration. This species has been identified as being an endangered species in Korea and artificial light is likely to be an important factor in the species decline (Bruce-White and Shardlow, 2011).

The effect of artificial light between insect populations

Artificial light alters the environment, possibly forming a selective factor in species. Langevelde *et al.* (2011) conducted a study to compare the behaviour of forty moth species in the Netherlands and found that a higher amount of larger moth species are found to be attracted to artificial light sources, compared to areas with low light emission at night. This might be due to the eye size of insects, which is significantly different between moth species. This could lead to a higher mortality rate in larger moth species compared to smaller species. These findings could apply to other insect species as well, proving that light can be an important selective factor in the presence of species. This way, artificial light at night can alter the composition of species that have the same niche in an environment.

Another way artificial light at night can be a selective factor is described by Davies *et al.* (2013). Street light is an addition of light to the naturally present light, enabling insects to see more at night, depending on the kind of wavelength and light intensity that is used. So when some species are favoured by artificial light at night, they have an advantage over other species and might outcompete them.

The effect of artificial light in insectivorous bat populations

Since there are two distinguishable groups of bat species that avoid or are attracted by artificial light at night, the effect of artificial light at night in bat species varies. For light-sensitive species, artificial light at night can have a huge impact, even causing a species to avoid whole lit areas. An example is Myotis Daubentonii, which is known to move their flight paths to avoid street lamps (Bat Conservation

Trust, 2009). This is a negative effect on the populations, since it is more costly to migrate, possibly causing fragmentation and a higher mortality rate.

The effect of artificial light between bat populations

Artificial light at night can be a selective factor for bat species. It may cause competition between species, when some species are more tolerant or adaptive to this changing environment. In south-west Switzerland, this scenario is happening between the pipistrelle bat (*Pipistrellus pipistrellus)* and the lesser horseshoe bat (*Rhinolophus hipposideros).* Both species feed upon the same prey, therefore being competitors. They use the same feeding grounds but the pipistrelle bat forages around street lights, while the lesser horseshoe bat avoids lamps. Arlettaz *et al.* (2000) hypothesize that the dramatic decline in the population of lesser horseshoe bat may be partly due to the fact that the pipistrelle bat is actually outcompeting this species. Since there are much more species avoiding light (like *Myotis Daubentonii*) or using street lamps in their advantage (Like *Eptesicus serotinus*) (Davies *et al.,* 2013; Fure, 2006), this is a scenario that could be happening in every area that is lit at night. This means that artificial light could cause the extinction of light-avoiding species in areas that contain artificial light at night.

Interaction between insect and bat populations under influence of artificial light

There are several possible scenarios concerning the withdraw effect of artificial light on populations and ecosystems. As discussed in previous chapters, artificial light can both benefit and harm species. This could lead to four different scenarios, as shown in figure 4.1. A side note to this table is the very likely scenario that the various insect species could react differently to artificial light. So, when Diptera populations decline but Coleoptera species increase, food availability for bat species will not change due to artificial light. However, these differences between species are not taken into account in the scenarios since its complexity is difficult to capture in a scenario approach.

Table 4.1 Four possible scenarios for the effect of artificial light on the interaction between insectivorous bat and insect species

Effect of artificial light at night	1. Positive for bats	2. Negative for bats
1. Positive for insects	1.1 Both species groups will increase in number. When the balance of species stays equal, the total effect might be positive regarding nature-conservation, especially when the situation involves endangered species. However, when other resources – like roost locations for bats – are limited, the proportions of species could get out of balance.	1.2 While bat population will decline, causing the insect population to grow due to less predation, the positive effect of artificial light at night will cause a further increase in insect numbers. This might lead to more food availability for bats, possibly compensating for their decline. When this is not the case, other predators might be favoured or –in worst case scenario - a plague of insects could erupt.
2. Negative for insects	2.1 While insect populations decline, due to artificial light at night, increasing bat populations – advantaged by these lights – will cause a further decrease in insect numbers due to a higher predation level. This might lead to less food availability over a larger timeframe, causing the bat population to decrease in numbers. When this vicious circle continuous, this could lead to extinction of local populations of insects as well as bats.	2.2 Both species groups will decline in numbers due to the consequences of artificial light at night. This might have serious implications for the persistence of the harmed species at a local level. However, since artificial light at night is present in more and more areas, over a larger timeframe, it might endanger species by causing extinction of populations over a larger scale.

Scenario 1 Artificial light at night has a positive impact on insects, therefore causing an increase in population number.

1.1 *Artificial light at night has a positive impact on bat species, therefore causing an increase in population number.*
By increasing the amount of light at night, some species might be more capable of detect their resources, their congeners (which might be helpful concerning mate selection) and navigation (Davies *et al.*, 2013), thus improving the viability of the species as a whole. In this scenario, both insects and bats benefit from the increased amount of light. When both predator and prey stay equal in proportions during this process, artificial light at night might be a positive factor regarding nature conservation, especially when concerning endangered species. An example of a species that benefits from artificial light is the pipistrelle bat (*Pipistrellus pipistrellus)* which uses light to improve their hunting efficiency by catching insects attracted to street lamps and therefore is more present at lit sites compared to dark sites (Stone *et al.*, 2012). Although literature on the subject was not found, it is in theory possible that some insect species can benefit from artificial light, for example when the light enables them to see their food better. On a larger timeframe, the population growth of one or both species could eventually decline, due to shortages in other resources like roost opportunities for bats.

1.2 *Artificial light at night has a negative impact on bat species, therefore causing a decline in population number.*
While artificial light might improve the ability of insects to navigate, detect their resources and find congeners (Davies *et al.*, 2013), this might not apply to bat species. Especially slow-flying bats like *Rhinolophus* and *Myotis* species do not forage at street lamps and are rarely seen in illuminated areas. It is difficult to estimate to what extend artificial light can cause a decrease in bat number, since other factors as the use of pesticides or noise disturbance can be a major cause as well. But, under experimental conditions, individuals of *Myotis dasycneme* reacted to light, modifying their normal flight trajectories (Pariarca and Debernardi, 2010). Also, *Rhinolophus hipposideros* showed a dramatic reduction in activity (bat passes) in illuminated conditions and the onset of commuting behaviour was found to be delayed in the presence of artificial light from 4.17 lux of more (Stone *et al.*, 2009). These findings all support the hypothesis that artificial light can have a negative impact on bat species, even though insect species might be favoured. Examples of how insects could be favoured were not found in literature. However, it is possible that some insect species are more efficient in finding food when artificial light is present. Light-avoiding bats are very likely to avoid specific illuminated areas, even though the amount of prey might increase. This scenario is less likely to apply to light-attracted bats like *Pipistrellus pipistrellus*, since these species do not avoid areas with artificial light.

Scenario 2 Artificial light at night has a negative impact on insects, therefore causing a decline in population number.

2.1 Artificial light at night has a positive impact on bat species, therefore causing an increase in population number.

An example of this scenario is found in the interaction between moths and light-attracted bats that forage around street lights. Langevelde *et al.* (2011) found that mercury vapour lamps interfere with the ability of moths to detect bats. In this situation, artificial light favours bat species while harming the population of moths, direct by attracting moths to the lamp and indirect by increasing their vulnerability to echolocating bats. A possible consequence for prey-specific bats is the decrease of food on the longer term, thereby decreasing the population of bats. The moths have learned over time how to avoid predation, but now street lamps interfere with this adapted behaviour. It is very likely that moth species will – in time – learn how to cope with this new environmental situation. As a result, bat species will have to adapt to this changed behaviour. It is hard to predict how this interaction between prey and predator will develop overtime.

2.2 Artificial light at night has a negative impact on bat species, therefore causing a decline in population number.

As described at 1.2, artificial light is very likely to be a major cause for light avoiding species to be repulsed from whole enlightened areas. This is not a very likely scenario to occur for light attracted bats, since they don't avoid these areas. However, when the amount of prey decreases, due to artificial light, those species might also disappear from a certain area.

A lot of insects also experience a negative impact from artificial light at night. The effects on reproductivity and mortality rates could be so severe the species goes extinct in certain regions.

Cumulative effect

Of course, species are influenced by other factors than only artificial light at night. Environmental impacts as noise disturbance, air and soil pollution, renovation of old roosting locations and the use of pesticides are also very important and influential factors. These factors could all enhance the effect of artificial light, causing a cumulative effect on populations and ecosystems. For example, the use of pesticides combined with the presence of artificial light could increase the predation rate in insect species even more. Or the combination of replacing old buildings and farms with new buildings that lack roosting opportunities, combined with the addition of street lamps next to the road, is very likely to drive bat species away from the area.

Summary

Artificial light affects individuals, but it also has an effect on populations and ecosystems. Literature to provide for examples of this phenomenon is very scarce. Artificial light can affect the population itself, by increasing the mortality or reproduction rate, but it can also change the interaction between species of the same family or even predator-prey relationships. For some species with small and fragmented populations, artificial light could cause local extinction. Also, some species that are favoured by artificial light could outcompete another species. Four different scenarios for the effect of artificial light on the predator-prey relationship between bats and insects are considered. However, the possible differences in effect between insect species or bat species is not taken into consideration. In general, it is recommended to perform more studies on the effect of artificial light on populations.

5. THE DEFINITION OF LIGHT POLLUTION AND ITS STANDARDS

In the previous chapter, the effect of artificial light at night on species, populations and ecosystems is examined. There are a lot of environmental impacts that are referred to as pollution, for example soil, air and noise pollution. Pollution is generally referred to as the introduction of contaminants into the natural environment that cause adverse change (Merriam-webster, 2010). Regarding artificial light at night, this is a phenomenon acting as a pollutant as well, since the introduction of it can cause adverse change in species. Light pollution is therefore an expression that is often used, but when does artificial light indeed act as light pollution? In other words, what is light pollution? In this chapter, this question will be answered and also ways to quantify light pollution will be discussed. Also some limit values as described by several authors are discussed.

The definition

As defined by Hollan (2009), light pollution is 'the alteration of light levels in the outdoor environment (from those present naturally) due to man-made sources of light'. This differs from the definition of pollution, as described in the intro, where it is referred to as a factor that causes adverse change in a natural environment. An alteration of light levels will not necessarily be a contaminating factor, so this definition from Hollan is not in line with the definition for pollution.

Falchi *et al.* (2011) give a slightly different definition, referring to it as 'the alteration of natural light levels in the night environment produced by introduction of artificial light'. It is basically the same as the definition from Hollan (2009) but with the introduction of 'night environment'. According to these authors, light pollution can only exist at night.

The Ministry of the Flemish community (Ministerie van de Vlaamse Gemeenschap, 2001) refers to light pollution as 'the increased illumination of the night environment, caused by excessive and wasteful use of artificial light'. Still, in this definition, no polluting characteristic of this artificial light is given, supposing they refer to light pollution as being light that is more than necessary for its purpose. They do introduce the words 'excessive' and 'wasteful', implying that only artificial light that is not efficient can cause pollution. So this definition is mostly referring to the way light is used, and not so much to the effect it has on the environment. Also, a new term is introduced. Light nuisance is introduced as being 'the disturbance that people and animals experience by artificial light at night'. This seems to be a relevant terminology, but why light nuisance is fundamentally different from pollution remains unexplained in this document.

Verheijen (1985) proposed the definition 'the degradation of the photic habitat by artificial light'. The photic habitat probably refers the 'light dimension' of an area, in other words 'the natural characteristics of the amount and type of light for a specific area'. The photic habitat at a forest floor, for example, is significantly different from an open grassland. From all the phrases presented above, this one is the most in line with the definition as given above. Artificial light at night might not always be a pollutant, since it can have a positive or even no significant consequences for the environment, especially when environmental-friendly lamps are used. So, an increased amount of light at night will not always be a pollutant, only if the photic habitat is degraded or adversely effected by this light. The definition by Verheijen (1985) is the most suitable for light definition and will be used in the rest of this study.

Quantification methods for light pollution

Now a definition is chosen to explain what light pollution actually is, a method for quantification is necessary. Since artificial light will not always cause a degradation in the environment, only some forms of artificial light – in specific situations – will be pollutant. This is dependent on the type of environment, the initial situation of the location before artificial light was introduced, the species that are present and the weather, the amount of light sources, the wavelengths emitted by the light source(s) and the direction of the light. The most difficult factor might be the initial situation, since in some situations this knowledge is impossible to regain.

Hollan (2009) presents a way to deal with this. A reference for a specific location with artificial light should be the same location with only light of natural origin. Since this is difficult information to regain, the added artificial light in an environment should be measured absolutely or relatively.

Absolute measures for artificial light

As other pollutants, light can be measured by concentration, for example in lumen per square meter. Also, the emission or amount of pollutant added to the environment within a specific time frame can be measured. Luminous flux or lumen seconds are usable units. For light, also the direction and spectrum are important properties. These two factors can be combined in the 'spectral radiance', usually expressed in Watts per steradian per square meter per nanometer. To combine the measurements of artificial light with the suspected impact on organisms, the luminance can integrate the spectral sensitivity of a species to the spectral radiance.

Relative measures for artificial light

If an artificial light source is pollutant, is often dependent on the light that is naturally present at location. For this reason, a single street light could be pollutant under an overcast sky, but not when the sky is clear. Also, the addition of artificial light at times where daylight is present, is usually not significant whereas at night it is. Therefore, if an artificial light source is pollutant is often dependant on the amount of light it adds in proportion to the natural light that is present. According to Hollan (2009) an addition of artificial light with 10% or less of the level of natural light that is present, is considered as insignificant. In overcast skies, especially with the additional presence of snow, light pollution is ten times greater compared to clear skies. This is due to the reflection of the light, the clouds and snow act as a mirror. This effect is shown in figure 5.1.

Figure 5.1 The reflection of light on clouds (source: http://www.merriam-webster.com/dictionary/pollution

Considering this, the formula for expressing the relative amount of light pollution is as follows:

$$relative\ light\ pollution = \frac{man\text{−}made\ part\ of\ any\ photometric\ or\ radiometric\ quantity}{natural\ part\ of\ the\ same\ quantity} \quad (1)$$

Regarding the visibility of illuminating objects like the moon, stars and illuminating insects like light fireflies, the measures mentioned above are not sufficient to determine the amount of pollution that artificial light has. Illuminated objects get dimmer due to light pollution, depending on the contrast with the luminance of the background. The contrast of a target is:

$$contrast = \frac{luminance\ of\ the\ target - luminance\ of\ the\ background}{luminance\ of\ the\ background} \quad (2)$$

This formula can be integrated in a measure for measuring pollution, by comparing a polluted and unpolluted situation:

$$ratio\ of\ two\ contrasts = \frac{contrast_{\ \ polluted}}{contrast_{\ \ clean}} \quad (3)$$

This formula is specifically useful since organisms often use illuminated targets of light for their navigation and to find each other. By examining how artificial light changes the visibility of these targets, the amount of pollution can be defined.

The wavelength of a light source is an important factor, so this should also be taken into account. Since shorter wavelengths generally cause more harm to wildlife, especially when containing ultraviolet light, these colours could be defined as being more pollutant compared to longer wavelengths at the yellow, orange and red side of the spectrum.

The measures from Hollan (2009) provide for useful techniques to quantify light pollution. The measures cover the most important factors to examine the amount of light pollution. The elements used are light concentration (lumen/m^2), light emission (luminous flux), direction, and wavelength Also the external factors are used; the condition of the night sky, presence of snow, presence of natural light and contrast of illuminated targets. To measure light pollution, the contrast formulas are probably the most suitable methods, since they take into account the luminance of the background.

Another quantification method is developed by IPO (2012). A calculation model, integrated in a software program, enables the examining of the amount of light pollution in a certain area. It is mainly applicable for situations where an addition of light is planned in a certain area, to calculate the impact of the specific addition of artificial light, for sky glow as well as illuminance of the area. The values that are used, were measured at seventeen measuring locations in two towns in the Netherlands were applied for the calculation in other situations as being standard values. The natural skyglow was calculated using an average for all nights measured (o.25 mcd/m^2). The software program is called “IPO licht” and until now only available for the Netherlands.

Limits for light pollution

To be able to fully quantify light pollution and to set measures to reduce its impact, limits should be set. Since the effect of artificial light is dependent on technical aspects like wavelength as well as external factors like cloud cover, an all-embracing limit cannot be constructed. This is reflected in the literature, where limits are hard to find. Some thresholds however have been found:

- Hollan (2009) considers a pollution of more than10% of the natural light level at that moment can be considered as significant.
- Falchi *et al.* (2011) recommend a ban of the outdoor emission of light at wavelengths shorter than 540 nm, to prevent disruption of circadian rhythms and decreased melatonin production in humans and animals. Where those colours are however needed, the wavelengths between 440 and 540 nm should be removed as much as possible. In practice, this means that the emission in this wavelengths should not exceed fifteen percent of the energy flux emitted in the photopic response pass band, measured in watts. Also, the emission in the scotopic response pass band should not exceed two-thirds of that emitted in the photopic response pass band, measured in lumens.
- The International Dark-Sky Association and the Illuminating Engineering Society (2011) have conducted a user’s guide to decrease light pollution. Some limitations for total initial lumens per site are given, taking into account different types of environments. Those limitations vary

between 0.5 lumens/m^2 for areas where the natural environment will be seriously and adversely affected by lighting, to 7.5 lumens/m^2 for areas with high ambient lighting.

- The ILE (2005) recommends that street light should not be directed at any potential observer with a beam angle more than 70^o. Also, vertical structures as advertising signs should be lighted from above instead of below, to prevent light to beam up in the sky. They also conducted some limitations for exterior lighting installations, making a distinction between different environmental zones, as shown in table 5.1.

Table 5.1 Obtrusive Light Limitations for Exterior Lighting Installations (source: ILE (2005)

Environmental zone	Sky Glow ULR (Max %)[1]	Light Trespass (into Windows) Ev [Lux][2]		Source intensity I [kcd][3]		Building luminance Pre-curfew[4]
		Pre-curfew	Post-curfew	Pre-curfew	Post-curfew	Average L [cd/m2]
E1	0	2	1*	2.5	0	0
E2	2.5	5	1	7.5	0.5	5
E3	5.0	10	2	10	1.0	10
E4	15.0	25	5	25	2.5	25

E1 = intrinsically dark landscapes (National Parks, Areas of Outstanding Natural Beauty, etc.)
E2 = Low district brightness areas (Rural, small village, or relatively dark urban locations)
E3 = Medium district brightness areas (Small town centres or urban locations)
E4 = High district brightness areas (Town/city centres with high levels of night-time activity)
ULR = Upward Light Ratio of the Installation is the maximum permitted percentage of luminaire flux for the total installation that goes directly into the sky.
Ev = Vertical Illuminance in Lux and is measured flat on the glazing at the centre of the window
I = Light Intensity in Candela (Cd)
L = Luminance in Cd/m2
Curfew = The time after which stricter requirements (for the control of obtrusive light) will apply; often a condition of use of lighting applied by the local planning authority. If not otherwise stated 23.00hrs is suggested.
*** =** From Public road lighting installations only
[1] = Upward Light Ratio – Some lighting schemes will require the deliberate and careful use of upward light – e.g. ground recessed luminaires, ground mounted floodlights, festive lighting – to which these limits cannot apply. However, care should always be taken to minimise any upward waste light by the proper application of suitably directional luminaires and light controlling attachments.
[2] = Light Trespass (into Windows) – These values are suggested maxima and need to take account of existing light trespass at the point of measurement. In the case of road lighting on public highways where building facades are adjacent to the lit highway, these levels may not be obtainable. In such cases where a specific complaint has been received, the Highway Authority should endeavour to reduce the light trespass into the window down to the after curfew value by fitting a shield, replacing the luminaire, or by varying the lighting level.
3 = Source Intensity – This applies to each source in the potentially obtrusive direction, outside of the area being lit. The figures given are for general guidance only and for some sports lighting applications with limited mounting heights, may be difficult to achieve.
4 = Building Luminance – This should be limited to avoid over lighting, and related to the general district brightness. In this reference building luminance is applicable to buildings directly illuminated as a night-time feature as against the illumination of a building caused by spill light from adjacent luminaires or luminaires fixed to the building but used to light an adjacent area.

These limits don't describe the maximum values for organisms in particular. There is no linkage between artificial light and the amount of deaths in insects or the decrease in bat population that is acceptable in a specific region. The limits are approximations, set for the environment in general while also taking into account the polluting effects for humans. This indicates that the measures for light pollution do not (yet) connect to nature conservation regulations as developed by the European Union. In these regulations, it is not allowed for protected species or habitats to degrade significantly, in quantitative nor qualitative perspective. The effect of a pollutant is dependent on several aspects, like the duration and frequency. A disturbance of a protected species or habitat is only significant when it leads to a significant degradation (Steunpunt Natura2000, 2009). So, what kind of light and what amount of artificial light is acceptable for bats, Coleoptera, Diptera and Lepidoptera species, should be examined using the significance of this light for those species. Using the values found in this study, table 5.2 describes the maximum amount of artificial light for the species that are examined. The same environmental regions are distinguished as used in table 5.2. The assumption is made that sensitive bat species are not present in districts E3 and E4, due to other pollutants as sound nuisance, air pollution, water pollution but also the absence of suitable roosts (for example for tree inhabiting bats). For the maximum intensity of artificial light in non-sensitive wavelengths, the values from ILE (2005) were used.

Table 5.2 Maximum amount of artificial light for bats, Coleoptera, Diptera and Lepidoptera species. Table was created using the data from studies mentioned earlier in this report.

	Sensitive wavelengths (nm) that should be banned	Maximum intensity of artificial light in sensitive wavelengths (lux)				Maximum intensity of artificial light in non-sensitive wavelengths (lux)			
		E1	E2	E3	E4	E1	E2	E3	E4
Light-avoiding bats (Chiroptera)	400-600	0	10^{-5}	[1]	[1]	2	5	10	25
Light-attracted bats (Chiroptera)	400-600	0	5	15	15	2	5	10	25
Beetles (Coleoptera)	348-620	0	0.004	1.00	1.00	2	5	10	25
True flies (Diptera)	335-530	0	0.004	1.00	1.00	2	5	10	25
Butterflies (Lepidoptera)	380-610	0	0.004	1.00	1.00	2	5	10	25

E1 = Intrinsically dark landscapes (National Parks, Areas of Outstanding Natural Beauty, etc.)
E2 = Low district brightness areas (Rural, small village, or relatively dark urban locations)
E3 = Medium district brightness areas (Small town centres or urban locations)
E4 = High district brightness areas (Town/city centres with high levels of night-time activity)
[1] = Species is not expected to be present at these locations. Furthermore, a level of 10^{-5} lux could already cause disruption of the circadian clock of very sensitive species (Erkert, 2004).

Light pollution in Europe

Light pollution definitely fits in the row of important ecological pollutants. It has the potential to disrupt populations and ecosystems, by changing their daily rhythm, species interaction and several physiological processes. Some species that suffer from light pollution, for example several mayflies in the United Kingdom, and beetles in Korea (Bruce-White and Shardlow, 2011). This is also the case for some bat species that are known for being light avoiding (Ministerie van Economische Zaken, Landbouw en Innovatie, 2013). At the moment, the most abundant lights are low-pressure sodium lamps, which do not emit polluting wavelengths. However, more and more street lamps are substituted by LED lamps which can emit a lot of different colours and could therefore become a very polluting source for insects and bats in Europe. Sensitive species could go (locally) extinct when their natural photic habitat is disrupted. In the next chapters, this will be further discussed.

Summary

Combining the findings described above, light pollution can be defined as being *the degradation of the photic habitat by artificial light*. It can be measured in absolute or relative ways, although relative measures are more suitable, since light pollution is dependent on internal as well as external factors. Several formulas are suitable to calculate the amount of light pollution, but there also is a software program to examine the impact of the addition of artificial light in a certain area. Several institutions have tried to give maximum values for light pollution. In general, these values differ between 0 kcd (kilocandela) for intrinsically dark landscapes to 25 kcd for high district brightness areas and 0.5 lumen/m^2 for dark landscapes to 7.5 lumen/m^2 for high district brightness areas. Furthermore, recommendation for general pollution is that only artificial light that increases total light intensities with more than 10% are significant. Concerning wavelengths, emission of light with wavelengths shorter than 540 nm should be banned as much as possible. In addition, street light should not be directed at any potential observer with a beam angle over 70 ^{o}. For the species examined in this study, table 5.2 gives the maximum acceptable values. In the European Union there is a lack of guidelines to determine the acceptable amount and types of outdoor artificial light. Formulas from Hollan (2009) or threshold values from the various sources described in this chapter could serve as a first step towards realistic and applicable policies. This is needed, since light pollution in the EU is potentially a problem, especially for vulnerable species that are already declining. In the future, more and more LED lamps will be used at the expense of the relative environmental-friendly low-pressure sodium lamps, which could lead to further decline in light sensitive species.

6. TECHNOLOGICAL MEASURES TO REDUCE THE NEGATIVE EFFECTS OF ARTIFICIAL LIGHT AT NIGHT ON INSECTS AND INSECTIVOROUS BATS

Now that the impact of artificial light at night on insects and bats are defined, this chapter will provide for some technological measures to reduce these effects.

The way that artificial light can influence the natural world can be divided in different aspects, but only some of them are really technological and could be changed in the light source itself:

- Intensity and wavelength
- Location, direction and range of the light
- Duration of the light emission

Other factors, like the weather and sky conditions and environmental conditions, are external factors and can only be taken into account through political measurements, as described in the next chapter. For every technical aspect, some measures can be taken to decrease the amount of disturbance it could cause for insects and bats.

Intensity and wavelength of light

For the species examined in this study, smaller wavelengths are more pollutant compared to longer wavelengths, especially when they contain ultraviolet light. Therefore, larger wavelengths are more environmental-friendly. If small wavelengths are used anyway, the intensity of a lamp should be as low as possible to avoid negative effects. At the same time, in any case, the amount of light should never be more than the task requires.

Concerning Coleoptera, Diptera, Lepidoptera as well as bat species, wavelengths close to and above 600 nm are very unlikely to have a negative effect on their livelihood. So light sources that emit those wavelengths can be defined as environmental-friendly. A wavelength of 617 nm attracted the least amount of moth species in a study by Langevelde *et al.*, 2011. As described in the past chapter, some values are given for the maximum value of artificial light at night (table 5.2). These values should be used as limit values. Also, artificial light that increases the total light intensities with more than 10% is possibly pollutant and should be further analysed, to examine what the effect on the environment is. Concerning wavelengths, emission of light with wavelengths shorter than 540 nm should be banned as much as possible. In addition, street light should not be directed at any potential observer with a beam angle over 70 º.

Location, direction and range of the light

Most artificial light is meant for activities directly below the lights, but still a lot of this light gets emitted in a widespread area and even in the sky where nobody needs it. This dispersion of light

Figure 6.1 Lamp that emits light in all directions (source: http://environmentallysound.wordpress.com/light-excreta-2/light-excreta/)

Figure 6.2 Lamp that emits light in all horizontal directions (source: http://viper007bond.deviantart.com/art/Mount-Tabor-Street-Lamp-Dark-481752)

Figure 6.3 Skyglow as a result of unshielded lights (source: http://www.livingwestof5.com/wordpress/wp-content/uploads//sd-lights.jpg)

causes a lot of disturbance, in urban areas due to the concentration of lights and the resulting sky glow, and also in rural areas where there are no obstacles to interrupt light. There is a huge difference in dispersion between several artificial light sources. For example, in figure 6.1 the light is emitted in all directions, while the main goal seems to be to illuminate the road. In figure 6.2, the street lamp mostly emits the light in a horizontal direction, not even concentrating light on the street. In figure 6.3 the sky glow, caused by these kinds of street lamps, is shown.

To prevent skyglow, the best measure is to shield lamps. Not only can the light be shielded directly at the source (figure 6.4) but also walls could be build next to roads or industrial areas. Those walls could also function to prevent noise pollution. Another option is to prevent light pollution at specific locations, for example on specific sites where bats migrate and cross a road or urban areas.

Figure 6.4 Shielding of light, directly at the source (source: http://www.asc-csa.gc.ca/eng/educators/resources/stars/light.asp)

Duration of the light emission

Even though the addition of artificial light at night feels like an improvement for safety to humans, it is mostly the sense of security that is improved by light (Clark, 2003). A lamp activated by a movement sensor might be the best option for preventing crime. This type of lamp goes on if it senses movement. Apart from the safety argument, this lamp is also much better for the environment, since it only emits light during short times at night. In houses, it is very normal to put the light off where nobody needs it, so why not extend this attitude outdoors? One of the technical solutions already put in use in limited locations, relies on this principle. Street lamps are dimmed, only activated when they are passed by, thus decreasing the duration and intensity of their emissions. A suitable solution for highways, where street lamps are mainly functional for observing the direction of the road, is to eliminate lamps but to introduce lines or whole roads that emit or reflect light. Those lines emit significantly less light compared to traditional street lights but serve the same purpose. Examples of those techniques can be seen in figure 6.5 and 6.6.

Figure 6.5 Glowing lines, showing the direction of the road (source: www.fietsguru.nl)

Figure 6.6 'van Gogh' cycling road, enlightened by thousands of 'glow in the dark' stones, taking up light in the day and emitting this light during the night (source: www.cultuurgids.avro.nl)

Another technological measure is the use of dimmable street light that can be activated from a distance. This is already put in use in Tilburg (the Netherlands) where officers can activate a zone of light – for example when criminal activities are present - by sending a text message. Also, light could be switched off during specific times of the night. This has been done recently in many highways in the Netherlands. When weather conditions require more light, this is not likely to influence bats and insects. Those species usually don't fly during conditions with a lot of rain or wind.

Summary

Several measures are suitable to minimize the polluting effect of artificial light on the environment, or to replace artificial light as a whole. These measures can be integrated in a plan specifically set up for the species examined in this study. Which measures are suitable for specific situations and which measure is the best? In table 6.1, the technical measures are summarized for different environments.

Table 6.1 Suitability of technical measures for specific environments

	Ban wavelengths below 600 nm	Shield light	Use of sensory lights	Use reflecting objects instead of light	Use light-emitting roads or lines	Use remote controlled lamps	Turning lights off during specific periods of the night	Turning lights off entirely
E1	x			x			x	x
E2	x	x	x	x	x	x	x	
E3	x	x	x		x	x	x	
E4		x						

E1 = intrinsically dark landscapes (National Parks, Areas of Outstanding Natural Beauty, etc.) where even the smallest amounts of artificial light can have tremendous effect

E2 = Low district brightness areas (Rural, small village, or relatively dark urban locations) where species are tolerant to small amounts of artificial light

E3 = Medium district brightness areas (Small town centres or urban locations) where very tolerant species are present and artificial light is needed for specific purposes.

E4 = High district brightness areas (Town/city centres with high levels of night-time activity) where a lot of human activity requires the constant abundance of artificial light.

7. POLICY MEASURES TO REDUCE THE NEGATIVE EFFECTS OF ARTIFICIAL LIGHT AT NIGHT ON INSECTS AND INSECTIVOROUS BATS

Policy measures are an important tool to make sure that positive changes in the management, use and technology of artificial light are made. This chapter gives a short and superficial overview of some examples of existing policies. Also, some recommendations are given to minimize light pollution through policy measures from the author's perspective.

To minimize light pollution in the European Union, a policy describing how to cope with light pollution is indispensable. Since the technical measures described in the previous chapter are often costly and could maybe receive criticism from civilians or companies, a policy is needed to establish specific and practical laws and requirements that are equal for a large area. Now, provinces, countries and cities are able to use various types of lamps, even when they could potentially harm organisms. And when a city decides to invest in eco-friendly lights, when the nearest town decides not to cooperate, these eco-friendly lights might not even have the desired effect. The following factors of artificial light can be influenced by policy:

The mandatory use of technical measurements

- Only use of lamps that illuminate the area needed are permitted. Dispersion of light in the surrounding area and sky is not allowed.
- Light should only be present when needed. So, for roads with few traffic, solutions like reflecting lines or roads should be used. Lights can go out if they are not needed.

The qualifications that have to be met before artificial light can be used (for example; a study of flora and fauna or impact assessment could be a requirement)

In multiple situations where the environment is altered, for example through the addition of roads or buildings, an impact assessment to examine the potential harm done to flora and fauna is required before a permission is granted. According to the use of artificial light at night, this might be a good method to control light pollution.

Norms and standards for the use of light (for example; which intensity and wavelengths are permitted)

Guidelines should be present to control the use of light. Specific wavelengths that potentially harm the environment should be banned. Excessive use of light is a waste of energy and have a negative effect on bats, insects and potentially other organisms. So, there should be maximum values for light intensity as well. The threshold values from table 5.2 are suitable for use in the EU and provide for limits that meet the needs of a specific area. So rural areas have lower maximum values compared to urban areas, since urban areas often require more artificial light for safety, recreational and work.

In the European Union, there are no laws or regulations that set specific measures for the maximum acceptable amount of artificial light at night. However, there are some countries, regions and cities that do have specific guidelines concerning this subject. An example of countries that have those regulations are given below:

- Since 2007, Slovenia has a law against light pollution. It is forbidden to have light emitted upwards to the sky. Furthermore, small wavelengths are being banned from light sources (Dark Skies Awareness, 2007)
- In the United Kingdom, light pollution is recognized as being statutory nuisance. In practice, it generally means that civilians have more rights to claim to ban light when it is disturbing them (Taylor, 2006)
- In Italy and some parts of Spain measures are taken, particularly in vulnerable regions and nature reserves.
- In Croatia and France a law is in the making for preventing light pollution.

In most regulations that exist, measures are mostly taken in shielding the light and conducting maximum values for light emission. In some cases, as in Italy and Slovenia, harmful wavelengths are banned. In La Palma, but also since recently in the Netherland, light is shut down at some hours of the night. The effort of these countries is a great improvement, but regulations and laws for the whole of Europe is needed. Since there is an open market between EU countries, the different laws could cause unequal economical environments for companies involved in artificial light. The use of eco-friendly lights and the need for specific impact assessments is costly, so when a business has to choose a location for their business, they are more likely to choose a country without these requirements over a country that has laws and demands concerning this artificial light. That is an important reason to integrate a law for the use of artificial light in the EU. Furthermore, there are already laws and regulations concerning the environment for the whole of the EU, like the Natura2000 legislations. Limits for artificial light in these natural areas could be integrated in their management plans.

<u>Summary</u>

A policy concerning the use of artificial light, for the European Union in its whole, is needed to prevent light pollution in the future and to minimize the pollution already present. When countries develop these regulations individually, this could create economical unequal environments for companies and individuals, thereby undermining the open economy principle of the EU. Examples of artificial light measurements are present throughout the EU, for example in Slovenia and the UK. Also, the technical measurements and threshold values given in the previous chapters are useful for practical policy measures.

8. DISCUSSION AND CONCLUSION

Now that the previous chapters have provided for information about several aspects of light pollution, this chapter will answer the main research question as well as the minor research questions as conducted in the introduction.

This study is conducted to examine the effect of artificial light at night on specific insect and bat species in the European Union. Several scenarios and plausible effects of artificial light have been discussed to prove that artificial light can have a significant effect on those species groups. However, it is clear that there are still gaps in the knowledge concerning the effect of light pollution. Especially regarding the effect on populations and ecosystems, it turns out to be a difficult task to measure how artificial light affects species. However, there are already some examples of species that are declining, while artificial light is very likely to be the cause for this. Since the study only describes the effect on specific insect and bat species, the recommendations for policy and technical measures are not yet complete for use. It is needed to examine the effect on other species groups as well, since they might have different requirements for the artificial light at night. Also, the guidelines might not be applicable for other parts of the world, since they inhabit different species and the environmental conditions are often significantly different.

1. **How do Lepidoptera, Diptera and Coleoptera use light for their survival, to what extend do they protect themselves from insectivorous bats and how have these predators adapted their hunting techniques to this behaviour?**
   Insects and bats both use light for their survival, by using it as a resource as well as an information source. Light tells these organisms, when to be active, where they can find food, mates and suitable habitat. It is the most important cue for these animals. Bats have adapted their hunting techniques to be able to catch their prey, but the prey is also constantly finding new ways to prevent themselves from being eaten. Some moth species, for example, can hear the echolocation call of a bat and respond to that by performing evading flights. So bat species use street lamps to catch moth species, since those moths behave like they are flying in daylight, not prepared for a bat encounter. Maybe, in time, moths will adapt their behaviour and will also perform evading flights near street lamps.

2. **What is the effect of artificial night-time lighting on the spatial, temporal and spectral components of natural light regimes?**
   Artificial light at night alters the light regime. Firstly the intensity of light is much higher compared to natural light intensities at night. And secondly, the wavelengths that are emitted are much different from the natural wavelengths that are available at night.

3. **What are the consequences of the alteration of natural light regimes on the physiology and behaviour of Lepidoptera, Diptera and Coleoptera that use light as a resource or as an information source?**
   By changing the natural light regimes, artificial light affects these insect species in their partitioning of activity between day and night, circadian clocks and photoperiodism, visual perception and spatial orientation. From all most-used street lamps, low-pressure sodium lamps have the least impact on the species examined in this study. If the emitted wavelength of a lamp is not visible for a species or if the light intensity is not high enough for the organisms to perceive, the lamp is not expected to have a negative effect.

4. **To what extent do changes in insect behaviour, caused by artificial light at night, influence the physiology and behaviour of insectivorous bats?**
   By changing the natural light regimes, artificial light affects these insect species in their partitioning of activity between day and night, circadian clocks and photoperiodism, visual perception and spatial orientation. This effect is considered to be significant when it illuminates bat roosts. Furthermore, for light-avoiding bat species, artificial light can cause the species to decline or even disappear in a certain illuminated area. However, lights that emit wavelengths that are not perceivable for the individual are not expected to cause significant effect.

5. **To what extent can changes in Lepidoptera, Diptera, Coleoptera and insectivorous bats, caused by artificial light at night, influence their populations and ecosystems?**
   Artificial light can affect the population itself, by increasing the mortality of reproduction rate, but it can also change the interaction between species of the same family or even predator-prey relationships. For some species with small and fragmented populations, artificial light could cause local extinction. Also, some species that are favoured by artificial light could outcompete another species. Four different scenarios for the effect of artificial light on the predator-prey relationship between bats and insects are considered. However, the possible differences in effect between insect species or bat species is not taken into consideration. In general, it is recommended to perform more studies on the effect of artificial light on populations.

6. **How can light pollution be defined?**
   Combining the findings described above, light pollution can be defined as being the degradation of the photic habitat by artificial light. It can be measured in absolute or relative ways, although relative measures are more suitable, since light pollution is dependent on internal as well as external factors. Several formulas are suitable to calculate the amount of light pollution, but there also is a software program to examine the impact of the addition of artificial light in a certain area. Several institutions have tried to give maximum values for light pollution. In general, these values differ between 0 kcd (kilocandela) for intrinsically dark landscapes to 25 kcd for high district brightness areas and 0.5 lumen/m2 for dark landscapes to 7.5 lumen/m2 for high district brightness areas. Furthermore, recommendation for general pollution is that only artificial light that increases total light intensities with more than 10% are significant. Concerning wavelengths, emission of light with wavelengths shorter than 540 nm should be banned as much as possible. In addition, street light should not be directed at any potential observer with a beam angle over 70 ^{o}. For the species examined in this study, table 5.2 gives the maximum acceptable values. In the European Union there is a lack of guidelines to determine the acceptable amount and types of outdoor artificial light. Several formulas or threshold values from the various sources described in this chapter could serve as a first step towards realistic and applicable policies. This is needed, since light pollution in the EU is potentially a problem, especially for vulnerable species that are already declining. In the future, more and more LED lamps will be used at the expense of the relative environmental-friendly low-pressure sodium lamps, which could lead to further decline in light sensitive species.

7. **Which technological measurements are able to reduce the negative effects of artificial light at night on Lepidoptera, Diptera and Coleoptera and insectivorous bats?**
   Which technological measurement is suitable, depends on the environment. For intrinsically dark landscapes, with a lot of vulnerable species, only banning wavelengths and turning off lights entirely are suitable. In high district brightness areas, however, only shielding light is a proper measure. For the environmental types in between, other measures are applicable as well.

8. **Which policy measurements in the EU are able to reduce the negative effects of artificial light at night on Lepidoptera, Diptera and Coleoptera and insectivorous bats?**
   There is a major deficiency in laws and regulations concerning light pollution in the European Union. Some countries and regions do have some proper policy measures, but a lot of regions are still unaware of the major impact of artificial light on the natural world. Also, when countries develop these regulations individually, this could create economical unequal environments for companies and individuals, thereby undermining the open economy principle of the EU. Examples of artificial light measurements are present throughout the EU, for example in Slovenia and the UK. Also, the technical measurements and threshold values given in the previous chapters are useful for practical policy measures. The European Union therefore should set up some maximum values for light emission.

Main research question: **How does artificial light at night affect Lepidoptera, Diptera and Coleoptera and their predators -insectivorous bats- , in what extend does this cause significant ecological problems for the viability of the species, and how can the negative effects be reduced by the use of specific regulations and technologies in the EU?**
Even though there are still huge gaps in the knowledge about the effect of artificial light at night on these specific species, the knowledge that already has been retrieved is worrying. For the majority of species, light provides for the most important cues for their behaviour and internal processes. The negative impact on these factors withdraws in essential reproduction and death rates, thus threaten the survival rate of populations and consequently also species. The problems are significant for at least some vulnerable species.

There are suitable technical measurements available, but the European Union should be taking the first steps in applying them. The current policy in the EU is outdated and inefficient. Even if the effects on the biological world are not even taken into consideration, a lot of energy is wasted in street lamps that are emitting light at locations where this is not needed. Often, the amount of light is more than is needed for human needs and a lot of money can be saved by regulating the amount and the type of lamp that is used. The European Union should set limitations for the use of artificial light to make sure every country is participating. Also, every city should have a light-plan where the amount of emitted light as well as the skyglow is regularly measured and regulated. When replacing old lamps, eco-friendly or interactive lamps should be used that are only on when needed to spare energy as well as the environment.

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