The Ecological Impact of Artificial Light at Night in Landscape Architecture

Strategies and guidelines for street lights for the benefit of biodiversity and local wildlife

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The Ecological Impact of Artificial Light at Night in Landscape Architecture – Strategies and guidelines for street lights for the benefit of biodiversity and local wildlife

Den ekologiska påverkan av artificiellt ljus under natten inom landskapsarkitektur – Strategier och riktlinjer för gatubelysning för biologisk mångfald och det lokala djurlivet

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Abstract

Artificial light at night (ALAN) is an increasingly common form of light pollution that contributes to biodiversity loss, loss of dark habitats, disrupting populations both on an individual- and population level by invading biodiversity hot spots. Recent studies show that artificial light is increasing at a rate of approximately 6% annually over Earth's surface, and 88% of Europe and 47% of the United States experience light pollution on a nightly basis. Although the primary function of artificial light is to enhance safety, security, aesthetics, and navigation, ecological disruption is often a resulting effect post-design. Despite its prevalence and ecological impact, there has been little research on avoiding light pollution in landscape architecture. This thesis presents precautionary methods and practices for landscape architects and other actors, to mitigate and avoid light pollution specifically integrating into areas and habitats where biodiversity is at risk.

In this thesis, various strategies and adaptations are used while utilising the Swedish legislation as a foundation and framework. In the context of the construction process (byggprocessen), landscape architects play a crucial role in the design department. However, they may face certain limitations when it comes to the construction of street lights. To create guidelines, it is important to identify and focus on the variables that landscape architects can take into consideration, manage, and design in relation to street lights. This thesis identified these variables as placement of street lights, type of light, colour, shielding, scheduling, appropriate light illuminance, and consideration of façade lighting.

By utilising strategies and guidelines, landscape architects and other professions can introduce a more informed and intentional design. The strategies and guidelines can help to reduce the negative impact of artificial light on biodiversity and local wildlife. This thesis offers important insights into the urgent need for effective solutions to address the growing problem of light pollution and provides guidance on how to achieve this in the context of landscape architecture.

Artificiellt ljus på natten (ALAN) är en allt vanligare form av ljusförorening som bidrar till förlust av biologisk mångfald, förlust av mörka habitat, störningar för populationer både på individ- och populationsnivå genom att invadera biologiska hotspots. Nya studier visar att artificiellt ljus ökar med circa 6% årligen över jordens yta, och att 88% av Europa och 47% av USA upplever ljusförorening varje natt. Trots att den primära funktionen av artificiellt ljus är att öka säkerhet, trygghet, estetik och navigering, så är ekologiska störningar ofta resultatet efter designfasen. Trots dess utbredning och ekologiska påverkan har det varit lite forskning om att undvika ljusförorening i landskapsarkitektur. Denna uppsats presenterar försikitighetsåtgärder och metoder för landskapsarkitekter och andra aktörer, för att minska och undvika ljusförorening speciellt i områden och habitat där biologisk mångfald är hotad.

I denna uppsats används olika strategier och anpassningar med den Svenska lagstiftningen som grund och ram. I kontexten av byggprocessen spelar landskapsarkitekter en avgörande roll i designavdelningen. Dock kan de möta visa begräsningar när det gäller konstruktionen av gatubelysning. För att skapa riktlinjer är det viktigt att identifiera och fokusera på variablerna som landskapsarkitekter kan ta hänsyn till, hantera och designa i relation till gatubelysning. Denna uppsats identifierade dessa variabler som placering av gatubelysning, typ av ljus, färg, skärmning, schemaläggning, lämplig belysningsstyrka och hänsyn till fasadbelysning.

Genom att använda strategier och riktlinjer kan landskapsarkitekter och andra aktörer introducera en mer informerad och medveten design. Strategierna och riktlinjerna kan hjälpa till att minska den negativa påverkan av artificiellt ljus på biologisk mångfald och lokalt viltliv. Denna uppsats erbjuder viktiga insikter i den brådskande nödvändigheten av effektiva lösningar för att hantera det växande problemet med ljusförorening och ger vägledning i hur man uppnår detta i kontexten av landskapsarkitektur.

Keywords: artificial light at night, light pollution, ecology, biodiversity, local wildlife, landscape architecture, guideline, strategies

Table of contents

List of tables **6**

List of figures **7**

Abbreviations **8**

Introduction **9**

1.1 Aim and research question 11

1.2 Method and materials 11

Swedish legislation **14**

Elements of light and the ecological impact **16**

3.1 Type of light 16

3.2 Colour 17

3.3 Illumination levels 19

3.4 Design and composition to reduce over-illumination and skyglow 20

3.5 Shielding 21

3.6 Scheduling 22

Strategies and guidelines **24**

Discussion/Conclusion **26**

1. A trade-off with anthropogenic benefits 28

References **30**

List of tables

Table 1. The ecological and functional impacts of artificial light at night. 9

List of figures

Figure 1. Example of shielding of luminaires 19

Abbreviations

ALAN	Artificial light at night
HPS	High pressure sodium
LED	Light emitting diodes
MH	Metal halide
K	Kelvin
SPD	Spectral Power Distribution
LIL	Low Impact Lighting
IDA	The International Dark Sky Park Designation Guidelines

Introduction

Light plays a crucial role in a wide ranges of species and is an essential component in functions such as vision, physiological processes, orientation as well as adaptations to seasonal and diurnal shifts for both plants and animals. (Hölker et al. 2010). Over the past decade, the use of artificial light has been increasing at a rate of approximately 6% per year globally, with variations ranging from 0 to 20% per year depending on the location (Hölker et al. 2010a; Bennie et al. 2015; Kyba et al. 2017). This causes effects such as "skyglow" which happens when the night is illuminated from below as well as ecological light pollution, pollution that comes from individual light sources (street lights, façade lights, etc.). Both types of light pollutions cause adverse effects on ecology and local wildlife (Gaston et al. 2015).

Current artificial light is adjusted for human luminous sensitivity and no other species, and the methods used to measure light are also adjusted for human luminous sensitivity. However, artificial light has a significant ecological impact which influences many species (Jägerbrand & Bouroussis 2021), Along with increased artificial light, biodiversity is showing a trend of decline worldwide and is at a threat of a sixth mass extinction due to anthropogenic causes (Pievani 2014). Certain activities cause significant impact on global biodiversity decline. These include fragmentation of habitats, overpopulation, chemical pollution, overexploitation of resources through hunting and fishing, pollution, and invasive species – the last two being aspects that light pollution contribute to (Pievani 2014).

Studies on artificial light generally specify on specific taxa (Hölker et al. 2021). One area where artificial light has various negative effects on are insects where attraction, disorientation, desensitisation, and reduced recognition are impacted. Street lights can cause physical harm to insects and disrupt their normal behaviour patterns, affecting important activities such as feeding, dispersal, mating, and egg-laying. This has led to a rapid decline in insect abundance and diversity. The effects of artificial light can also impact species such as songbirds which can cause disturbance in migration patterns, orientation, mating and foraging success, increased stress hormones, etc. (Hölker et al. 2010b; de Jong et al. 2017).

In general, across most species, artificial light at night affects mortality, migration, population size, indirect competition, communication, and health circadian rhythm (Justice & Justice 2016; de Jong et al. 2017, 2018; Ouyang et al. 2017; Owens & Lewis 2018; Wakefield et al. 2018).

Table 1. Directly imported table (Table 1, page 2 of 24) from Jägerbrand & Bouroussis 2021 with additional, collected data of ecological and functional impacts of artificial light at night on varying species such as birds, insects, and invertebrates.

Ecological impacts	**Functional impacts**
Mortality	Species attracted/exposed to light may be killed (Gaston & Bennie 2014; Pérez Vega et al. 2022).
Migration	Artificial light disturbs natural movement patterns, migration, and orientation (Hölker et al. 2010; Gaston & Bennie 2014; Pérez Vega et al. 2022).
Population size	Reduced or increased foraging because of presence of light (Pérez Vega et al. 2022).
Indirect competition	Light can benefit certain species at the expense of other. Affecting predator and prey relationships (Longcore et al. 2018; Jägerbrand & Bouroussis 2021).
Communication	Light can disturb species communication (Pérez Vega et al. 2022)
Health and circadian rhythm	Light can influence various physiological processes that can impact health and circadian rhythm (Welbers et al. 2017)

Pollination has also been shown to be affected by ALAN (artificial light at night). Nocturnal pollinators may get disrupted and thus affecting pollination networks which leads to negative consequences for plant reproductive success (Knop et al. 2017).

One way of combating this is through effective management of outdoor lighting which requires an interdisciplinary approach and thus collaboration among various professionals, including landscape architects, light designers, and ecologists. While current guidelines for light pollution such as guidelines locally (Gaston et al. 2012; IDA 2018) or regionally (IDA 2018) provide a useful starting point, they may not fully address the ecological needs, especially of sensitive or protected environments and the species that inhabit them. Instead, the guidelines for outdoor lighting focus generally on light pollution and lack a specific focus on ecology, protected areas, sensitive environments, and areas in near vicinity of such areas, even though these environments may require more strict and tailored regulations to ensure long-term survival of specific species (Jägerbrand & Bouroussis 2021). Therefore, the best practice guidelines for outdoor lighting, should include knowledge on ecological impacts and be tailored and adapted to a specific site or habitat.

This thesis starts by describing the Swedish legislation to give an overview on how light pollution may be handled and considered in a Swedish context (Section 2). Section 3 breaks down the different elements of light technology and how these elements affect biodiversity in both a positive and negative way. It also presents an overview of how street lights can be designed and placed to reduce light spill over skyglow. The fourth section presents a suggested guideline for outdoor street lights for landscape architects, and the last and fifth section concludes the thesis along with a discussion.

1.1 Aim and research question

The aim of this thesis is to provide effective strategies and guidelines to avoid or mitigate light pollution and reduce the negative impact of artificial light on biodiversity and local wildlife. The strategies and guidelines are recommended to be adapted to specific locations and habitats, be it urban, rural, sensitive, or non-sensitive environments.

What strategies can landscape architects employ in the planning, design, and management of street light installations to mitigate and/or avoid the negative impact of artificial light at night (ALAN) on biodiversity and local wildlife?

1.2 Method and materials

In order to establish guidelines for street lights, a literature scoping review was conducted to gather and compose relevant research. The literature was found through a specific keyword combinations. The combining key words were: “light pollution”, “artificial light at night”, “biodiversity”, “wildlife”, “street lights”, “strategies”, and “guidelines”. To include the impact on ecology and species, an additional scoping review was conducted on specific species to dig deeper. The key words were: “light trap”, “bats”, “birds”, “insects”, “colour”, and “shielding”.

The literature study focused on identifying which variables of street lighting a landscape architect could work with, manage, and take into consideration, specifically in planning and management of projects. From the literature study, several key variables of street lighting were frequently brought up and assembled. These key variables were identified as: type of light, colour, illuminance levels, façade lights and the placement of street lights, scheduling and shielding. Type of light was divided into the three most common types: HPS, MH and LED. Colour was divided to green, white, blue, and red light, in accordance with the most common colours found in the literature study, specifically across the literature that focused on specific species, i.e., de Jong et al. 2017 or Spoelstra et al 2017. Illuminance levels were measured in lux. These variables, with additional data are then conducted into guidelines.

The research findings were analysed to assess the impact of various variables on species, such as songbirds, bats and insects and invertebrates. A comprehensive review of the literature on light pollution's effects on these species was conducted, incorporating both positive and negative findings. These three groups of species (bats, birds, and insects and invertebrates) were chosen due to their prevalence in the literature research.

To create a set of guidelines for street lighting, the research team identified the least invasive value of each variable across all species. For example, yellow light was found to be least invasive colour across all species. This approach allowed for a comprehensive understanding of the variables and how they each affect biodiversity and wildlife.

The Swedish legislation, specifically Species Protection Ordinance (Artskyddsförordning, (Riksdagsförvaltningen n.d.a)), Act on the construction of railways (Lag om byggande av järnväg (Riksdagsförvaltningen n.d.b)), The Swedish Environmental Code (Miljöbalk (Riksdagsförvaltningen n.d.c)), Planning and Building Act (Plan- och bygglag (Riksdagsförvaltningen n.d.d)), Environmental Protection Road Act (Väglag (Riksdagsförvaltningen n.d.e)), Agency (Naturvårdsverket, (Handbok för artskyddsförordningen. D. 1, Fridlysning och dispenser 2009), and their requirements and recommendations for street lighting was also considered as framework and to apply and adjust the guidelines to a Swedish context. By combining documents from various sources, the best, general practice, and emerging trends in street lighting design was identified.

These guidelines are, in this thesis, mainly intended to help landscape architects, but could aid other professions such as urban designers, engineers, and city planners to make informed and intentional decisions when selecting street lights, and to ensure they are minimising any negative effects on the environment and wildlife.

Overall, the literature study paired with the Swedish legislation provides a valuable resource and a strong basis for anyone involved in the planning and implementation of artificial light in projects, and will in large aid the local wildlife, biodiversity and ecology.

1.3 Limitations

In this thesis, I have focused on the variables that landscape architects can manipulate or take into consideration within the context of their role in the design department of the construction process. While landscape architects play a crucial role in shaping outdoor spaces, there are certain limitations inherent to their work that affect their ability to fully control all aspects of a project. The identified variables are colour of street lights, illuminance levels of street lights, surrounding facades and the lights that emit from them, shielding of street lights, scheduling of street lights and lastly the placement of street lights. These variables, with additional data are then conducted into guidelines.

I have decided to exclude aspects of street lights that regard human safety, feelings of safety, navigation, aesthetic qualities, and other anthropogenic elements, and have instead opted to focus exclusively on the less researched aspect: the ecological impact. This is due to the overwhelming information readily available to avoid light pollution for the human benefit, and to the underwhelming amount of information for the benefit of ecology and biodiversity. The guidelines and strategies will thus act as a tool for the ecological benefit for landscape architects and other professions.

There are also limitations to the number of species studied and included in the literature review, as not all species have been studied and not all articles have been reviewed. However, the literature review includes at least one article of the species bats, insects and invertebrates, and songbirds. The literature review also includes species that can be found in a Scandinavian context.

This thesis will not apply the guidelines on a site or location, although it is an imperative and crucial aspect to consider adaptations to environment and habitat.

Swedish legislation

To establish how strategies and guidelines can be implemented in a Swedish context, there needs to be a focus on applicability within the Swedish legislation. The Swedish legislation is comprised by a set of laws, regulations, and guidelines that govern various aspects of social, economic, and environmental activities in Sweden. These legal frameworks are included to make sure national, and EU standards are followed while promoting sustainable development, social welfare, and public health. In this section of the thesis there is a focus on the environmental part of the legislation. By using the Swedish legislation as a foundation, this section will show how the strategies and guidelines of street lights can comply with the national rules and laws, while addressing the challenges of light pollution and their impacts on ecology and biodiversity.

The Swedish legislation can act as an important legal tool to protect and conserve the country's wildlife populations and their habitats. It includes several statutes, of which many share similarities with the European legislation. It is a must that any effects on the environment must be incorporated and listed when strategizing for new roads or railways, which includes operation and maintenance (Jägerbrand & Bouroussis 2021, Naturvårdsverket). These ecological effects must be considered and align with the Swedish Environmental Code (Riksdagsförvaltningen n.d.d, n.d.e, n.d.c). According to the Planning and Building Act (Plan- och bygglag, (Riksdagsförvaltningen n.d.d)) it is mandatory to consider the environmental factors, as well as promote the development of green spaces and improve the overall environmental conditions.

Regarding light pollution and its impact on ecology, the Swedish Environmental Code, under General Rules of Considerations, Chapter 2 pays special interest:

> "Arguably, the general rules of consideration all relate back to the Precautionary principle, which sets out the fundamental requirement for anyone who pursues an activity to take all necessary environmental precautions in order to limit the impact on human health and the environment. The mere risk of damage and detriment triggers this obligation. Such precautions may, for example, involve limiting the scale of operations or applying the best possible technique, the Best Possible Techniques Principle (interpreted together with the Proportionality principle, this corresponds to the requirement of applying Best Available Techniques, BAT).

Summarised, if outdoor lighting is deemed to be detrimental or potentially harmful to the environment, it is necessary to take preventative and precautionary actions.

In case of wild birds and wild animals, the Swedish legislation, so called the Species Protection Ordinance, integrates both the EU Birds Direction as well as the Habitats Directive. The Species Protection Ordinance also prohibits the hunting, capture, killing, or destruction of nests and eggs of all species that are protected by law in Sweden. The ordinance, which is applicable to the whole life cycle of species, also prohibits the disturbance of protected birds during their breeding, rearing, hibernation, and migration, as well as deterioration or destruction of breeding sites or resting places. The Swedish Environmental Protection Agency recommends prioritising species that are in a negative trend and are included in the Swedish Red List. The Swedish Red List is a collection of information on the conservation status and extinction risk of species in Sweden. The species that are listed are reviewed to align with the guidelines of the International Union for Conservation of Nature (IUCN). It is serving as a tool to prioritise nature conservation efforts, however despite its significance the list lacks legal status (Jägerbrand & Bouroussis 2021).

Although there is no clear definition of disturbance among the statutes in the Swedish legislation, SEPA clarifies that noise or light can be seen as disturbances and that the impacts can be indirect (*Handbok för artskyddsförordningen. D. 1, Fridlysning och dispenser* 2009). Indirect impacts include disruptions that can put certain species in unfavourable situations. Examples are situations that lead to an increased risk for prey species, such as drawing more attention to them, or causing offspring to be exposed to danger due to movement or starvation. Due to this, it is imperative to clarify what possible ecological and biological impacts light pollution has regarding disturbances of protected and endangered species and their respective habitats and environments. A few exceptions to this can be approved, such as a need for public health and safety, or light being enabled for specific roads in certain circumstances.

The Swedish legislation provides a clear and legal framework for landscape architects when working with environment and species that should be protected against various impacts, including the disruptions of light. More importantly, the Swedish legislation underscores the need to act and to address the potentially negative effects that light pollution has on species and habitats when working in projects or with illuminance installations in general.

Elements of light and the ecological impact

3.1 Type of light

High-Pressure Sodium (HPS), Light-Emitting Diode (LED), and Metal Halide (MH) lights are the most common form of light types used in street lighting systems. All three types of lights have their advantages and disadvantages depending on which context to look at (Davies et al. 2012). In this section of the thesis, the prime focus is on the different ecological impacts each light type contributes to. The impact that is mainly looked at is the attraction of insects (and in turn the predator species of the insects), and in a smaller scale the sensitivity. A discussion on how customisable and energy-saving each light type is also included, as these factor in on adjusting to the environment and thus the ecological impact at large.

High-pressure sodium (HPS) is the commonly used lighting technology that emits light dominated by long wavelengths and has the potential to significantly impact communities of organisms (Davies et al. 2012). However, HPS street lights are being replaced worldwide with broad-spectrum white lights, such as light emitting diodes (LED) and to a lesser extent metal halides (MH) (Owens & Lewis 2018). The reason is because these new technologies require less energy to operate and are often regarded as more ”eco-friendly” (Wakefield et al. 2018).

With artificial light, it is important to note that there is a correlation between insect mass and bat activity, as the more insects are attracted to lights, the more bats are going to congregate around the lights for foraging (Haddock et al. 2019). Wakefield, et. al. (2018) showed that the family diversity of the insects that were attracted to light was the greatest with MH lights, followed by LED and then HPS light. Despite being viewed as a newer lighting technology, LED lighting still has a few negative impacts on various species (Wakefield et al. 2018). For instance, the broad-spectrum light emitted by LEDs can intensify the artificial lighting on environment, affecting a wider range of wavelengths. This can be especially problematic for species that are sensitive to such ranges of wavelengths, particularly those that are nocturnal (Wakefield et al. 2018). Also, a reduction of the light suggested that a greater diversity of insects was caught with LED than HPS lights

(Wakefield et al. 2018). When it came to MH, the lights attracted more insects while white LEDs attracted a greater diversity of insects than HPS lights with long wavelength dominance (Wakefield et al. 2018). The same study also showed that there was no significant difference in the attraction of the insects between the LED and HPS lights and no statistical difference in the numbers of insects for most taxa that was caught.

The main difference between MH and LED is that LEDs typically does not emit ultraviolet (UV) light, whereas MH does (Wakefield et al. 2018). Studies done on light attractiveness of the three different light technologies has shown that MH lights attract significantly more insects, greater than five times as many than LEDs and HPS lights, which may in part be explained by the presence of UV light in the MH spectrum (Wakefield et al. 2018). This is also supported by a study from Haddock et al. 2019 (Haddock et al. 2019) which showed a reduction in UV radiation of artificial light could result in a decline in some insect-eating bats in cities, as a lar. A study by Wakefield, et al. (2018) found that, in general, there was no significant difference in the number of insects caught at HPS street lights and LED street lights based on their study of various species.

Although there are some pros and cons of the three lighting technologies regarding the effects on species, studies on environmental impact indicate that LEDs may still be a better choice of the three, at least with respect to HPS- and MH lights and bulbs using incandescent technology (Davies et al. 2012; Justice & Justice 2016). This is due to several reasons: 1. the energy efficiency, causing lower greenhouse gas emissions, 2. the long lifespan of LEDs which leads to less frequent replacements and in turn energy consumptions (Davidovic & Kostic 2022), 3. the customisable spectral output so that the wavelength can be adapted to species present and the habitat (Owens & Lewis 2018), 4. the option of directionality of illumination 5. dimming and instant on- and off capability (Justice & Justice 2016) and lastly 6. not containing any toxic materials compared to MH- and HPS lights which might pose as potential harm to humans and other species. This makes LEDs a more sustainable, environmentally friendly, and adaptive option compared to the other two lighting technologies.

3.2 Colour

The colour of light can have ecological impacts, particularly on nocturnal animals but other species as well (de Jong et al. 2017; Ouyang et al. 2017; Owens & Lewis 2018). The colour of light is perceived through colour temperature and is measured in units of Kelvin (K). It can also be based on the wavelength of the light which is measured in nanometres (nm). Yellow/orange light is generally considered lower temperature around 2000-3000 K, while cool white/blue light is considered higher colour temperature from 3000 K to 6000 K (Pérez Vega et al. 2022). When it comes to nanometres, colours going from violet/blue to red ranges from 400 nm to 750 nm.

In this section of the thesis, colour is being tested on different taxa and species. It is important to note that it is one of the elements that is highly subjective to the species on site where one species can react negatively to a colour where the other reacts positively.

Varying responses have been seen in bats when it comes to the reaction to different colours, where white and green light affect species of bats that are light shy and agile, whereas red light has no effect (Spoelstra et al. 2017). Another study shows that red might instead be a disruptive colour and that certain colours can cause stress hormone concentrations (corticosterone) in song birds (Ouyang et al. 2015). Because different species have varying sensitivity to different wavelengths, the impact on ecology is dependent on the distribution of light energy in different wavelengths, known as the Spectral Power Distribution (SPD). To minimise the ecological impact of outdoor lighting, it is recommended to adjust the SPD to habitat and location. Blue light (wavelengths less than 500 nm) may have non-visual effects on vertebrates' circadian rhythms, as seen in humans (Grubisic et al. 2019). Many species, including mammals (Bowmaker 1998), birds (Hart 2001), insects, reptiles, and amphibians (Kelber et al. 2003) have photoreceptors that are particularly sensitive to blue light, making them more vulnerable to its effects than humans. Therefore, it is suggested that blue wavelengths in outdoor lighting should be either diminished, reduced, or entirely ruled out. It is important to note that the forementioned solutions has no guaranteed effect on organisms, as light with even less blue light has may still have some impact (Falchi et al. 2011; Gaston et al. 2012; Aubé et al. 2013).

A general consensus across several recent studies show that white light is not always as environmentally friendly as advertised. To produce white light with a certain colour temperature, blue LEDs are coated with phosphor material, which absorbs some of the light and then emits it in longer wavelengths. This means that most white LED street lights emit more blue light than other types of artificial light at night (Justice & Justice 2016).

From studies (de Jong et al. 2017; Ouyang et al. 2017; Owens & Lewis 2018) there seems to be a trend of white light being more or less disruptive across most species, such as songbirds, bats, insects and even mice. One cause is that white and yellow

LED light still contain green light (light that is below 500 nm) (Jägerbrand & Bouroussis 2021).
To reduce disruption, it is recommended to emit as little light as possible under 500 nm, therefore amber LED lights with a yellow hue is the preferred alternative, with a peak at 590 nm. (Dick 2016). Although this will not eliminate the ecological impact on certain species, it is likely it will be less harmful to most species in this spectrum (Longcore et al. 2018). Additional options are to absorb unwanted wavelengths through filters, thus reducing blue rich lighting and HPS lights, and instead utilising filtered amber, yellow and green LED as these been shown to cause less of a negative impact on wildlife (Dick 2016, Longcore et al. 2018).The International Dark Sky Park Designation Guidelines (IDA) suggest using lamps that emit less than 25% of their total spectral power distribution below 550 nm or below 5000 K (IDA 2018).

3.3 Illumination levels

Illuminance levels refer to the measurement of the amount of light falling onto a surface, more commonly known as brightness or light intensity. It is measured in units of lux (lx), which represents the amount of light energy per unit area. The illuminance level in a particular space or area is a critical factor in determining the quality of lighting and its suitability for various activities. Different tasks and environments require different levels of illuminance to ensure adequate visibility, safety, and visual comfort. In this section, the focus is on suitable and appropriate amount of light intensity for the environment and wildlife.

Sunlight can reach illuminance levels of around 100,000 lux, whereas road lighting typically ranges between 0.5-30 lux at ground level. Moonlight and skyflow often have illuminance levels below 1 lux (Jägerbrand & Bouroussis 2021).When it comes to combining the illuminance levels with colours it is important to note that the intensity of light can be affected by the colour temperature - different illuminance levels can be used depending on what colour is being emitted.

A reduction of the light intensity is one way of ensuring a better light scape for the environment and wildlife (Owens & Lewis 2018). Some studies show that levels of ALAN as low as 0.09 lux (luminous flux per unit area) significantly impacted some nocturnal insects, such as fireflies’ attraction to mating females. When the brightness increased to 0.18 lux or higher, none of the males approached the simulated females for mating (Owens & Lewis 2018). This shows that low levels illuminance can have significant impact, and is a matter of keeping illuminance levels as low as possible without retracting from important anthropogenic factors such as safety, navigation, transport, etc.

To reduce the impact of light on the environment, the Low Impact Lighting (LIL) suggests limiting the energy flux to below 500 nm to less than 6% of the overall emitted light in the visible spectrum. It is also recommended to utilise a colour temperature of ≤ 2200 K. The usage of 2200-2700 K is permitted if the energy flux below 500 nm remains below 10% of the total emitted light (Licht und Natur).

3.4 Design and composition to reduce over-illumination and skyglow

Even in protected or sensitive environments, certain outdoor lighting is sometimes required to ensure safety for people in general and safe transportation. However, there is a risk of outdoor lighting spilling and reflecting towards surrounding areas. This may be particularly important for areas close to nature reserves or nature conservation areas where the light pollution will negatively impact potentially protected species.

Areas with façade lighting might reflect onto the street and contribute to the street illumination. When street and façade lighting are installed without taking each other into consideration, it can lead to excessive lighting on the street, known as over-illumination and light spill over. Façade lighting has the potential to reflect onto the street and add to the street lighting. Studies have revealed that a moderately illuminated façade can result in a horizontal illuminance of at least 5 lux on the street and a vertical illuminance of at least 4 lux at a height of 1.5 meters above the sidewalk. (Saraiji & Oommen 2012)

With a street width of less than 15 m, façade lighting alone may be able to illuminate the street with the required levels according to IES RP-8-00 (Illuminating Engineering Society, recommended practise for lighting roadways and parking facilities), resulting in no need for additional street lighting. Standards for Low Impact Lighting (LIL) suggest that the distance between poles must be at least 3.7 times greater than the pole height (Licht und Natur).

Studies have found that least light pollution is found when only street lights are used without any façade lighting. If the objective is to only light up the street, then the most efficient way is to only use street lights. Furthermore, by positioning the street lights only on the sidewalk will also reduce the light spill over (Saraiji & Oommen 2012).

3.5 Shielding

Shielding of street lights is another way of reducing spillage onto the sky and working as a light pollution blocker. The use of shielded light technology has the potential to decrease the amount of skyglow by reducing the amount of upward-directed light emitted into the night sky (Owens & Lewis 2018).

By using physical barriers, such as shields, street lights can be prevented from illuminating certain angles. This method reduces the amount of light that spills into the surrounding areas and limits the impact of glare and skyglow. When it comes to LED street lights and lights on facades, the lens in front of the LED chips can reduce light spillage by distribution of light (Jägerbrand & Bouroussis 2021).

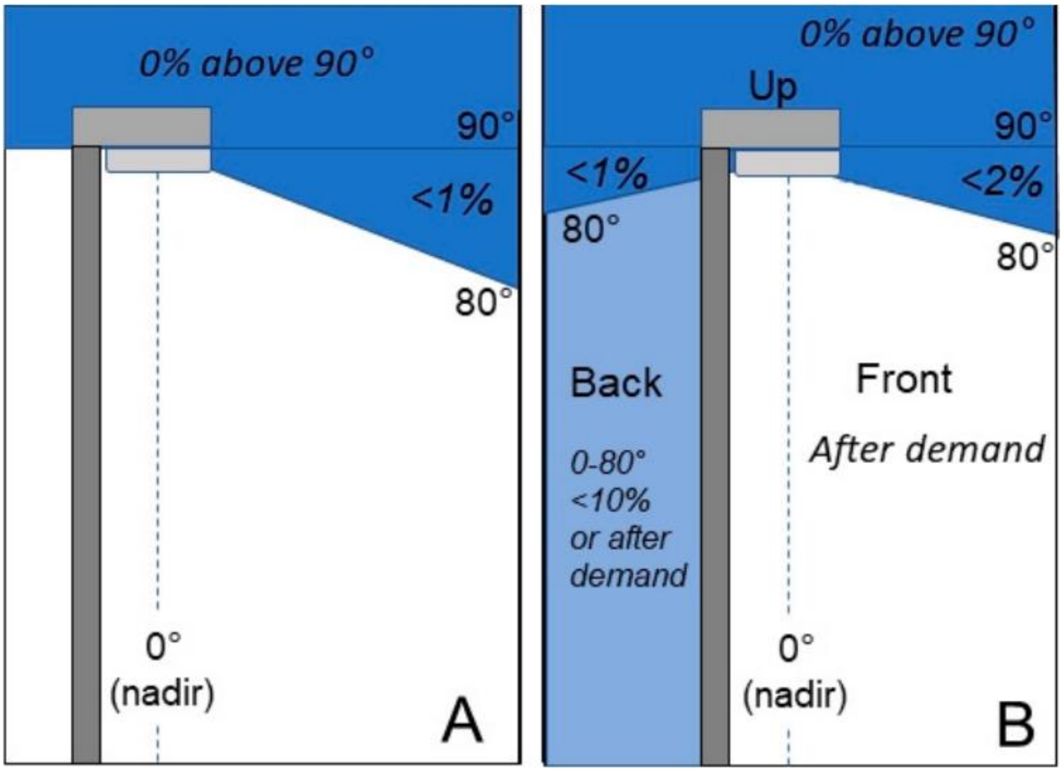

Figure 1. Directly imported figure (Figure 1, page 7 of 24) from Jägerbrand & Bouroussis 2021 shows example of shielding of luminaires to reduce ecological light pollution in protected areas: (A) sharp cut off, SCO (B) BUG system. Non-correct scales and angles.

The International Dark Sky Association (IDA) has developed a system called the Backlight, Uplight and Glare (BUG) system (IDA 2009), which provides more stricter and detailed requirements for shielding street lights and other luminaires. This system allows for the control of the amount of light emitted at different angles from the street light, which can be divided into backlight, front light, and uplight. One possible suggestion is to adjust the luminous flux in the direction pointing directly below the light source, by limiting it to 0% above 90°. (see Figure 1A), in the backlight, less than 10% in all other angles of the backlight. In the front light it is possible to limit less than 2% at or above 80° above the nadir, with additional restrictions on other front angles as needed (see Figure 1B). To prevent light pollution and skyglow it is recommended to keep uplight at zero and limit the backlight as much as possible in protected areas, as demonstrated in Figure 1B.

3.6 Scheduling

Another technology which becomes increasingly popular is the use of motion sensors and light-dimming devices that enable to adjust illumination levels to the actual need and reduce energy consumption (Archibong et al. 2020).

In order to minimise the negative impact of artificial light on animals, especially those that are adapted to low-light environments, such as nocturnal or crepuscular species as they are mainly active in dawn or twilight. It is therefore necessary to preserve natural lighting or install programs that can turn off or dim the artificial light in or around protected or sensitive areas (Jägerbrand & Bouroussis 2021).. This approach not only benefits the wildlife but also conserves energy, which is generally considered a positive outcome from both an energy and climate perspective.

By turning off or dimming the light in certain areas, it is possible to create periods of darkness that are more conclusive to the survival of nocturnal or crepuscular species, thereby improving the conservation of both the species and the surrounding environment (Jägerbrand & Bouroussis 2021). Fortunately, modern technology provides several solutions for controlling the lighting in a more effective way. For instance, street lights can be programmed to dim automatically at different levels through schedules or by using inputs from field sensors. In the case of LED street lights and other luminaires, unique profiles can be created with pre-programmed drivers specifically catered to area and time of year without adding extra expenses for the equipment(Jägerbrand & Bouroussis 2021).

For areas that are sensitive or protected it is highly suggested to incorporate more strict curfews, and or with periods of switching off the lights to prevent unwanted light pollution. This can only be achieved in areas that are not heavily trafficked by humans, residential areas, cities or roads (Jägerbrand & Bouroussis 2021). As an illustration, the LIL (Lighting Infrastructure Legislation) standard specifies that during curfew hours (outside of peak traffic periods), all street lights should be dimmed from 100% to 10%, or at least to 50% if older technology is still in use (Licht und Natur). For areas that are sensitive to light, it is advisable to solely use outdoor lighting, , only in necessity, and based on the activity of humans surrounding the area. It is additionally recommended to switch off street lights two hours before sunrise and after sunset (Dick 2012). It is also helpful to provide the public with a notice prior about these curfews so that visitors are informed and understand the reasons for the measures. In Vienna, Austria, for example, implementing the curfews for certain street and decorative façade lightings resulted in an improvement of approximately 1.4% in the brightness of the night sky, as measured during the night in 2012 (Puschnig et al. 2014).

Strategies and guidelines

Smart street lighting and scheduling

Use timers and motion sensors to automatically turn lights on and off as needed., all street lights should be dimmed from 100% to 10%, or at least to 50% if older technology is still in use (Licht und Natur). For areas that are sensitive to light, it is advisable to solely use outdoor lighting, only in necessity, and based on the activity of humans surrounding the area. It is additionally recommended to switch off street lights two hours before sunrise and after sunset with a prior notice for humans about the curfews (Dick 2012).
Program street lights to dim automatically at different levels through schedules or by using inputs from field sensors.

The street lights can be programmed to dim automatically at different levels through schedules or by using inputs from field sensors. In the case of LED street lights and other luminaires, unique profiles can be created with pre-programmed drivers specifically catered to area and time of year without adding extra expenses for the equipment (Jägerbrand & Bouroussis 2021).

Shielded lighting

All outdoor lighting fixtures should be properly shielded to minimise glare and upward light. This will reduce the amount of light that reaches the sky and decreases the amount of light pollution. Use the backlight, uplight and glare (BUG) system (see Figure 1B) from The International Dark Sky Association (IDA 2009). Additionally, use highly focused and shielded LED lights that are designed to filter out specific wavelengths, particularly short wavelengths, which does less impact across most species (Wakefield et al. 2018).

Colour and type of light

Use amber LED lights with a slightly yellowish hue and a peak at 590 nm, as they emit less light below 500 nm. (Dick 2016). Additional options are to absorb unwanted wavelengths through filters, thus reducing blue rich lighting and HPS lights, and instead utilising filtered amber, yellow and green LED as these been shown to cause less of a negative impact on wildlife (Longcore et al. 2018). Restrict using lamps to below 3000 K, or if lamps are above 3000 K make sure that less than 25% of the emitted light of the total spectral power distribution, is below 550 nm. (IDA 2018). After analysing the current research and placing the results alongside the existing literature, white, broad-spectrum street lights is likely to have negative effects on wildlife.

Illuminance levels

To reduce the impact of light on the environment, the Low Impact Lighting (LIL) suggests limiting the energy flux to below 500 nm to less than 6% of the overall emitted light in the visible spectrum. It is also recommended to utilise a colour temperature of ≤ 2200 K. The usage of 2200-2700 K is permitted if the energy flux below 500 nm remains below 10% of the total emitted light (Licht und Natur).

Composition of street lights

Standards for Low Impact Lighting (LIL) suggest that the distance between poles must be at least 3.7 times greater than the pole height. Studies have found that least light pollution is found when only street lights are used, without any façade lighting adding to the illuminance levels. If the objective is to only light up the street, then the most efficient way is to only use street lights. Furthermore, by positioning the street lights only on the sidewalk will also reduce the light spill over (Saraiji & Oommen 2012).

Discussion/Conclusion

While this thesis gives general guidelines and strategies to combat light pollution in areas where biodiversity and local wildlife is at risk, there are some important aspects to consider. The guidelines do not consider all species worldwide as different species have different sensitivities and some even benefit from light pollution, such as predator species of certain insects and invertebrates (Spoelstra et al. 2017; Haddock et al. 2019). However, they ensure that most species will be less affected.

To apply the guidelines, landscape and habitat adaptations are imperative. Biodiversity, number of species and how many are present, population of humans, how much light is present, are important variables to factor in when applying the guidelines. A prioritisation of areas in the habitat, of different habitats and the species in the habitats is recommended. By finding what species are red listed in an area, one can start trimming and pinpointing what aspects of artificial light is more disruptive than others regarding illuminance levels, colour, type of light, etc. and thus avoid them, as spectral sensitivities within habitats may be common to the organisms living there (Hölker et al. 2021). It is important that every variable has the capability to be adjusted. Jägerbrand means that protection of areas can be achieved through means of precautionary methods and principles that integrate into the management plans of such areas, emphasizing on the local impact. On a broader level, Jägerbrand also notes the importance of addressing issues like skyglow. By focusing on the national legislation as skyglow generally covers a larger area and has an impact across many ecological communities, one can start regulating light pollution on a larger scale.

It is also important to note that light pollution can affect not only singular species but populations and communities at whole, affecting the function of ecologies. There have been several studies done on animals and their attraction to light on an individual level, such as effects on mating success, foraging patterns, numbers of offspring, etc. (de Jong et al. 2017; Owens & Lewis 2018; Grose & Jones 2021), however, there is a lack of information on how this affects the higher levels of biodiversity, such as population, intra-species relationships, communities of ecology, and so on (Hölker et al. 2021). Hölker et al. means that multiple biodiversity levels are interconnected, i.e., one level may respond to ALAN which in turn changes the process at other biodiversity levels. Therefore, an initial, minor change such as the introduction of street lights in a habitat, may impact ecosystem processes and nocturnal environment at large, which in turn has an influence on all levels of biodiversity.

To guarantee a protection of specific species in a habitat there must be knowledge of the species' visual system, physiology, ecology, etc. prior to any work on site. This way the appropriate light sources and illumination levels will be achieved without excessive ecological disruption. Such information on species is available on published research studies, such as by Spoelstra. An additional aid are through tools to help with identification of protected or vulnerable species, such as International Union for Conservation of Nature (IUCN) as well as the European/Swedish Red List. By finding which species reside and what their status are on the local site, one can pursue prioritisation of habitats and said species.

The ecological impact of light pollution is a new area of study (Hölker et al. 2021). It is therefore important to note that the current lack of available information does not reflect the magnitude of the problem regarding the environmental impact of artificial light. Additionally, light measurements done on species would ideally be done in biologically relevant ways with a focus on how light is perceived through physiology and senses of different species but are (Hölker et al. 2021) instead based on human physiology and senses only (Kempenaers et al. 2010). Furthermore, light pollution does not affect all species negatively, as some studies show that some species even benefit from the effects of ALAN (Haddock et al. 2019). Thus, it is imperative to look at the habitat and environment and tailor the guidelines to the species present on site.

Another aspect that has not gained much attention but is an important one to consider is the effect artificial light has on snow-covered ground, a phenomenon called *snowglow* (Jechow & Hölker 2019). This phenomenon is thus a type of light pollution that occurs when artificial lighting reflects off snow, creating a bright, diffuse glow in the night-time environment, and is emphasized in presence with clouds. This effect can be particularly pronounced in areas with high levels of light pollution along with snow during most of the year, being a relevant issue in Sweden's urban or suburban regions. Snowglow can have several negative impacts, like the effects of light pollution but are even more pronounced during the snowy parts of the year (Jechow & Hölker 2019). It shares the same ecological impacts such as migratory patterns, navigation, behaviour, etc. Since snowglow is a phenomenon that is new and not fairly studied, it has not been included in this thesis as it is difficult to find appropriate solutions regarding it. One possible way around it is to reduce the illuminance levels of the street lights in suburban areas during snowy and cloudy circumstances, which is where scheduling profiles for street lights can play an important role in monitoring illuminance levels and setting timers depending on the time of year and weather. The reduction of skyglow and snowglow especially applies to sensitive areas in near vicinity to urban or suburban areas. Light installations on specific sites should thus be adapted for summertime and wintertime.

It is also important to note the international and national aspect of these strategies and guidelines. As this thesis focuses on a Swedish context, they allow additional research to be conducted on specific national sites, such as place studies in urban, sub-urban or peri-urban places. However, these strategies and guidelines can also be applicable in international settings with provided and appropriate legislation of said country.

1. A trade-off with anthropogenic benefits

Street lighting is an essential feature of urban, sub-urban and other areas with visiting humans, serving multiple anthropogenic purposes such as aiding navigation, providing orientations, ensuring safety, and instilling feelings of security. In the field of urban design, striking a balance between ecological and the positive attributes of street lighting to humans is a crucial consideration, especially in professions such as landscape architecture, urban designers, and more.

While urban lighting is generally perceived to enhance safety in terms of traffic accidents and crime prevention, efforts to mitigate light pollution often come into conflict with these positive aspects and functions. Increased illuminance levels and a greater number of street lights tend to have a negative impact on biodiversity and local wildlife (Saraiji & Oommen 2012), posing a challenge when attempting to reduce light pollution. The notion of improved feelings of safety and security associated with street lights is deeply ingrained in modern societies, along with other positive connotations such as aesthetics and modernity (Hölker *et al.*, 2021).

Feelings of safety, navigation and orientation experienced by pedestrians are influenced by various elements and components, including illumination. Consequently, reducing the illumination level in street lights, while beneficial in certain respects, may diminish these needs. Achieving the optimal trade-off between required illuminations levels and selecting appropriate attributes such as light colour, type of light, scheduling, shielding, and designing is crucial (Saraiji & Oommen 2012). Adopting a mindset that embraces trade-offs and views light as a resource becomes imperative when including street lights in projects.

There has been a severe lack of research attempts to estimate how much potential energy can be saved based on pedestrians' perception and preferences for streetlights, specifically savings that are correlated with the stated feelings of safety. Therefore, the best general strategy for landscape architects is to focus on reducing brightness levels to the greatest extent possible without jeopardising safety and other important anthropogenic factors. Thus, it is crucial to consider ecological aspects by minimising the adverse effects on biodiversity and local wildlife, and at the same time providing adequate illumination for human needs.

In conclusion, light pollution is a major environmental issue that can have significant adverse effects on the environment, ecology, and local wildlife. It is important to consider the impacts of our designs on the surrounding environment and to take steps to mitigate any negative effects while at the same time providing adequate illumination for human needs. This thesis has provided guidelines for landscape architects and other actors to reduce light pollution and minimise its impact on the ecology. These guidelines include installing scheduling and motion sensors for street lights, placing them at appropriate distance, using types of lights, utilising colours, wavelengths, illuminance levels, and shielding lights to minimise the impact of lighting on the surrounding environment.

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