Shedding Light on Biodiversity

A Framework with Ecological and Human Trade-offs in Street Lighting

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Swedish University of Agricultural Sciences, SLU
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Shedding Light on Biodiversity – A Framework with Ecological and Human Trade-offs in Street Lighting

Sprida ljus över biologisk mångfald – Ett ramverk med ekologiska och mänskliga avvägningar i gatubelysning

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Abstract

Artificial light at night (ALAN) is currently posing a significant challenge to ecology and biodiversity in urban environments. The effects of ALAN, from mainly street lighting, are disruption of natural light patterns for species, contribution to light pollution, and leads to loss of dark habitats which contributes to effects on an individual- and population level and physiological changes in species. Studies have found that ALAN is expanding at a rate of 6% across Earth's surface and affects approximately 80% of the global population on a nightly basis. While artificial light has benefits that primarily serves to improve security, perception of safety, navigation, and aesthetics for pedestrians, it frequently leads to ecological disruption. Furthermore, street lighting design has prioritized motoric traffic over pedestrian usage which has still led to excessive, uneven, and poorly optimized illumination for pedestrians. Despite ALANs increasing expansion and prevalence, research is still relatively undeveloped and there is a lack of practices and effective measures to prevent negative side effects.

This thesis addresses the need to mitigate the adverse effects of ALAN by finding the optimized design of street lighting components at different types of locations to benefit humans and biodiversity. Components have been identified as correlated colour temperature (CCT), light sources (LED, MH, HPS), illuminance levels, uniformity of light, scheduling with motion sensors, direction, and shielding. A transect walk was conducted to reveal perception of light for humans and create site analyses. The components are customized to mitigate the adverse effects on biodiversity while improving the benefits for pedestrians, specifically perception of safety, navigation, and visibility. To find a middle ground between humans and ecology, a trade-off was conducted and analysed. After trade-offs are analysed and conducted, a framework of ecological and human trade-offs in street lighting is suggested based on three different locations.

Keywords: artificial light at night, ALAN, light pollution, framework, biodiversity, ecology, environment, pedestrians, perception of safety, transect walk

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Sammanfattning

Artificiellt ljus på natten (ALAN) utgör en växande påfrestning för ekologin och den biologiska mångfalden i urbana områden. Studier visar att ALAN påverkar allt större delar av jordens yta och påverkar ungefär 80% av den globala befolkningen varje natt.

Trots att ALAN är ett relativt nytt fenomen har det visat ha en rad negativa effekter, främst i form av bidragandet av ljusföreningar och förlust av mörka habitat. Detta i sin tur påverkar individ- och populationsnivåer samt fysiologiska processer hos arter. Även om artificiellt ljus har fördelar som ökad säkerhet, känsla av trygghet, navigation och estetik för fotgängare leder det ofta till ekologiska störningar.

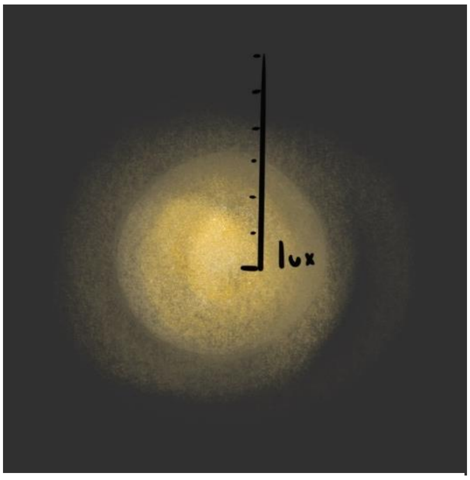
I och med att gatubelysning är den mest dominerande formen av artificiellt ljus, fokuserar detta arbete på gatubelysning inom urbana områden med omgivande naturområden. Designen av gatubelysning har främst prioriterat fordonstrafik och därför lett till allt för ljusstark, ojämn och dåligt optimerad ljusstyrka för fotgängare. Trots ökade problem med ALAN är forskningen fortfarande relativt outvecklad och det saknas praxis och effektiva åtgärder.

Komponenter av gatubelysning

Detta arbete möter behovet av att minska de negativa effekterna av ALAN genom att hitta en optimal design av gatubelysning för olika typer av platser. Vid implementation av gatubelysning är det därmed viktigt att förstå gatubelysning och dess komponenter och hur de påverkar människor och andra arter. De komponenter som identiferats är: korrelerad färgtemperatur (CCT), ljuskällor (LED, MH, HPS), belysningsnivåer, ljusets enhetlighet/ljusenhetlighet, schemaläggning med rörelsesensorer, riktning och avskärmning. Komponenterna är främst anpassade för att minska de skadliga effekterna samtidigt som de förbättrar anvädningarna och fördelarna för fotgängare, specifikt känsla av trygghet, navigering och sikt.

Belysningnivåer

En av de avgörande komponenterna för sikt, känsla av trygghet, och visuell komfort är belysningsnivåer. Hög belysningsnivå har visats vara en stark faktor till påverkat beteende, fysiologi och relationer mellan arter, och kan även påverka visuell komfort för fotgängare genom bländning. Gatubelysning varierar vanligtvis mellan 0.5-30 lux, belysning från månen faller under 1 lux. Lägre belysningsnivåer på gatubelysning är att föredra av ekologiska skäl men det krävs en tillräckligt hög nivå för att ge tillräckligt med sikt.



Figur 1. Illustration av belysningsnivåer, mätt i lux.

Färgtemperatur och ljuskällor

När det gäller ljuskällor kan olika varianter påverka beteenden och fysiologin hos olika arter. Inom gatubelysning är de dominerande ljuskällorna främst LED (light emitting diodes), HPS (high-pressure sodium) och MH (metal halide), vilka har olika för- och nackdelar. Forskning visar att ljuskällor som inte är statiska, men som är dynamiska och kan anpassas är att föredra för både biodiversitet och fotgängare.

Färgtemperatur påverkar både människors upplevelse och fysiologin hos andra arter. Många arter, inklusive människor, reagerar på olika våglängder, där vissa arter är känsligare för viss spektra än andra. Generellt anses blått ljus vara störande hos de flesta arter, men vitt ljus, som ofta anses vara mer miljövänligt och ofta används mer inom gatubelysning, kan också störa naturliga beteenden hos arter. Studier om människors upplevelse och andra arters påverkan av ljustemperatur visar att varmare färgtemperatur är att föredra.

Figur 2. Illustration av varierande färger inom gatubelysning.

Avskärmning av ljus

Avskärmning av gatubelysning fungerar som en blockering av oönskad ljusspridning (se figur 3). Avskärmning kan skapas genom fysiska barriärer som blockerar ljusspill mot himlen och minskar ljusföroreningar.

Figur 3. Illustration av avskärmad gatubelysning, ett sätt att minimera att ljus färdas upp.

Schemaläggning med rörelsesensorer

Schemläggning och rörelsesensorer (se figur 4.) är ett annat sätt att anpassa belysningsnivåer till områden som har varierande grad av känslighet eller aktivitet och funktion. Med tidsinställda timers och förprogrammerade profiler kan gatubelysning bli anpassade till platser och miljöer som är känsliga eller skyddade. I andra platser som bostadsområden är rörelsesensorer ett sätt att minska ALAN.

Riktning

Riktning av ljus (se figur 5.) säkerställer att ljuset lyser upp avsedda områden, vilket minskar bländning och ljusintrång t.ex. häckningsområden eller andra känsliga lokala områden. Riktning av ljus kan även tillföra bättre ljusenhetlighet.

Figur 4. Illustration av schemläggning av gatubelysning.

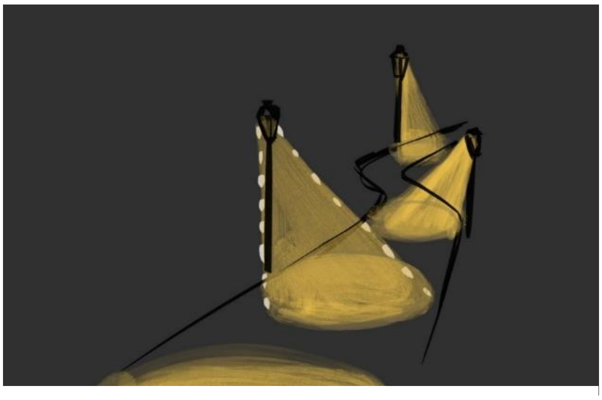
Ljusets enhetligthet

Med ljusenhetlighet menas hur jämnt ljuset är distribuerat (se figur 6.). Det är en viktigt komponent inom gatubelysning med många fördelar, där en jämn distribution av ljus minskar kontrasten mellan ljusa och mörka delar av vägen, och förbättrar både visuell komfort men även bidrar till en ökad känsla av trygghet.

Avvägning och rekommendationer

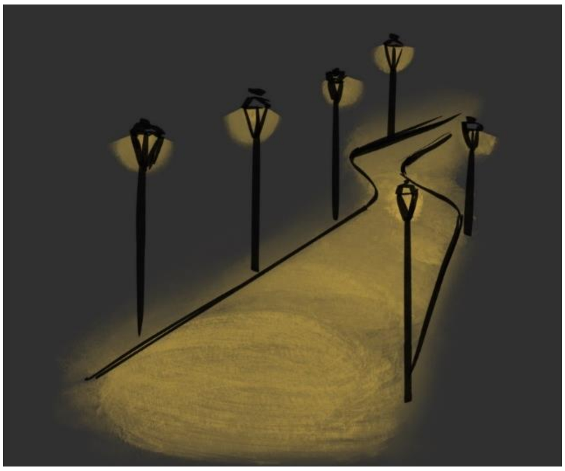
För att hitta optimala anpassningar är det viktigt att integrera de ekologiska aspekterna med de mänskliga. Därmed görs en avvägning, s.k. trade-off, mellan behoven för fotgängaren samt de ekologiska behoven. Genom litteratur hittas För att kvantifiera fotgängarens upplevelse av trygghet utfördes en Transect Walk, där

4 deltagare har gått en sträcka mellan 3 olika platser med varierande grad av aktivitet och diskuterat känsla av trygghet. Efter att aväggningar mellan de olika komponenterna analyserats presenteras ett ramverk för gatubelysning. För en vidare anpassning appliceras ramverket på olika typer av platser med varierande aktivitet och funktion. Genom detta exemplifieras olika anpassningar av gatubelysningen till olika platser och behov.



Figur 5. Illustration av riktad ljus inom gatubelysning.

Sammanfattningsvis tar detta arbete fram lösningar för gatubelysning som är anpassade till platser och dess funktioner och aktivitetsnivåer samt omgivande habitat, med fokus på bevarandet av ekologiska funktioner. Genom en anpassning av gatubelysning till plats minskas den negativa påverkan det artificiella ljuset har på miljö och biodiversitet, samtidigt som hänsyn tas till fotgängarens upplevelse och platsens egenskaper.



Figur 6. Illustration av enhetligt ljus från gatubelysning.

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Abbreviations

ALAN	Artificial light at night
HPS	High pressure sodium
LED	Light emitting diode
MH	Metal halide
CCT	Correlated colour temperature
IDA	International Dark Sky Association
LIL	Low Impact Lighting
POS	Perception of Safety

1. Introduction

Light is a fundamental for species. Ecosystems and the physiology of species are dependent and organized around cycles of light and darkness (Bradshaw & Holzapfel 2010). Due to climbing population densities and urban expansions, humans are increasingly altering natural light and daily light cycles through introduction of artificial light at night (ALAN) (Gaston et al. 2014). Studies show that 80% of the world's population is experiencing light pollution (Pérez Vega et al. 2022). It is considered one of the significant drivers of global change and is closely correlated with other man-made pressures on the environment such as land-use change, climate change, and anthropogenic noise, especially in urban settings (Perkin et al. 2011).

Although a lot of sources contribute to light pollution, street lighting is the most dominant source of ALAN, based on satellite and aerial imagery (Kuechly et al. 2012). Additionally, it is the most persistent, expansive, and intense source of artificial lighting in urban settings (Gaston et al. 2012).

The current problem with street lighting is linked to the function of street lighting and from where these functions are established. As they are regulated by different lighting class categories that are mainly based on motorised traffic dynamics, it excludes smaller scale targets such as pedestrians and bikers, so called soft traffic users (Fotios & Gibbons 2018). This causes excessive and inconsistent brightness levels on places where it may not be needed, as it is not entirely based on pedestrian light sensitivities (Amoruso et al. 2022). The presence of excessive brightness is found in many different scales of the urban environment (Amoruso et al. 2022). Since the lighting class categories generally provide light to fulfil an areas' needs, consideration to surrounding areas and environments remain unprovided for (Amoruso et al. 2022). In addition, there is a lack of consideration and consciousness to biodiversity, as the biological impact of ALAN has been neglected in planning and design in urban settings (Grose & Jones 2021). This results in street lighting causing excessive brightness levels for humans in urban places, while at the same time impacting ecology, biodiversity, and local wildlife negatively (Hölker et al. 2021; Amoruso et al. 2022).

While there is an effort to move towards more energy-efficient and smart street lighting systems (Hölker et al. 2010a), there lacks a significant drive to integrate ecological solutions into the design process. In addition, urban lighting has opted to switch to smaller but more intensely bright light sources due to advancement of light source technology, which has in turn increased to the overall brightness exposure. This links to the lack of human centric solutions in the design of street lighting (Amoruso et al. 2022).

As it stands, there are still several benefits for human needs, namely navigation, perceived safety as well as aesthetic qualities (Boyce 2019) however the impacts on environment and biodiversity are at large loss of biodiversity and invasion of light onto hot spots (regions containing high level of biodiversity), loss of dark habitats, fragmentation, and population disruptions and changes within species, ecological interactions and community compositions (Hölker et al. 2010b, 2021; Gaston et al. 2014).

1.1 Effects of ALAN on biodiversity and local wildlife

ALAN has the effect of artificially extending daylight hours, increasing the overall light exposure and disrupting circadian rhythms (Hölker et al. 2021). One key role in light is melatonin which is crucial in timings of physiological processes. As such, even a small exposure with high intensity levels of ALAN, or exposure over long time, has altering changes in gene expression and melatonin production in humans and other species (Arendt 1998; Gaston et al. 2014). Studies on the effects of ALAN on insects and invertebrates generally show a negative trend on disorientation, desentisation, attraction and recognition, which results in disrupted behaviours (Hölker et al. 2010b; Gaston & Bennie 2014; Ouyang et al. 2015; de Jong et al. 2017; Pérez Vega et al. 2022). This can be seen as affected feeding, dispersal or movement, mating, and egg-laying behaviours (Pérez Vega et al. 2022). Ultimately, a rapid decline in insect diversity and abundance has been found due to the effects of ALAN (Hallmann et al. 2017).

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 impact	**Functional impacts**
Mortality	Species attracted and/or exposed to light may be killed (Gaston & Bennie 2014; Pérez Vega et al. 2022)

Migration	Natural movement patterns, migration, and orientation get disturbed by artificial light (Hölker et al. 2010b; Gaston & Bennie 2014; Pérez Vega et al. 2022)
Population size	Presence of artificial light causes reduced or increased foraging in species (Pérez Vega et al. 2022)
Indirect competition	Certain species may benefit by artificial light at the expense of other species, resulting in altered predator-prey relationships (Longcore et al. 2018; Jägerbrand & Bouroussis 2021)
Communication	Communication may be disturbed by artificial light (Pérez Vega et al. 2022)
Health and circadian rhythm	Physiological processes, such as increased corticosterone levels, may be altered by artificial light (de Jong et al. 2017; Welbers et al. 2017)

Similar effects can be found in birds due to ALAN as they are sensitive and tuned to seasonal changes and typically adjust their behaviours to take advantage of longer days. Some examples of this type of disruption can be found in the timing of bird song, where birds have been observed to start singing earlier than usual, also known as early onset of song (de Jong et al. 2018) as well as changes in reproductive timing (Senzaki et al. 2020). Higher cortiscosterone levels due to stress hormones – increased in birds due to specific light spectra (Ouyang et al. 2015). In other organism groups, around 11 studies have reports of bats exhibiting altered behaviours due to exposures of ALAN, such as abundant and active bats displaying attraction to ALAN resulting in higher foraging and activity around such light sources (Da Silva & Kempenaers 2017). In contrast, other families of bats were also found to display repulsive behaviour to ALAN with altered paths of flight (Kuijper et al. 2008; Stone et al. 2012; Lewanzik & Voigt 2014).

When it comes to physiological changes, certain traits may be more sensitive to ALAN, causing advantages and disadvantages interspecies (Secondi et al. 2020). This type of shift can be seen predator and prey relationships, causing incremental changes that may affect ecosystems and communities at large (Hölker et al. 2021; Pérez Vega et al. 2022). As ALAN is one of the drivers to global change, it is contributing to the decline of biodiversity worldwide (Hölker et al. 2021).

1.2 Aim and Research Question

This thesis main focus is to reduce the effects of ALAN on ecology and biodiversity. To apply to urban areas, a secondary focus on human needs and requirements will be applied. By mitigating biodiversity impacts and at the same time adopting human compatibility, this thesis will present a solution through a framework in the design and application of street lighting. This framework will act as a plan/approach intended for landscape architects and other actors within the realm of urban design to mitigate the impacts of ALAN on ecology and biodiversity. The results will be exemplified with recommendations and solutions on three specific locations. The neighbourhood was chosen due to the author being a resident of 15 years with close connections to all three locations.

To apply adaptability to various urban areas and the lighting requirements in each area, lighting zones will be taken into consideration. The lighting zones (LZ) range from LZ0 (low or no ambient lighting) to LZ4 (high ambient lighting). The lighting zones have been sourced from Dark Sky Association (2024) and have been estimated onto the locations in Gottsunda, Uppsala, based on the descriptions of the lighting zones from Dark Sky Association (2024).

This thesis is building upon my previous bachelor's thesis, where street lighting exclusively for ecology and biodiversity was explored. The design of street lighting has potential for mitigating its' adverse impacts on the environment, biodiversity, and local wildlife. This thesis adds the aspect of human needs, where I suggest that for environmentally conscious street lighting designs to be effectively implemented it is imperative to integrate to existing needs and activity of spaces with ecological concerns. Thus, the need to identify trade-offs or potential compatibility between these two fields is necessary. This includes comparing the different effects of artificial light on humans and biodiversity, finding the most optimized solutions, and applying it to a site or location.

Summarised, this thesis aims to present a framework for mitigation purposes in public city management as well as provide knowledge in the use of street lighting for the benefit of ecology. By adopting a framework that primarily focuses on mitigating impacts while still maintaining benefits for humans, such as perceived safety, the framework introduces a more optimized and sustainable approach to outdoor light design. It also introduces an adaptable approach to human activities on sites, habitats, and the residing species.

1. How can street lighting primarily mitigate the effects of ALAN on biodiversity and ecology, while maintaining sufficient benefits for pedestrians?

2. How does a trade-off between optimizing street lighting for human purposes and mitigating the impact on biodiversity look like on different types of locations/zones (town centre, residential, nature)?

2. Method

2.1 Literature review

In order to conduct and gather relevant information a scoping literature review of the phenomenon of ALAN and the effects on humans and ecology was conducted. The databases that were used were SLU Primo and Google Scholar. Additional research was found through citations and Connected Papers. The initial research was found through Routledge Handbook of Urban Ecology under chapter 12 (Grose & Jones 2021) which touches on the impacts of ALAN on urban ecosystems. From Routledge Handbook, references from Kevin J. Gaston and Jonathan Bennie were identified and reviewed for the impact of light pollution on species, populations, and biological processes. Additional work from Gaston & Bennie was reviewed (Gaston et al. 2012, 2013, 2014). Routledge gave an initial foundation of areas to discover, namely impact on animals, individuals and communities, implications for conservation, and future research directions.

To apply to a Swedish context with protected and sensitive areas, Annika Jägerbrand and Constantinos Bouroussis (2021) was identified through Google Scholar by using keywords such as "Artificial light at night" with "Sweden" and was used as a main article referenced in this work. From Jägerbrand & Bouroussis (2021) references, Hölker et al. was identified. Additionally, main components of street lighting were identified from Jägerbrand & Bouroussis (2021) namely correlated colour temperature, illuminance levels, light sources, uniformity of light, direction, shielding, and scheduling.

From literature reviews, specific keyword combinations the was found and assessed. These include keywords such as "artificial light at night", "light pollution", "street lights/street lighting", "strategies", "guidelines", "management". An additional scoping review was conducted to include the impact artificial light has on specific classes and families of species and the usage of street lighting for human purposes/functions. These keywords include "biodiversity", "wildlife", "animals", "species", "human", "perception", "pedestrian", "trade-off", "light-trap", "bats", "birds", "invertebrates", "insects", "nocturnal".

To find the effect of specific lighting components, keywords such as “colour”. “brightness”, “composition”, “LED” was used. Thus, information and studies were found regarding the impact street lighting has on species/ecology/biodiversity and the usage and design of street lighting. Information about ALAN was identified, selected, processed, and analysed with the interest and aim of conducting a framework for the design of street lighting. Two fields were identified and explored: 1. the effects on humans. 2. the effects on ecology. The main articles used in this thesis are (Gaston et al. 2012; Boyce 2019; Hölker et al. 2021; Jägerbrand & Bouroussis 2021; Amoruso et al. 2022).

Seven key components of street lighting were identified by how frequently they were brought up in the literature study. There was also a focus on parts that landscape architects can manage, work with, and manipulate. These are namely correlated colour temperature (CCT), light source (LED, MH, and HPS), illuminance levels, uniformity of light, direction, shielding and scheduling (with motion sensors).

The components will be reviewed from the literature study to find the most optimized settings to mitigate the effects of ALAN on majority of species. The literature review will also identify how to enhance benefits for pedestrians, such as perception of safety.

2.2 Analysis and locations

Due to different areas having different types of activity, density and traffic, different levels of outdoor lighting are required. To find the optimized settings of street lights specific to different zones, a trade-off will be conducted to identify negotiables and non-negotiables catered to three different locations (town centre, residential and nature) in Gottsunda, Uppsala. The analysis will demonstrate how each location has different negotiables and non-negotiables and show where human and ecology intersect and align in terms of street lighting. The analysis with the results from a Transect Walk will be applied to an existing passage in Gottsunda to apply a practical context.

The site is selected by being in near vicinity to residential areas as well as protected areas such as the nature reserve called Gottsunda Gipen in Uppsala, Sweden. In addition, it includes different ecological habitats ranging from forest to open grassland. This peri-urban area introduces the conflicting issues regarding residential area with areas of high biodiversity and is thus a point of interest (SLU Artdatabanken (2024). It also includes areas with several levels of light zones, ranging from no ambient light (LZ0) to high ambient light (LZ4) (Dark Sky International 2024), and was thus selected as it can demonstrate the framework to several different types of areas with different levels of human activity. The reasoning in the choice of the passage is due to it being in near vicinity of protected areas such as nature reserves and passing through centre of the neighbourhood, the mall. The nature area is also in proximity of near-threatened species such as *Cucujus cinnaberinus, Chloris chloris* and *Nyctalus leisleri* (SLU Artdatabanken (2024).

Areas that seem to have the highest contrast between bright and dark areas are those at the perimeter of nature and urban environment (Amoruso et al. 2022), which includes the nature reserve and the surrounding fields. Peri-urban areas, such as Gottsunda, are also deemed to have high amount of biodiversity. This may be due to factors such as abundant resources (food supply and shelter) found in comparison to their natural habitats (Mackenstedt et al. 2015). Studies have shown that an abundance of threatened species are found in cities, being largely dependent on the urban habitats, and thus are hotspots for threatened species (Ives et al. 2016).

2.3 Transect Walk

To quantify the human experience and perception of street lighting, the methodology of Transect Walk (BSR 2021) was conducted on a specific passage in the neighbourhood Gottsunda located in Uppsala, Sweden, where a group of 4 participants walked between two set points, starting from high ambient light levels to low ambient light levels. The participants consisted of 1 male (40) and 3 females (21, 31, 60). Throughout the passage, three stops were included where assessment, observations, and conversations on the perception of safety (PoS) were noted. These stops were included in three different zones: town centre, residential area, nature area. To discuss perception of safety, the participants walked alone on at each stop. The questions (see Appendix 2) were entirely based on the perception of safety, which is comprised of various factors. These include external threats such as humans or wildlife, and direct factors such as navigation and visibility, which glare can affect negatively. Question 1 surveyed the participants initial perception of safety by themselves. Question 2 and 3 surveyed the participants perception of safety if met by external factors. Question 4 and 5 surveyed the participants visibility and navigation and lastly question 6 surveyed the glare that may or may not be emitted by the street lighting, which may affect visibility and navigation (see Appendix 2).

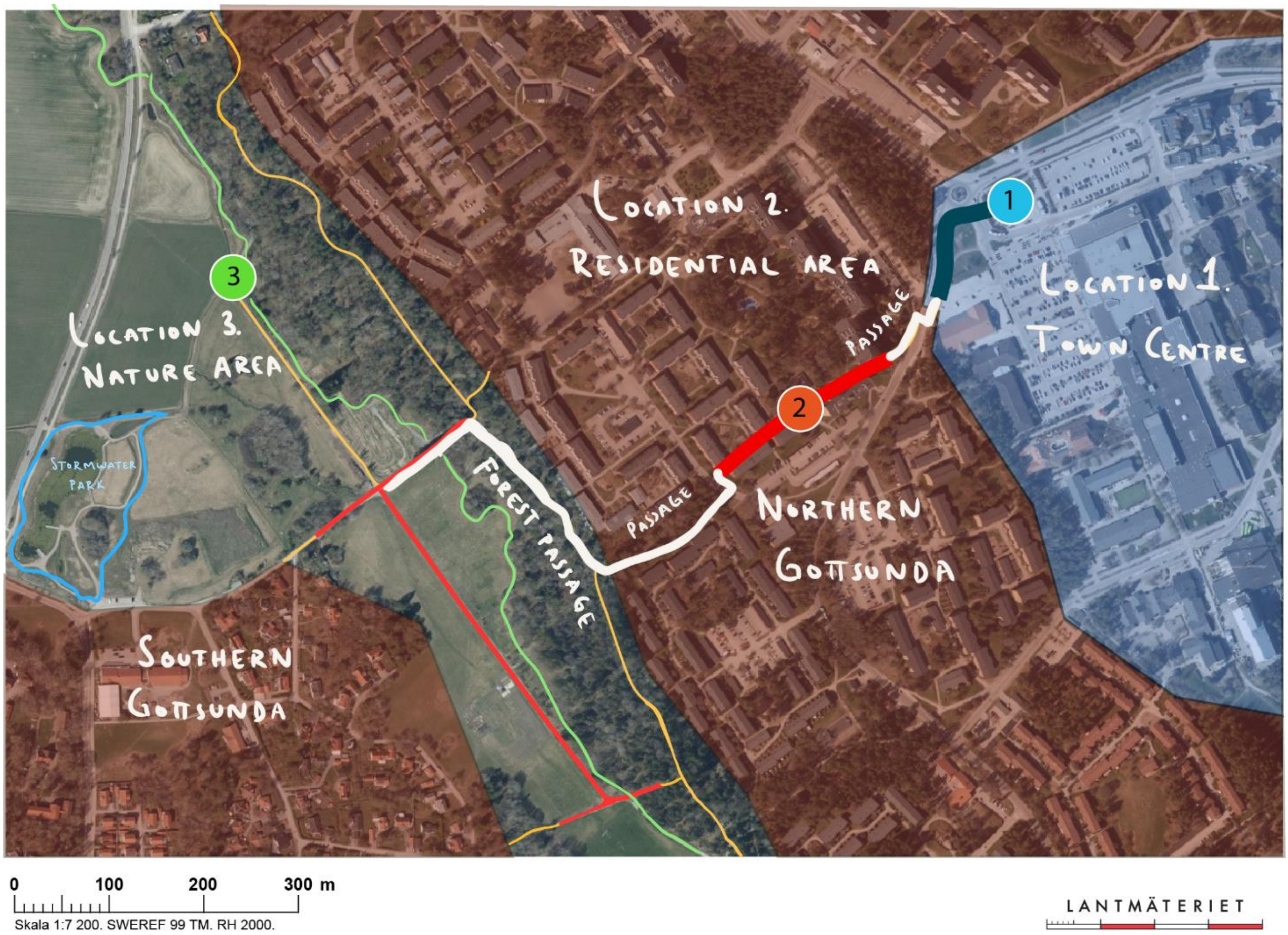

Figure 1. White strip represents the passage. Blue area (1.) represents mall centre area. Red area (2.) represents residential area. Green area (3.) represents nature area. Aerial image from © Lantmäteriet with added zones. Scale 1:7200/A4.

The passage was chosen due to having several lighting zones ranging from almost no ambient light (LZ0), close to the nature reserve and the surrounding fields, to high ambient light (LZ4), the neighbourhood centre and mall Gottsunda Centrum (Dark Sky International 2024).

2.4 Application of framework on a passage

The framework was applied and exemplified to the same passage as of the Transect Walk survey. By exemplifying and applying the framework to the same passage, the proposed measures were put into practice and highlighted the importance of adaptation to the residing species on site, population and human activity, and residential buildings/settlements.

Street lighting for biodiversity and street lighting for human purposes and functions, was developed with the least invasive value of each component for biodiversity, while still functioning and integrating human purposes. With the analysis on each type of location different types of zones in urban cities will also be considered. This way the framework will potentially optimize lighting for both humans and ecology, customized to varying urban settings.

2.5 Limitations

Due to street lighting being the most dominant source of artificial light, the framework will solely focus on street lighting. This excludes lights from inside buildings, art installations, and marketing signs. Additionally, the literature review will focus on pedestrians and will exclude lighting for drivers. Although road light is one of the most widespread uses of artificial light and is a major contributor to light corridors, the primary functions differentiate itself from street lighting for pedestrians, as it aims to produce light for faster movement and direction, as well as approaching vehicles (Owsley & McGwin 2010; Boyce 2019).

When it comes to components in street lighting, there are several one can change to accommodate for biodiversity and humans. These can be façade lights, colour temperature, light source, composition, and placement. Considering many professions play a crucial role in developing lights, the components that are chosen are ones that landscape architects can work with and manage within their role in the design department of the construction process. Thus, this will exclude lights from roads, moving light sources such as vehicles, pedestrians and bikers, and façade lights. Existing lights will be taken into consideration.

Certain indirect effects of artificial light on humans have been excluded due to lack of relevance, this includes the potential crime reduction of artificial light. Although Gottsunda has been viewed as a problematic area the source may delve from media perception of the area and many other factors that is not relevant to this work.

3. Effects of ALAN and potential solutions

3.2. Components of street lighting

To find what aspects of street lighting are good and less good, there is a need to dissect street lighting into components. As such, there are several components that street lighting is comprised of. In this section I will focus on three components, namely correlated colour temperature, light sources, and illuminance levels. I will also focus three solutions in the design of street lighting, namely uniformity (which includes placement and composition), direction, and scheduling.

3.2.1 Correlated colour temperature

The colour of light, specifically the range of wavelengths (called spectra or spectrum), can have several effects on perception as well as physiology. Colour in this thesis will be seen as both a spectral component which refers to specific wavelengths affecting species physiologically and as a perceptual concept, which contributes to the way humans view objects and space. This section of the thesis will touch upon both aspects respectively.

When it comes to the composition of light colour and temperature, also known as correlated colour temperature (CCT), it tends to be measured in units of Kelvin or, if it is based on wavelength, measured in nanometres (nm). To give an estimate, temperatures ranging from warm (~2000 K) to cold (~10000 K) ranges from 700 (warm) to 400 nm (cold) respectively.

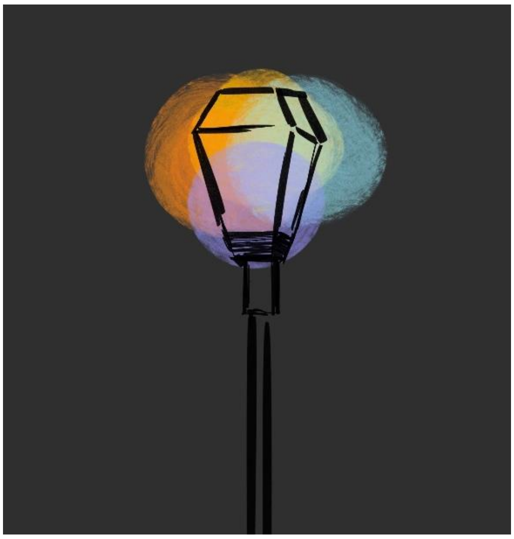

Figure 2. Illustration of varying colours on street lighting.

Figure 3. A range of spectra going from warm temperatures (1000 Kelvin) to cold temperatures (9000 Kelvin). Image is directly imported from source: DPJ Workspace (2024).

From existing knowledge, varying species show different sensitivity to wavelengths. However, numerous organisms, namely mammals (Bowmaker 1998), birds (Hart 2001), insects, reptiles, and amphibians (Kelber et al. 2003) have photoreceptors that are more sensitive to blue light, potentially making them more susceptible to the effects of these wavelengths than humans. Studies have observed the impacts of red, white, green, and blue light on different species, revealing differences in their responses (Ouyang et al. 2015; Spoelstra et al. 2017; Grubisic et al. 2019). For instance, white and green light have been observed to influence a species of light shy and agile bats, while red light demonstrated no effect (Spoelstra et al. 2017). Conversely, an alternative study suggested that red light could potentially disturb the circadian rhythms of songbirds, possibly leading to higher concentrations of corticosterone, a stress hormone (Ouyang et al. 2015). This links to the importance of adapting street light temperatures to existing species residing in the habitats.

However, research from de Jong et al. (2017); Ouyang et al. 2017 and Owens & Lewis (2018) show that a consistent pattern emerges indicating that white light tends to have disruptive effects on various species, including songbirds, bats, insects, and even mice. These present results are significant in that they challenge the consensus of white light being more environmentally friendly, as it often is advertised as. Because white light contains a large spectrum of different colours, one factor that disrupts some species is the presence of green light, which is present in both white and yellow spectrum (Jägerbrand & Bouroussis 2021). To mitigate these disruptive effects, it is advised to minimize the emission of light below 500 nm. There are also implications in white light emitting more blue light than other types of spectra. Thus, amber LED light with a yellow hue, peaking at 590 nm (2200K) are recommended as a preferable solution (Dick 2016). While this may not eliminate the impact on species, it is likely to not affect majority of species (Longcore et al. 2018).

Other sources that correlate to similar recommendations are from Licht und Natur, which suggest keeping the light energy in the range below 500 nm (roughly corresponds to the blue-green part of the visible spectrum) to less than 6% of the total visible light emitted. The International Dark Sky Park Designation Guidelines (IDA 2018) also suggest an almost similar range, light below 550 nm or 5000 K should emit less than 25% of the total emittance.

In simpler terms, these sources (IDA and Licht und Natur) recommend reducing the blue-green part of the spectrum to a small amount (of the total light emitted) to reduce the negative effects of ALAN on the environment. This will change the temperature of street lighting to look more amber coloured for humans. Other options outside CCT, are filters that absorb unwanted wavelengths, which reduces HPS lights and blue rich wavelengths (Dick 2016).

When it comes to human perception, there can be different preferences in varying temperatures ranging from warm to cold light (see fig. 2). When LED was initially adopted, the CCT ranged from 5500-6500 K, much colder than neutral light sources which read at 3500 K (Hao et al. 2022).

Studies from Newsham et al. 2004 and Veitch et al. 2008 have found that certain lighting preferences in participants can induce positive feelings, increase satisfactions or have healing effect. Furthermore, warmer CCT along with low illuminance levels were found to make participants feel emotionally relaxed and ease, in contrast to cooler CCT along with higher illuminance levels which made participants feel more awake and focused (Shamsul et al. 2013).

When it comes to safety perception, identification and intention recognition are important. Using street lighting with a colour spectrum of around 3000 K resulted in higher recognition, including facial recognition (Hao et al. 2022). Combined with LED light sources studies have found better facial recognition, specifically in combination with CCT of around 3800 K (Rahm & Johansson 2018). Other studies on pedestrians have shown that CCT were preferred at the range of 2700-3200 K for recognition, safety, and comfort (Hao et al. 2022).

Summarised, this section mentions how colour temperature can affect both the perception of humans and the physiology other species. It explains how species, including humans, respond to various wavelengths, with some species being more sensitive to certain spectra, specifically blue light. Research show that white light, while often advertised as being environmentally friendly, may in fact disrupt natural behaviours and causing larger ecological impacts. Recommendations include minimizing light emissions below 500 nm and utilizing amber LED lights around 2200 K to mitigate disrupting effects. Studies on the human perception show that warmer colour temperatures may be preferred for relaxation and improving safety perception by helping in comfort.

3.2.2 Light sources

Light-emitting diode (LED), high-pressure sodium (HPS), and metal halide (MH) are the three most dominant light sources used in street lighting systems. While each lighting technology presents its own set of advantages and drawbacks on their impact on species and environmental impacts, research suggests that LED's may in fact be the better option, at least in regard to HPS and MH lights (as well as incandescent bulbs) (Davies et al. 2012; Justice & Justice 2016).

This is due to several factors: first, LEDs' being more energy efficiency results in reduced greenhouse gas emissions; second, their prolonged lifespans translate to fewer replacement, lower maintenance as well as decreased energy consumption (Davidovic & Kostic 2022); third, their customizable spectral output allows for various wavelengths to be adapted to different species and habitats (Owens & Lewis 2018); fourth, LED's offer the option of directing the light; fifth, allowing the option of dimming and instant on-and-off functionality (Justice & Justice 2016); and lastly, LEDs do not contain any toxic materials, unlike MH and HPS lights, which may pose risks to humans and other species.

Summarised, three light sources used in street lighting systems, namely LED, HPS, and MH. Research show that LEDs may be the preferable option compared to HPS and MH due to several reasons. LEDs are more energy-efficient, resulting in reduced greenhouse gas emissions, and they have longer spectral output which allows for adaptation to different species and habitats. Additionally, LEDs offer directional lighting, dimming, and instant on-and-off functionality. Unlike MH and HPS light sources, LEDs do not contain toxic materials, reducing the risks to humans and other species.

3.2.3 Illuminance levels

Illuminance levels, often synonymous with brightness or light intensity, measures the amount of light reaching the ground or a surface. This measurement, often used in units of lux (lx), represents the light energy per unit area where 1 lux equals to the illumination of candle light one meter away. In terms of utilising street lighting in urban spaces, the illuminance level is crucial for determining the suitability for different spaces and activities. Various tasks and environments require specific illuminance levels to ensure enough visibility, safety perception, and visual comfort. This section of the thesis focuses on finding the right illuminance level for pedestrians while mitigating the effects on biodiversity.

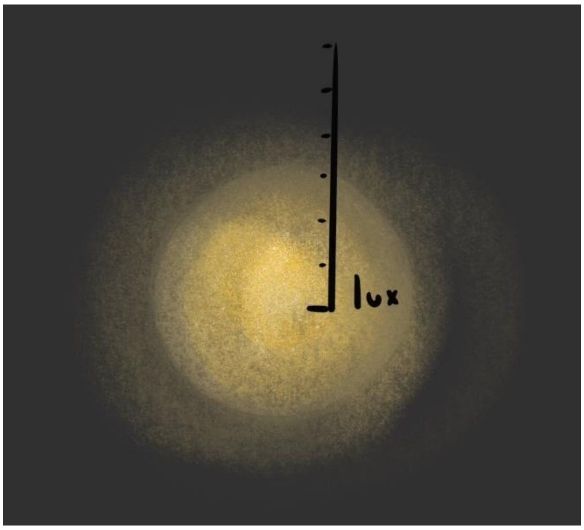

Figure 4. Illustration of varying illuminance levels, measured in lux.

As a reference, sunlight can reach illuminance levels of approximately 100,000 lux, while road lighting typically varies from 0.5 to 30 lux (Gaston et al. 2013). Moonlight and skyglow usually fall below 1 lux (Gaston et al. 2013; Jägerbrand & Bouroussis 2021) and levels up to 150 lux can be reached in urban areas (Grubisic et al. 2019). When working with illuminance levels with CCT, it is important to note that the intensity of light may be affected by the colour – as different illuminance levels may be used depending on the colour emittance (Amoruso et al. 2022).

The general praxis of illuminance levels for the environment and biodiversity is to keep it as low as possible, as the lower the illuminance the better for the environment. However, for human utilisation, street lighting must be sufficiently bright at night to see obstacles and avoid collision after dark. Boyce 2019 means that an illuminance level of around 2 lux is enough for safe movement. Fotios & Cheal 2009 and Uttley et al. 2017 means that 0.10 to 0.62 lux is sufficient for pedestrians to avoid collision and provide hazard detection but recommends illuminance levels between 1 and 2 lux for bikers to navigate in urban settings. Any higher illuminance levels (around 2 and 20 lux) showed diminishing returns (Fotios & Cheal 2009).

When considering illuminance levels in street lighting for human perception, it becomes important to consider the transition between lit and dark spots. Although seen as a potential beneficial aspect, higher illuminance level may in fact reduce overall uniformity. Research (Amoruso et al. 2022) show that a reduction in illuminance levels contributes to more evenly distributed brightness on ground.

Lower illuminance levels are also supported by the process of dark adaptation, a rapid process by which the human eye adjusts to low-light conditions after being exposed to high levels of brightness. In summary, this adjustment temporarily impairs human vision after entering dark spots from a well-lit one and is a crucial aspect to consider in the design of street lighting (Amoruso et al. 2022). To combat stark contrasts between dark and lit areas, maintaining a balanced light distribution is crucial, and by lowering and dimming the illuminance levels not only supports a more uniform distribution but also diminishes glare, contributing to visual comfort.

Summarised, illuminance levels, which measure light intensity and are crucial for determining visibility, safety, and visual comfort in urban areas. Street lighting typically ranges from 0.5 to 30 lux, with moonlight and skyglow falling below 1 lux. Lower illuminance levels are generally preferred for environmental and ecological reasons, but human safety requires sufficient brightness. Research recommends around 2 lux for safe movement and collision avoidance for pedestrians and bikers. Higher illuminance levels may reduce overall uniformity and contribute to glare, impacting visual comfort. To maintain balanced light distribution and minimize glare, lowering and dimming illuminance levels are suggested.

3.2.4 Uniformity

Moving on now to consider uniformity. Placement and pole height has a major role on good uniformity, as it may distribute light evenly, and as a result reduces the contrast between high and low illuminance levels and glare while contributing to visual comfort for the pedestrian.

Figure 5. Illustration of good uniformity from street lighting.

Standards for Low Impact Lighting (LIL) recommends the distance between street lighting poles of at least 3,7 times greater than the height of the pole (Licht und Natur).

Although the composition and placement play an important role, it is important to consider the topography of the area to provide good uniformity (Amoruso et al. 2022). Lighting requirements and the spatial geometry of the environment determines the physical placement of the street lights, which includes the distance between poles and the mounting heights of the light fixtures (Amoruso et al. 2022). Moreover, it is crucial to consider the surrounding environment, as ecological aspects may be prioritised over visual comfort of the pedestrian in certain areas. This includes areas in near vicinity of protected or sensitive habitats/areas Thus, good uniformity of light is an incredible resource as it can improve perception of safety, and as a result allows reducing the illuminance levels, making it a crucial component for both pedestrians and biodiversity.

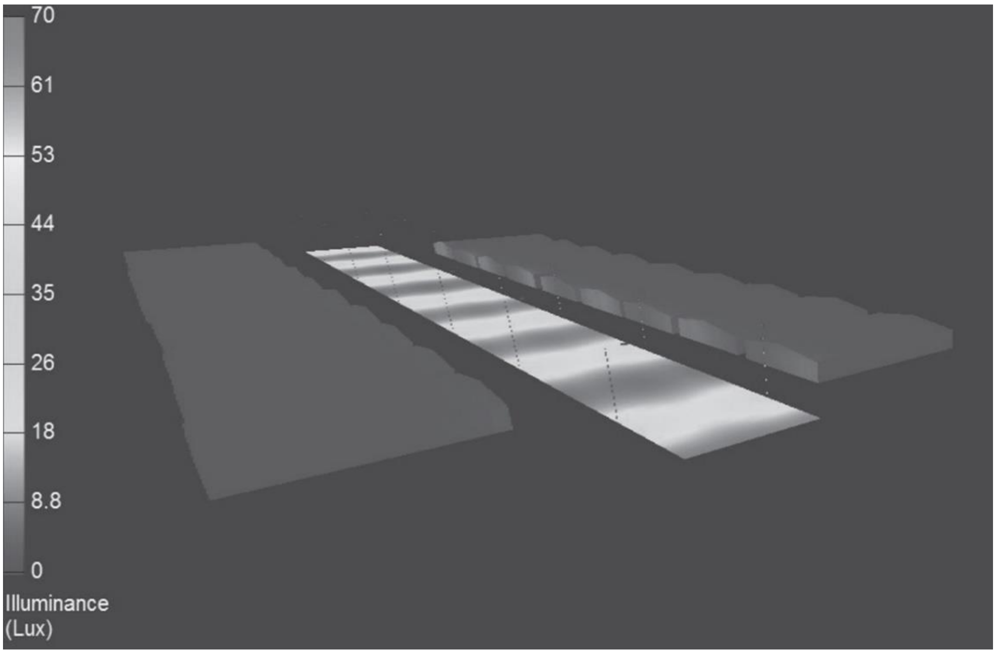

Figure 6. A street in Melbourne, Australia. Showcases patterns of illumination (measured in lux) ranging from lit to unlit spots on the ground. Shows poor uniformity of light. Source: Image by Adam Carey, Werribee, Australia. Directly imported image from Routledge Handbook of Urban Ecology.

Summarised, the importance of uniformity in street lighting, which can be achieved through intentional placement and appropriate pole height. Uniform distribution of light reduces the contrast between high and low illuminance levels, minimizes glare, and in turn enhances visual comfort for pedestrians. Standards recommend a distance between street lighting poles to be at least 3.7 times greater than the pole height. Consideration of the area’s topography and activity level is important to achieve better uniformity. In certain areas ecology and biodiversity will be prioritized over pedestrian comfort, especially near sensitive or protected areas and uniformity is a solution for dimming illuminance levels while still contributing to perception of safety for pedestrians.

3.2.5 Scheduling with motion sensors

The use of motion sensors and light-dimming devices are technologies that are becoming increasingly popular and enables the option to customize illumination levels to the required need (Archibong et al. 2020). It is highly recommended to incorporate scheduling and timers with strict curfews to minimise the negative effects of ALAN on species, especially for nocturnal or crepuscular species that are adapted to environments with low light. By incorporation of motion sensors in areas such as residential areas, it will allow pedestrians to roam after dark while still limiting light and creating periods of darkness. Fortunately, unique programs can be installed in street lights with pre-programmed drivers that can be specifically adjusted to area and time of year, which provides control in a more effective way (Jägerbrand & Bouroussis 2021). In sensitive or protected areas, it is highly recommended to apply strict curfews and occasionally turn off lights to minimize the effects of light pollution. This can only be applied in areas that are not populated or highly trafficked such as residential areas, city centres, or roads. With this approach, natural lighting will be preserved and not only will it benefit the local wildlife, but also reduce energy consumptions (Jägerbrand & Bouroussis 2021).

Figure 7. Illustration of the light being set on timers on street lighting.

The Lighting Infrastructure Legislation (LIL) recommends that all outdoor lighting should be dimmed from 100% to 10% during curfew periods (outside of peak traffic hours), and if older lighting technology is still in use, to dim it to at least 50%. Additionally, it is advised to switch off street lighting two hours prior sunrise and after sunset (Dick 2016). This type of approach can be seen in Vienna, Austria, where curfews were implemented in 2012 for certain streets which resulted in an improvement of the night sky brightness of 1.4% (Puschnig et al. 2014). As with all types of curfews, providing the public with prior notice about curfews and the reasonings allows visitors to be informed regarding any changes and measures.

Summarised, this section discusses the importance of incorporating scheduling and motion sensors in street lighting systems to customize illumination levels to area. Scheduling with timers with strict curfews are recommended to minimize the negative effects of ALAN on species, especially those that are adapted to nocturnal environments. Motion sensors in residential areas allow pedestrians to move after dark while limiting light and creating periods of darkness. Unique programs installed in street lighting with pre-programmed drivers provide control over illuminance levels. In sensitive or protected areas, even stricter curfews are advised to minimize light pollution. Research also recommends dimming street lighting during curfew periods and switching the lights off two hours before and after sunset, with prior notice provided to the public.

3.2.6 Direction and shielding

Street lighting remains poorly designed when it comes to directing light, as it is not managed or designed to emit light where it is required (Gaston et al. 2012). Gaston et al. 2012 means that by finding solutions to reduce the emitted light spilling onto the sky, the impacts of ALAN on a local scale will be dramatically decreased.

Figure 8. Illustration of shielding on the top of the street lighting, prohibiting light from emitting upwards.

Shielding street lighting and directing the light are two options that mitigates the effects of skyglow by reducing the light trespass. The former working as a light pollution blocker, and the latter allowing light to only emit onto the intended area. By utilising both technologies it has potential of reducing the amount of light being emitted upwards towards the sky (Owens & Lewis 2018). It also limits less wanted effects such glare, by directing the light to certain angles (Jägerbrand & Bouroussis 2021). Direction of light is dependent on area, as certain areas may be more sensitive or contain specific habitats for wildlife, however, as a general consensus light should only emit where it actually is required. Shielding can be achieved by using physical barriers. The International Dark Sky Association, also known as IDA, has developed a shielding system which allows a stricter and detailed requirements called the Backlight Uplight and Glare (BUG) system (IDA 2009). The system is divided into three categories, backlight, uplight, and front light of the street lighting and provides control of the amount of emitted light from several angles.

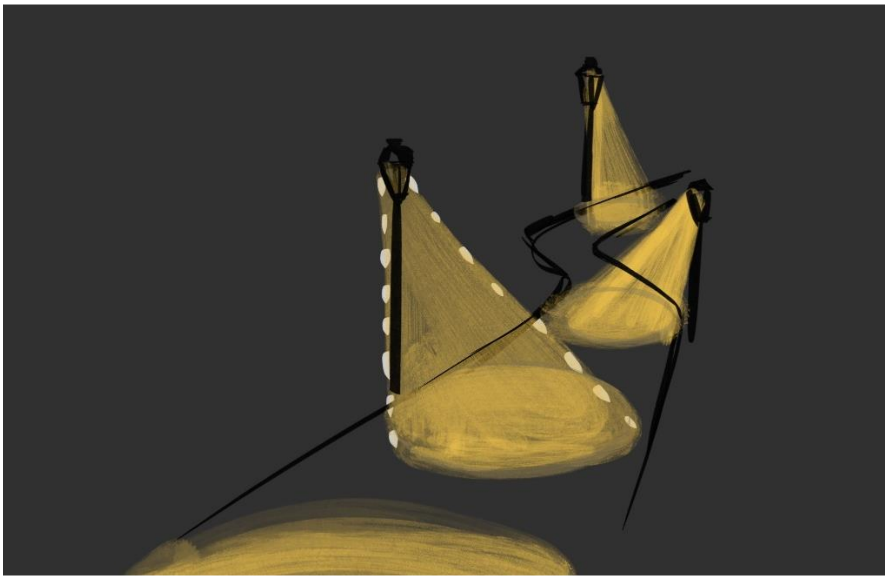

Figure 9. Illustration of directed light from street lighting. Also showcases poor uniformity of light.

Figure 10. Images of unshielded street lights. Source from left to right, Nicolas Jarmillo from Pexels, Spencer Quast from Unsplash, Karl Solano from Pexels.

Summarised, there is a need for improved design in street lighting to direct light where it is needed, as current setups cause light spillage onto the sky. Solutions such as shielding and directing light can significantly reduce the impact of ALAN. Shielding acts as a light pollution blocker, while directing light ensures it lights up areas intended areas, reducing light trespass and glare. Combining both techniques has the potential to decrease light spillage upwards. The direction of light should also be customized to specific spots of habitats, avoiding nesting areas or similarly sensitive local spots. Shielding can be achieved using physical barriers, with the International Dark Sky Association's Backlight Uplight and Glare (BUG) system giving suggestions on how to avoid emitting light from various angles.

3.3 Benefits for humans

The most fundamental use of artificial light at night is to enable visibility for outdoor walking after dark and in turn improve navigation. The increased vision allows us to see obstacles and avoid collision and opens possibilities of activity after dark (Boyce 2019). Artificial light does not only show an impact on other species, but also humans, as excessive brightness, poor direction, glare, and light trespass have been shown to affect peoples' stress levels (Longcore & Rich 2004) and visual comfort (Amoruso et al. 2022).

3.3.1 Perception of safety

Several studies highlight the importance of street lighting as it increases the walkability in neighbourhoods (Ewing & Cervero 2010; Kim et al. 2014; Park et al. 2015). It is generally found that the presence of street lighting improves perception of safety, particularly in women and the elderly (Rahm & Johansson 2018; Boyce 2019). Rahm & Johansson 2018 also mean that a certain illuminance level to view faces is deemed important to ensure perception of safety (PoS) for humans as it allows judging the intent and distance of oncoming pedestrians. According to Jan Gehl (2020) the distance where humans see facial recognition and expression is 20-25 metres. However, in dark settings, this may be affected by other factors such as glare, dark adaptation processes, and bad uniformity.

Within the theme of illumination levels, studies have in fact found that illuminance levels as low as 10 lux increases perception of safety, any higher shows diminishing returns (Boyce 2019). However, it is important to bring up that while illuminance may play a role in street lighting, uniformity of light should be considered as well as it allows better surveillance and proves to be effective for better safety perception (Boyce 2019). The formal control the government issues as a way to handle higher degree of safety, is through more surveillance which in turn justifies higher brightness levels in street lighting (Newman 1996). Studies that contradict this have shown other ways of promoting perceived safety in a domestic scale of urban lighting, which is through an increase of presence of people that naturally promotes a sense of collectiveness and pride and safety (Newman 1996).

Interestingly, a study done by Haans & De Kort 2012 showed that dynamic lighting and static lighting resulted in different perceptions of safety. Dynamic lighting (which refers to lighting systems that can customize their intensity, colour, or direction depending on environment) showed higher ratings of perceived safety, better prospect perception, a reduction in feelings of concealment and better escape perception, than static lighting.

Studies done on the pedestrian response of street lighting with varying light sources (LED and MH) and different CCT showed that obstacle- and facial detection was found to be most effective under lighting conditions with LED with a CCT of 3800 K as it allowed pedestrians to better distinguish street signposts and identify facial expressions, than lighting conditions with LED and MH with a CCT of 2800-2900 K (Rahm & Johansson 2018).

To summarize, illumination levels can affect safety perception and has been used as a formal control by the government to handle issues regarding safety, however, lower illuminance levels may still be sufficient, and may in fact contribute to increasing visual comfort due to less glare. When it comes to colour temperatures, studies on pedestrians have shown that CCT were preferred at the range of 2700-3200 K for recognition, safety, and comfort (Hao et al. 2022). Other viable options that contribute to safety perception are uniformity. Good uniformity allows for passages and roads to be evenly lit resulting in higher visibility (Haans & De Kort 2012), facial recognition (Rahm & Johansson 2018), better surveillance (Boyce 2019) visual comfort (Amoruso et al. 2022), in turn promoting a higher degree of safety perception. To contribute to good uniformity, a dynamic lighting is essential, as it allows for customizable settings, such as dimming, CCT, or direction, to be set depending on area and the activity requirements, surrounding area, topography, and function. Thus, the utilisation of LED is important, as it allows for customisation and adjustability, as well as contributing to better facial recognition, specifically in combination with CCT of around 3800 K (Rahm & Johansson 2018).

3.4 Dark Habitats

Dark habitats are natural environments or areas that are entirely or relatively free from artificial light and light pollution, allowing for optimal conditions for stargazing, biodiversity and local wildlife, and ecological processes that depend on natural light cycles. With the continuous loss of dark habitats, specifically around more urbanized areas, it is imperative to protect those areas that remain. By protecting, keeping, and creating dark habitats it may identify dark habitats that are present, highlight their status and possibly encourage steps to maintain such habitats (Hölker et al. 2021). This may also encourage communities to take initiatives to reduce ALAN in small and localized changes, for example with motions sensors or timers, as it may reduce large impacts (Hölker et al. 2021).

Solutions for maintaining dark habitats may also be found in Germany where one example shows implementation of “insect protection” law in the Federal Nature Conservation was applied (Hölker et al. 2021). An additional solution at a larger landscape level is the conservation strategy of interconnected dark ecological networks, which include core areas, corridors, and protective buffer zones to mitigate the effects of ALAN (Challéat et al. 2021).

Dark habitats remain largely unexplored in terms of their potential benefits, which not only provide environmental conservation/preservation but also provides benefits for humans. These areas may offer experiences of tranquillity, solitude, and aesthetic enjoyment by providing a break from urban environments.

4. Results

While various aspects of artificial light have been recognized for the impact on biodiversity and influence on human perception in previous chapters, the intersections between these two fields remain relatively unexplored, especially on how one can integrate them in a practical way. Chapter 3 identifies potential solutions to mitigate the effects on ecology and biodiversity. The site analysis on this section will identify what parameters one can work with based on area and activity, and the survey on the passage explores the aspect of human perceptions and where they may lack on the whole passage.

4.1 Site Analysis regarding ALAN

4.1.1 Town centre – Location 1

The area consists of a small square with bus traffic of five lines, several parking lots, and a smaller church further southeast. It is the main centre for the neighbourhood with several stores such as grocery markets, clothing stores, restaurants, etc. This area has higher population density and activity, and surrounding areas mainly consists of residential zones. Additionally, Uppsala municipality plans on expanding further (Uppsala Kommun 2022). When it comes to topography the location is flat. The area has a moderately high ambient light (LZ3) (Dark Sky International 2024) due to the large lit signs across the mall building, billboards, and street lighting. Lighting poles are around five meters in height.

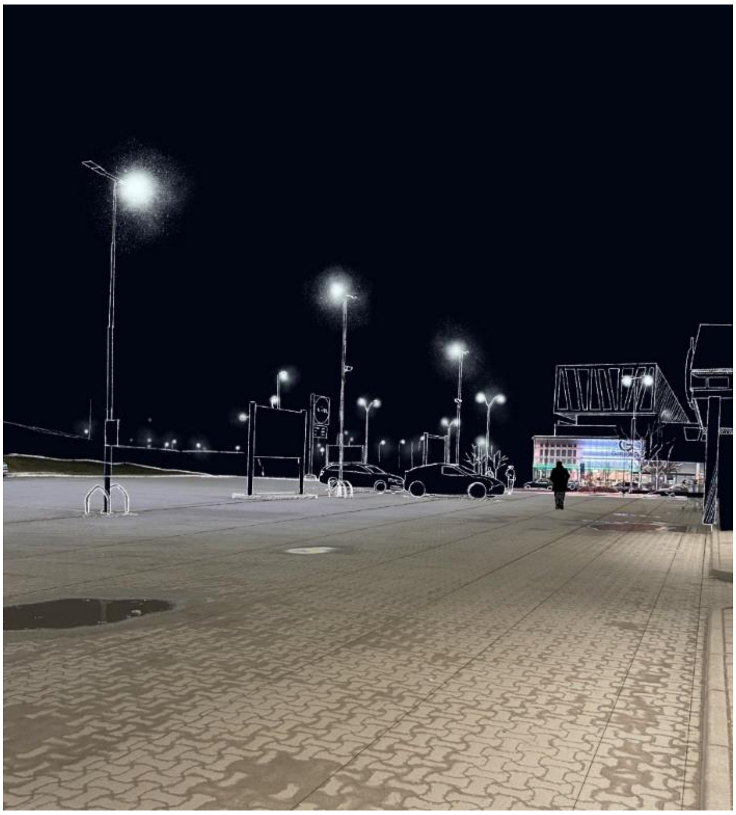

Figure 11. Illustration of a photo of the centre mall in Gottsunda Centrum, Uppsala, with the abundance of street light and ambient light, with good uniformity of light.

4.1.2 Residential area – Location 2

This area is the neighbouring area of the town centre, towards the south. It mainly consists of residential buildings with high-rise and rowhouses, on a higher topography than town centre. The ambient light is moderate (LZ2) (Dark Sky International 2024) consisting of mainly street lighting. This area has a lower activity than the town centre, with surrounding area that consists of recreational nature areas and fields.

Figure 12. Illustration of a photo of the residential area in Gottsunda Centrum, Uppsala. Shows relatively good uniformity of light.

4.1.3 Nature area – Location 3

This area consists of two nature areas, a forest passage of older trees and field areas. Both areas function as recreational areas as well. The topography in the forest passage is varying, ranging from low and high points, while the field area consists of a flatter topography. The ambient light ranges from low ambient light (LZ1) to no ambient light (LZ0) (Dark Sky International 2024) consisting of mainly street lighting.

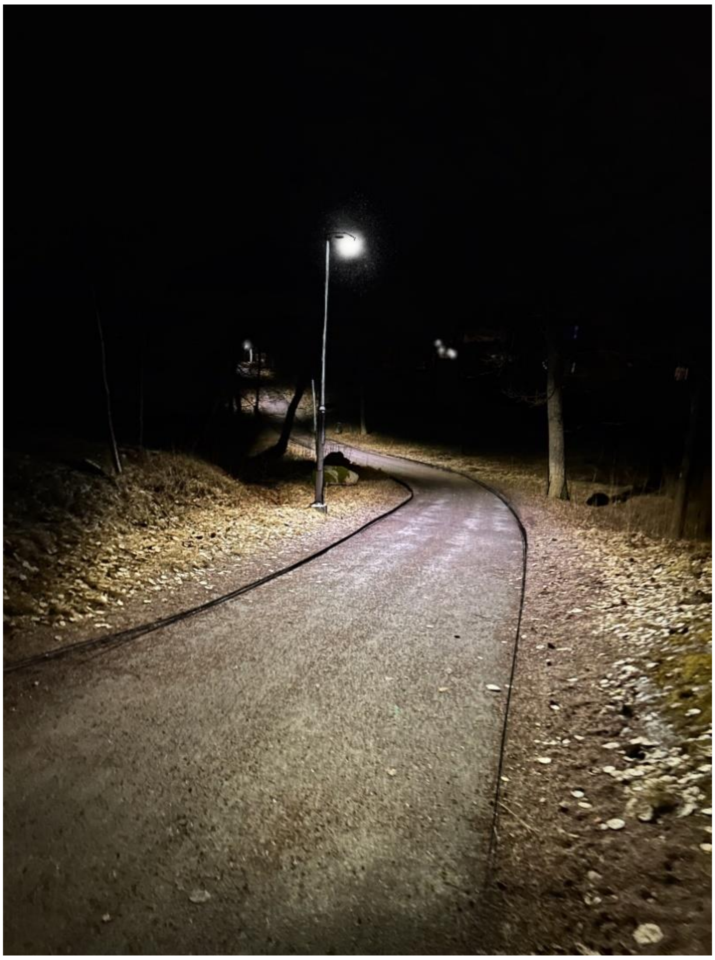

Figure 13. Illustration of a photo from the passage in the nature area. Showcases poor uniformity of light in darkness, as well as varying topography.

Summarised, the different locations have somewhat varying street lighting such as pole height, colour, and uniformity, but more importantly the site analysis show that customization of street lighting has not been properly applied to the different types of areas.

4.2 Results of Transect Walk

Table 2. Results of survey (see Appendix 2) from Transect Walk done from town centre, residential area, and nature area. Grading system where 1. is low and 5. is high.

Location	**General level of safety**	**PoS meeting stranger**	**PoS meeting wild animal**	**Navigation**	**Visibility**	**Glare and or discomfort**
1. Town centre	3.75	2.5	4.25	4	4.5	3.5
2. Residential area	4.25	2.5	4.25	5	5	3
3. Nature area	2.25	1.75	2.25	5	3	2.5

Results from the transect walk survey show varying ranges of perception of safety (with strangers and/or wild animal), navigation, visibility and whether glare or visual discomfort is present. Perception of safety (in both types of meeting) was found to be similar in town centre as in residential area, and poor in the nature area. There was a difference found in the perception of safety when meeting wild animals and when meeting strangers, where meeting strangers scored lower. Navigation was found to be highest in both the residential area and the nature area, and lowest in town centre. Visibility was highest in the residential area, followed by the town centre and lowest in the nature area. Glare and discomfort from the street lighting followed a steady decline from mall centre to residential area and lowest in the nature area.

4.2.1 Town Centre

Street lighting in location 1 provided a generally good level of safety, scoring 3.75 out of 5. However, the perception of safety, particularly when it comes to meetings with strangers received a lower score of 2.5 out of 5. This discrepancy may be due to other external factors such as neighbourhood reputation, lack of escape routes, lack of surveillance, lack of facial recognition of oncoming pedestrians, etc.

While uniformity of light is a suggestion to improve on perception of light (Boyce 2019), location 1 already emits good uniformity, which allows for good facial recognition of oncoming pedestrians from a distance. Glare and visual discomfort, however, scored 3.5 out of 5. This may be due to the lack of directed light from the street light, as well as external light sources such as billboards, lit signs, and facades that emit high ambient light. The low score of glare and visual discomfort may also directly affect perception of safety due to affected facial recognition of oncoming pedestrians.

4.2.2 Residential Area

Street lighting in this location showed very high levels of perception of safety, scoring 4.25 out of 5, the highest among all the surveyed locations. This may be because of the higher surveillance and proximity from residing homes, adding to the perception of safety. However, the score regarding meetings with strangers was notably low, with the same score as location 1, 2.5 out of 5. This discrepancy between general safety provided by street lights and meetings perception of safety when meeting strangers may again be due to other external factors mentioned in the previous chapter. Meetings with wild animals scored the same as location 1, 4.25 out of 5, suggesting a generally high perception of safety in that regard. However, uniformity of light is relatively good with room for improvement.

When it comes to navigation and visibility, the residential area scored the highest possible of 5 out of 5, which indicates optimal street lighting conditions for navigating and being able to see obstacles. Glare and visual discomfort scored slightly lower, 3 out of 5, which may suggest lack of directed light.

4.2.3 Nature area

This location resulted in the area with the lowest overall safety score, of 2.25 out of 5. Specifically, it ranked poorly in perception of safety concerning meetings with strangers (1.75 out of 5) and wild animals (2.25 out of 5). These results demonstrate a need for better measures in overall perception of safety in this area.

In contrast, navigation scored similarly to other location the highest possible score of 5, which indicates ease of movement and direction. However, visibility scored lower than other areas with a score of 3 out of 5. Glare and discomfort also scored lower than other areas with a score of 2.5 out of 5. Feedback from the survey mentions the glare and discomfort may be from the height of street lights landing at an eye level. This may be due to the local topography and/or inadequate pole height.

Summarised, the general level of safety was found highest in the residential area, followed by town centre and lowest in the nature area.

4.3 Analysis of trade-offs and Proposed Measures

This section will analyse the different components at each location and analyse potential trade-offs of components based on what is appropriate at each location. Thus, a plan of action on the passage will be conducted with recommendations, demonstrating how alignments and intersections between pedestrians and ecology might look like at each location, by utilising the site analysis on chapter 4, the results from the transect walk and potential solutions in chapter 3.

Firstly, certain parameters must be established before a trade-off is conducted. Activity and requirements of different areas play a crucial role for a working, social, system to function well. This introduces implications regarding the importance of artificial light for humans, as it has many benefits (Boyce 2019). Thus, it is highly dependent on the activity of the area, how it is used by humans, as population density and activity of place changes lighting requirements. However, there is a need to mitigate the effects of ALAN on biodiversity, especially in close vicinity to protected or sensitive areas. To navigate around this, each component will be categorized into negotiables, aspects that are subject to change, and non-negotiables, aspects that are not subject to change, based on the inherent traits of the locations. Summarised, the analysis will be based on the proximity of the locations to sensitive or protected areas – the lower priority for humans and higher priority for biodiversity and environment.

Each location explores the usage of all the components of street lighting. The components have then been categorized into negotiables and non-negotiables which are based on activity of area and surrounding areas. This results in each location having customized negotiables and non-negotiables with varying potentials. The only non-negotiable in the analysis are illuminance levels, where sufficient levels for pedestrians (and bikers) to see and avoid collisions is required and a must. For street lighting that are made for humans there is a requirement to continue functioning the way it was intended – to illuminate after dark (Boyce 2019).

For potential changes, shielded street lighting is included at all locations, as it does not have any major downsides (Jägerbrand & Bouroussis 2021), however this component is already applied at all locations. Directed light is the other component that is applied as a potential change at all locations to reduce glare and discomfort as well as skyglow, as it does not have any major downsides (Jägerbrand & Bouroussis 2021).

4.3.1 Town Centre – Location 1

Table 3. Shows non-negotiables, negotiables, current conditions, and potential changes in location 1, the town centre.

Non-negotiables	**Current Conditions**	**Potential Changes**
Illuminance levels	High illuminance levels.	None.
Negotiables	**Current Conditions**	
Shielding	Upward light is shielded.	None.
Correlated colour temperature and Light source	Ranging from warm neutral (~4000 K), white (~5000 K) to blue (~6000 K).	Change and adjust to amber LED of around 2200K.
Scheduling and/or motion sensors	No scheduling or motion sensors	None.
Direction	No directed lights	Direct downwards using (BUG)-system from IDA (2009).
Uniformity of light	Evenly lit.	None.

Scheduling with motion sensors and dimming of street lights is not included as a potential change as it may not be appropriate at such a highly active area. For the same reasons, illuminance levels may stay at a high level and not be subject to dimming.

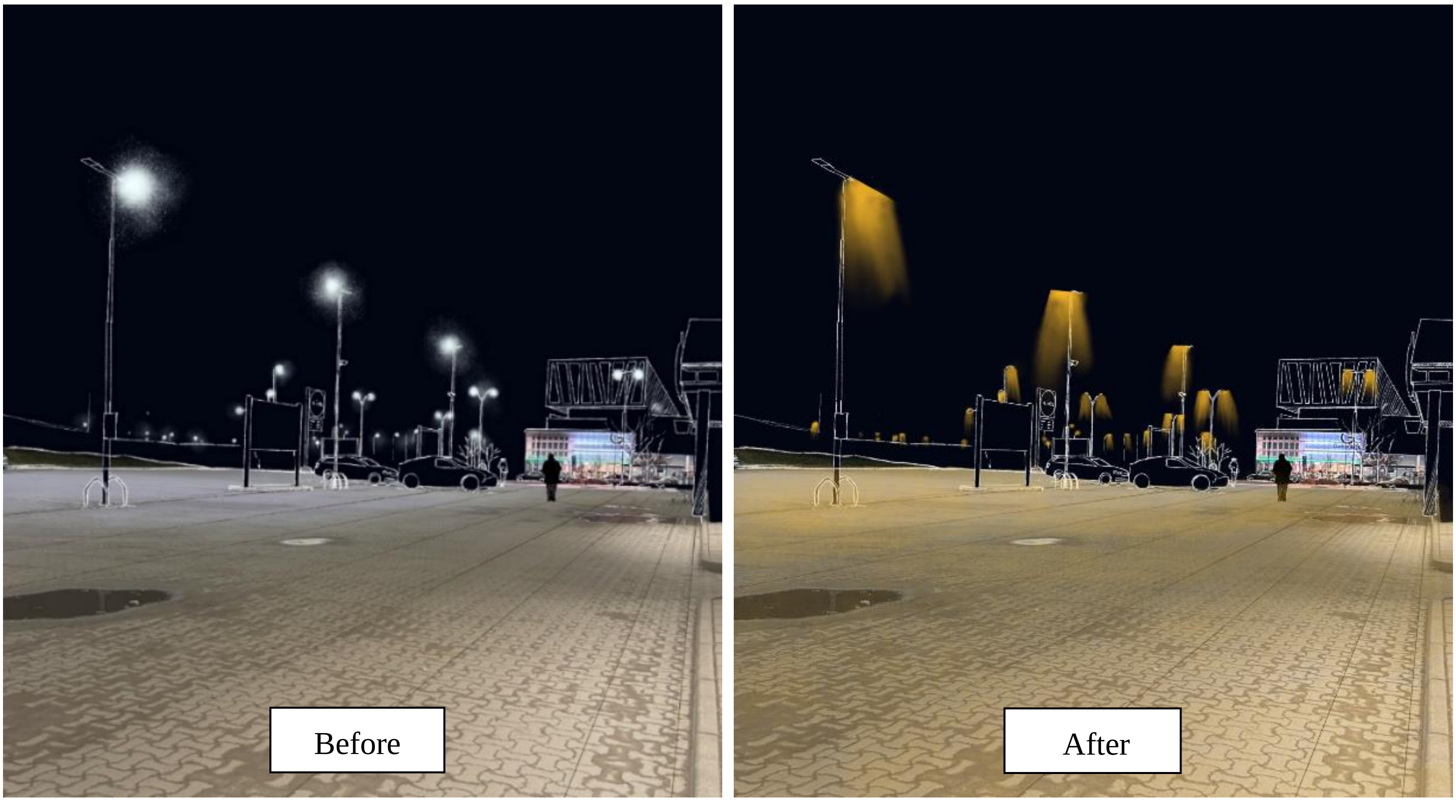

Figure 14. Illustration of before and after changes of applied colour temperature and direction of light.

Recommendations or solutions for improvement

1. Direct light downwards. By directing the light downward, it can mitigate the glare and visual discomfort for the pedestrian (if the source is from street lights), while also reducing light spillage onto the sides of the light source and improving perception of safety by increasing visibility for facial recognition.
2. Change the correlated colour temperature of street lights. In highly active areas with existing mixed lighting, integrating amber-coloured LED lighting will generally mitigate the negative impact on biodiversity and ecology and beneficial for pedestrians.

4.3.2 Residential Area – Location 2

As for negotiables, correlated colour temperature is included as it does not cause any major downsides changing from cold to warm temperatures, and instead may be beneficial for pedestrians and majority of species (Newsham et al. 2004 and Veitch et al. 2008).

Illuminance levels were moderately lit, due to moving vehicles, lights from facades and street lighting. As there needs to be sufficient illuminance levels to move after dark no change it is considered a non-negotiable. This area included pole heights of around 4 meters.

Non-negotiables	**Current Conditions**	**Potential Changes**
Illuminance levels	Sufficient illuminance levels.	Dim to 2 lux.
Negotiables	**Current Conditions**	
Scheduling and/or motion sensors	No scheduling or motion sensors.	Install scheduling with motion sensors.
Direction	No direction on street lights.	Direct light downwards using (BUG)-system from IDA (2009).
Shielding	Light is shielded	None.
Correlated colour temperature and Light source	Warm white (~3500-4000 K).	Change and adjust to amber LED of around 2200K.
Uniformity of light	Somewhat evenly lit	Improve to evenly lit ground using LIL recommendations of pole heigh and distances (Licht und Natur).

Table 4. shows non-negotiables, negotiables, current conditions, and potential changes in location 2, the residential area.

Recommendations or solutions for improvement

1. Improve uniformity of light slightly by reducing the distances between poles by 1-2 meters.
    a. Implement dimming and direction of light. By dimming and reducing illuminance levels down to 2 lux is recommended in this location, as it is not as highly active and surrounding areas consists of more sensitive habitats.
2. Install scheduling with motion sensors on street lights. By installing programs with unique profile for the area strict curfews can be applied and lights occasionally turned off.

3. Change colour temperature. The current colour temperature is white, around 5000 K. A better suggestion is to change to amber LED light with a yellow hue, peaking at 590 nm (2200K), as it generally mitigates most damage to majority of species and beneficial for pedestrians.

Figure 15. Illustration of before and after changes of applied colour temperature, direction, additional poles, and slightly reduced illuminance levels, resulting in improved uniformity of light.

4.3.3 Nature area – Location 3

Table 5. shows non-negotiables, negotiables, current conditions, and potential changes in location 3, the nature area.

Non-negotiables	**Current Conditions**	**Potential Changes**
Illuminance levels	Relatively low illuminance levels	Dim to 2 lux.
Negotiables	**Current Conditions**	
Direction	No direction on street lights.	Direct light downwards.
Shielding	Upward light is shielded.	None.
Correlated colour temperature and light source	White (~5000 K)	Change and adjust to amber LED of around 2200K.
Scheduling and/or motion sensors	No scheduling or motion sensors.	Install scheduling and motion sensors.
Uniformity	Not evenly lit.	Improve to evenly lit ground using LIL recommendations of pole height and distances (Licht und Natur).

This area has a lower population density compared to the other areas, as it mainly consists of forest and grass fields. Along with that, it has a higher biodiversity with some red listed- and threatened species (SLU Artdatabanken (2024). The activity of the area is mainly recreational activities, and the surrounding area consists of residential buildings, namely two-story rowhouses. The forest areas hold higher biodiversity than the other areas, and houses more threatened species (SLU Artdatabanken (2024). This results in the table including more negotiables, allowing components to cater to said species.

Similarly to the other locations, sufficient illuminance levels are a non-negotiable, however dimming is highly recommended. Scheduled street lighting with motion sensors is also highly recommended, as it is appropriate for the activity and ecology of the area. CCT of street lighting were white and considered subject to change. When it comes to uniformity of light, it was not even and could contribute to dark adaptation for pedestrians (Amoruso et al. 2022), thus subject to change. Lastly, to improve on uniformity is to adjust the pole height and the distances between the poles. This area included pole heights of around 3.5 meters.

Recommendations for improvement or solutions:

4. Improve the uniformity of light. The inconsistency and uneven light distribution that alternates between dark and lit spots is the main problem. Better uniformity of light not only improves perception of safety (Boyce 2019) but also helps in minimizing the negative impact on both pedestrians (Amoruso et al. 2022) and the environment, as it allows for lower illuminance levels without lowering levels of perception of safety (Amoruso et al. 2022). This is notably important at an area that houses threatened and sensitive species (SLU Artdatabanken (2024).
    a. Implement dimming of street lighting down to 2 lux.
    b. Optimizing pole placement and light direction. By adjusting the distance between street light poles to at least 3.7 times the pole's height it will improve uniformity. In this location where poles stand at 3.5 meters, reducing the distance between poles to 13 meters is recommended (Licht und Natur).
    c. Install scheduling with motion sensors on street lights. By installing programs with unique profile for the area strict curfews can be applied and lights occasionally turned off.
5. Change colour temperature. The current colour temperature is white, around 5000 K. A better suggestion is to change to amber LED light with a yellow hue, peaking at 590 nm (2200K), as it generally mitigates most damage to majority of species and beneficial for pedestrians.
6. Implementing a Dark Habitat Zone. Introduce a dark habitat zone, specifically where the section of forest transitions into the open field (the nature reserve). This will preserve natural darkness, ecological values, and introduce dark zones as a resource of tranquillity for humans as well.
    a. Installing motion sensors along the passage of Southern Gottsunda to Northern Gottsunda as well as the passage going southwest (see figure 14.), will accommodate for safe passage between the two residential areas while preserving the present dark corridor, preserving the existing ecological values, and contributing to biodiversity. Compared to the passge in the forest, this passage (red strip in figure 14) will solely rely on motion sensor without scheduling. To increase perception of safety, all the street lights on the whole passage will be dimmed to 10% in default and lit up to 100% when detecting a pedestrian.

Figure 16. Illustration of before and after changes of applied colour temperature, direction. additional poles, and reduced illuminance levels resulting in improved uniformity of light.

Figure 17. Illustration of nature area. Yellow strip shows paths. Red strip shows paths with potential of installing motion sensors. Aerial image from © Lantmäteriet.

5. Discussion

This thesis primarily aims to address the concerns of the ecology and environment, and secondarily the concerns of the pedestrians. As such, the analysis and results reflect this approach such that environment and biodiversity is as optimized as possible, and no changes made is due to the strict requirements of light for pedestrians and places.

This thesis presents a framework that can be applied to varying locations resulting in mitigated effects of ALAN on ecology and biodiversity. The site analysis show that customization of street lighting has in current conditions not been properly applied to the different types of areas in the neighbourhood. However, the results show that the possibility of trade-offs between human needs and ecological needs can be achieved to different types of locations and zones, with the aim of customization and optimization. This may reduce the one-size-fits-all mindset regarding street lights in varying locations and areas.

The findings from the results indicate that the town centre (location 1) has the least recommendations and solutions, the residential area had a few more, and the nature area had the most recommendations and solutions. This suggests that customization and optimization can apply to different areas with varying degrees of activity and sensitivities. It also suggests that the framework can be applied to other places. In other places where the same type of street lighting is applied in nature, it will naturally require more changes to reduce the adverse effects of ALAN. Installing the street lighting at first implementation to avoid future changes is recommended. It also suggests that in densely populated and highly active areas, such as the town centre, changes are still appropriate as these areas may still spill light onto surrounding areas, e.g. light spillage and skyglow. The reasonings behind specific selection of components in the recommendations and solutions, align with the findings in chapter 3.

When it comes to colour temperature, all locations had more or less same colour temperature of neutral white around 3000 K. Since white light appears to be generally disruptive across most species (de Jong et al. 2017); Ouyang et al. 2017 and Owens & Lewis 2018) and amber less so (Dick 2016; Licht und Natur) it has been suggested as a recommendation across all locations. For pedestrians, the warmer colour temperature may also be beneficial for pedestrian perception (Hao et al. 2022).

The same suggestion of change goes for LED as it has been found to be the better choice of light sources (Davidovic & Kostic 2022; Justice & Justice 2016; Owens & Lewis 2018). This also falls in line with LED potentially improving perception of safety, prospect perception, and better escape perception, as it is able to customize intensity, colour, or direction of light. (Haans & De Kort 2012). Thus, LED is beneficial for both ecology and humans. However, since the current light source currently operating on the street lights is unknown, it is only seen as a suggestion of change.

The usage of directing light and shielding has many benefits (Owens & Lewis 2018). In the case of the residential and nature area, uniformity of light was lacking and also contributed to some glare and visual discomfort. While directing the light and shielding can help with uniformity of light and reduce light spillage onto the sides and upwards of the light source (Owens & Lewis 2018) it also aims to improve the perception of safety by increasing visibility for facial recognition in areas where perception of safety was low. This is particularly applicable to the nature area that scored the lowest in perception of safety that also had poor uniformity of light. It also especially important in the nature area to avoid light spilling to important local spots for species of birds, bats and insects that have been found in the area. For a more detailed recommendation the BUG system is suggested (IDA 2009).

Dimming the illuminance level to 2 lux in the residential and nature area had several reasonings. Firstly, improving the overall uniformity of light by reducing the stark contrasts of lit and unlit spots (Amoruso et al. 2022). Secondly, minimising the glare and visual comfort made by stark contrasts, causing a process in human eyes called dark adaptation (Amoruso et al. 2022). Thirdly, and most importantly, mitigating the effects of ALAN in these locations. By dimming and reducing the illuminance levels to levels of 2 lux has been found to be adequate for obstacle detection and visibility for pedestrians and bikers (Fotios & Cheal 2009; Fotios & Gibbons 2018; Boyce 2019), and thus chosen as an illuminance level.

Scheduling with motion sensors was suggested in the residential area and nature area as a recommendation to be turned on from sunset to midnight, and midnight onwards street lighting would solely be turned on by motion sensors from pedestrians. By installing programs with unique profile for the area strict curfews can be applied and lights occasionally turned off to minimize the effects of light pollution (Jägerbrand & Bouroussis 2021), particularly for a location that is in close proximity to sensitive or protected areas such as the nature reserve. One example of such a program in this location is to have the street lights on a dimmed to 0-10% at default and lit up to 100% when detecting motion from pedestrians. Furthermore, this type of customization may be appropriate as this location is not too highly populated or trafficked, compared to the town centre. The scheduling with motion sensors will preserve natural darkness that is found in the nature area and also preserve the ecological values that are present (Jägerbrand & Bouroussis 2021). This will introduce dark zones as a resource of tranquillity for humans as well.

As all areas in this neighbourhood already contain shielding in the street lighting, no recommendations for this component were included in this thesis. However, it is important to note that not all areas contain shielded street lights, and it is thus included in the framework.

From the analysis of trade-offs, the various number of changes at each location seems to link with the area's different activity levels and sensitivities in terms of biodiversity. Higher human activity in an area links to less changes required, as to allow the area to function as intended. Contrastingly, the higher sensitivities in an area links to more changes required. After site analysis and results, the current conditions of street lighting in Gottsunda have been found to apply similar settings of street lighting to three different types of zones, with a lack of measures made for more sensitive and protected in nature areas. This causes implications, as an area with more nature, more sensitivities and threatened species requires a more intentional design that is considering said sensitivities. As such, it is especially important as the nature areas in urban settings have also been found to contain higher biodiversity, which includes the nature parts of neighbourhoods such as Gottsunda (Ives et al. 2016).

From the results of the survey, the perception of safety being moderately high in the town centre and residential area and low in the nature area may be due to the prevalence of homes and thus higher surveillance. The perception of people residing in their respective homes after dark may contribute to feeling safer, compared to the lack of people found in the town centre later in the evening. Nature area grading poorly may be due to the distance from said homes. The difference in safety between meetings with strangers and wild animals may be due to other factors such as social, cultural and media may highly influence the perception of safety, as wild animals may not be seen as dangerous as interactions with strangers. Navigation scoring highest in the residential and nature area, and lowest in the town centre may be due to the lack of other navigational factors in the town centre, such as being surrounded by parking lots, lack of clear paths leading outwards and landmarks, direction ambiguity, etc.

Just as different species may have varying sensitivities, brightness in humans is differently understood and is managed differently depending on socio-cultural contexts. While there are individual differences in what constitutes as bright, it does not entirely rely on physiological differences but also expectations that are based on cultural background and prior experiences (Amoruso et al. 2022). This furthermore acknowledges that design in street lighting is fundamentally flawed and based on motoric traffic, not human centric approaches and is in need of re-evaluation for just human benefits (Amoruso et al. 2022).

The connection between landscape architecture and the aspect of working with light. While light is highly appropriate to the role of the landscape architect as a tool and resource in creating landscapes and enriching experiences outside of functional use, it is often not as touched upon as other aspects in the work field, as it an endeavour more connected to light designers. However, light and landscape architecture are closely related and connect to the same issues. It is important to bring up working with light in the field to fully understand it and utilize it correctly as a component that affects the environment, as well as the human experiences. Thus, this thesis aims to bridge the role of the landscape architect with street lighting, and how to work with and manage with such a resource.

5.1 Choice of method

The aim of the transect walk survey was to find how the human perception of safety from the street lighting changes from one location to another, and interestingly, the results did not show a clear trajectory from location 1 to location 3. The perception of safety of pedestrians showed varied results, of residential areas being seen as safer than a centre mall. The analysis however, showed a clear trajectory from location 1 to location 3, where more trade-offs are argued in location 3 compared to location 1. Thus, the results showed more changes in nature area, less in residential area, and least in centre mall.

One critique against the choice of conducting a transect walk survey is the produced results may not be as relevant as initially thought, as the main aim is to mitigate the effects on the environment and biodiversity, and the changes in street lighting will always prioritize that and not the perception of safety for pedestrians as that is a secondary priority. Thus, the resulting changes in street lighting will always be the same regardless of the produced results of the transect walk, with uniformity of light being a general solution for better perception of safety in street lighting (Boyce 2019; Amoruso et al. 2022). However, what the survey did show was how crucial and important uniformity of light is, as it linked the perception of safety on these specific locations to possibly uniformity of light.

There is the question of ideal circumstances to conduct the transect walk, as several external variables play a role. Ideally, weather conditions, seasonal changes, snow or no snow, and place such surveying in differing neighbourhoods and cities would be taken into consideration. Additionally, a higher sample size with different demographics to apply a more interdisciplinary approach would also be ideal.

As there are constraints such as physically installing new street lighting, or difficulties assessing subjective factors (such as perception of safety in humans), evaluating the results is challenging. Ideally direct evaluations from citizens would be conducted to provide feedback on perception of safety, but because of the innate constraints', citizen evaluations may be difficult to conduct. Despite the limitations, there are possibly other methods that can be used to evaluate the proposed street lighting designs. One example is to create virtual simulations that can emulate the site with- and without the proposed street lighting designs. Another is to install temporary street lighting that will be tested over time and removed after an evaluation is conducted.

5.2 Limited and Future Research

When it comes to ALAN, research is still relatively new and unexplored. And even further unexplored are the practical measures (Hölker et al. 2021). There is especially a need for implementation of general praxis in street lighting use. The framework is one way of introducing practical measures, but it is a base and foundation and needs further customization to different habitats and areas. This is specifically important due to the myriads of different landscapes, seascapes, habitats, species and seasonal changes.

One important aspect to consider is that the framework does not consider all species, as different species have varying sensitivities and particular species might even benefit from increased ALAN (Spoelstra et al. 2017; Haddock et al. 2019). For even further optimization, it is crucial to adapt to site and the prevalent species, and when working with several habitats, such as forests and fields, different residing species need to be taken into consideration in each habitat. An example is snowglow is a phenomenon that is unexplored, but highly relevant in terms of ALAN, where artificial light is further exacerbated by the presence of snow reflecting the light (Jechow & Hölker 2019).

Using the Red List (SLU Artdatabanken 2024) or finding specific species and their sensitivities from experts in the field such as Spoelstra or de Jong, are ways of identifying which species reside in the habitats and then change and incorporate the design of street lights to the respective needs, particularly with sensitive or threatened species.

As of currently there are too many "unknowns" regarding impact of ALAN on biodiversity and particularly on multiple levels of biodiversity, such as cells and genes, population, and individuals (Hölker et al. 2021). Additionally, there is a lack of research about the micro-evolution that occurs due to ALAN since the nature of the subject being challenging and difficult to conduct studies on as it takes too long (Hölker et al. 2021). To delve even deeper into specific species insects are found to be the most studied classes, but research on ALAN barely scratches the surface on the impacts of majority of insects (Kooi et al. 2021), and even plants (Knop et al. 2017). Studies have found that there is the potential of that ALAN having the possibility of influencing photosynthesis, however, there is little research regarding photophysiology of plants and as such is lacking in concrete conclusions (Gaston et al. 2013).

In conclusion, ALAN causes significant and adverse effects on the ecology, biodiversity, and the local environment. Effective measures are needed in a field of that is still relatively unexplored. One potential solution is initial implementation of street lighting with that is tailored to areas and residing species may be a solution to reducing the adverse effects of ALAN. Nevertheless, addressing the challenges requires continued research into its effects coupled with the development of better practices and measures.

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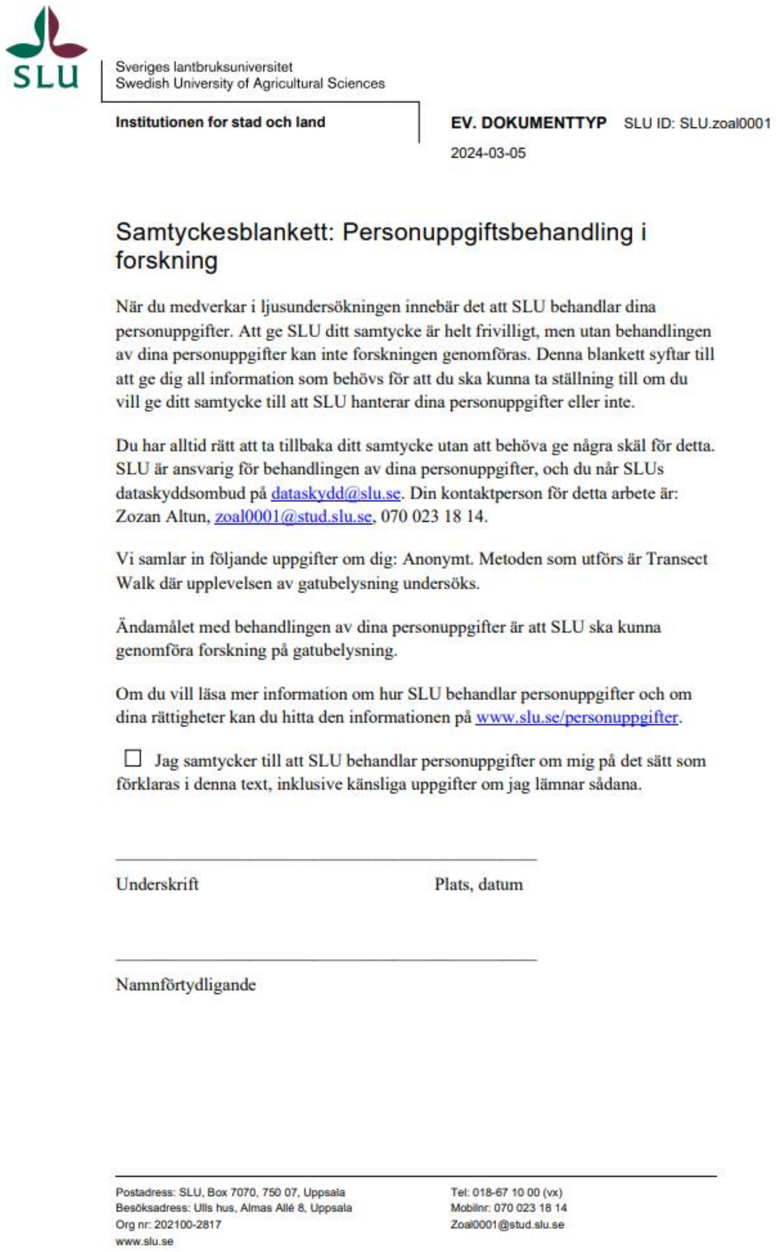
Appendix 1



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Samtyckesblankett – for volunteers of the survey Transect Walk

Appendix 2

The questions that are surveyed at every location stop:

1. How do you feel about the level of safety provided by the lighting?
    a. Very good
    b. Good
    c. Fair
    d. Poor
    e. Very poor
2. How safe or unsafe would you feel if met by a stranger?
    a. Very safe
    b. Safe
    c. Neither safe nor unsafe
    d. Unsafe
    e. Very unsafe
3. How safe or unsafe would you feel if met by a wild animal?
    a. Very safe
    b. Safe
    c. Neither safe nor unsafe
    d. Unsafe
    e. Very unsafe
4. Does the lighting affect your ability to navigate or find your way?
    a. Yes
    b. No
    c. Unsure
5. Can you see obstacles such as sticks, cracks, or other things on the ground?
    a. Yes
    b. No
    c. Unsure
6. Do you experience any discomfort or glare from the street lighting? If so, how?
    a. Yes (describe)
    b. No
    c. Unsure

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