Carinthia University of Applied Sciences
Master Management of Conservation Areas

MASTER THESIS

Natural Darkness and its Significance for Nature Protection Measures

Ecological assessment of the zonation of a planned International Dark Sky Reserve using light-averse bats as indicator species

Submission for the academic degree of
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Content

1 Abstract

Daily, lunar, and seasonal cycles of natural light have existed for millions of years, guiding life on Earth. These rotations are among the most stable environmental parameters, unlike temperature or atmospheric composition. Biological systems and processes are intricately organized by natural light patterns.

Recently, light pollution and artificial light at night (ALAN) have gained significant attention from both scientists and the public. Concerns range from the impact on human health to economic and environmental issues linked to increased energy demand. Nature conservation actions have become crucial, particularly in response to the current energy crisis, the accelerating climate change and increasing biodiversity loss. In central Austria, an alliance of six protected areas aims to preserve dark landscapes, potentially forming the largest contiguous darkness conservation area in the Eastern Alps.

This thesis complements the planning and application process of an International Dark Sky Reserve by providing an ecological assessment using light-averse bats as indicator species, explicitly Myotis and Rhinolophus species. The research focuses on two primary questions: 1) Can the proposed core zone of the target area sufficiently protect nocturnal biodiversity? 2) What needs to be done to ensure a well-connected, dark, and natural landscape in the whole target area? To answer these, the study employs GIS analysis of bat data and light pollution data, as well as a screening of different light pollution mitigation strategies and responsible lightning plans.

Findings show that only 10,00% of recorded maternity roosts are inside the core zone of the proposed International Dark Sky Reserve. Nearly half (46,81%) of all maternity roots investigated are directly impacted by light pollution, increasing to 68,09% within a 2,5 km radius. To enhance protection, including maternity roosts in the core zone is challenging in practice. Light management strategies, such as those outlined in the ÖNORM O 1052, provide a structured basis to mitigating light pollution across the entire target area. Seasonal variations in lighting schedules, adjustments to spectral composition, direction, and intensity, and a hierarchical approach based on bat sensitivity are critical for effective conservation.

By integrating ecological knowledge with structured lighting regulations, this study contributes to ensuring a well-connected dark landscape that supports nocturnal biodiversity while balancing conservation and human activities.

2 Introduction

2.1 Motivation and actuality

I have a strong interest in dark skies, nighttime ecology, and chronobiology. However, my initial motivation for exploring this topic stems from a nature conservation perspective. I see the protection of dark skies as an elegant approach to preserving landscapes. In Central Europe, establishing new protected areas like national parks has become increasingly challenging due to factors such as complex property ownership and high population density (von Ruschkowski, 2009). Dark sky conservation offers an innovative and feasible alternative. Safeguarding dark skies not only preserves ecosystems but also protects a shared human heritage, as the beauty of a star-filled sky resonates with people universally (DarkSky International, 2024a).

Furthermore, light pollution is a relatively new environmental challenge, with potentially profound but still poorly understood consequences for biodiversity and human health. While research highlights significant impacts, the long-term effects are still unclear and difficult to isolate, as they cannot easily be studied independently of other environmental factors. By integrating dark sky protection into broader conservation efforts, we contribute to the 30 by 30 goal of the Convention on Biological Diversity (CBD), which aims to protect 30% of Earth's land and sea by 2030, while addressing the critical yet often overlooked issue of light pollution (DarkSky International, 2024b; Secretariat of the Convention on Biological Diversity - Target 3, no date).

2.2 Research question

The aim of the empirical part of this thesis is to investigate how dark sky protection looks like from a nature protection perspective on the example of a defined target area. The target area encompasses an area in the tri-border-region of Lower Austria, Upper Austria and Styria belonging to the Northeastern Limestone Alps (description of project area in 4.1). Moreover, methods and strategies are elaborated on how nocturnal biodiversity can be protected on the example of *Myotis* and *Rhinolophus* bat species.

The following research questions are therefore proposed:

<u>Question 1:</u> **Can the proposed core zone of the target area sufficiently protect nocturnal biodiversity?**

<u>Question 2:</u> **What needs to be done to ensure a well-connected dark and natural landscape in the whole target area?**

3 Theoretical background

3.1 Light pollution

Natural darkness is becoming more and more precious nowadays. In April 2007 at the International Conference in Defence of the Quality of Night Sky it was recognised that "the quality of the night sky and, therefore, the capacity to access the light of stars and other celestial bodies within the Universe, is deteriorating at an alarming rate in several areas, that its contemplation is increasingly difficult, and that this process faces us with the generalised loss of a cultural, scientific and natural resource with unforeseeable consequences" (`La Palma Declaration´, 2007). Due to increasing urbanization and technologization artificial light at night (ALAN) is increasing. This has significant effects on our health, on our energy consumption and on the environment, including migratory birds, insects, plants, mammals, and other living beings (Russart and Nelson, 2018; DarkSky International, 2024a).

Fifty years ago, in 1973 Kurt W. Riegel published an article in the science magazine about the growing threat of outdoor lighting for astronomy. He coined the term "light pollution" and defined it as "unwanted sky light produced by man, because of population growth and increased outdoor illumination"(Riegel, 1973). The NGO DarkSky International states: „Light pollution is the human-made alteration of outdoor light levels from those occurring naturally" (DarkSky International, 2024a). In other words, light pollution can be described as the inappropriate or excessive use of artificial light.

3.1.1 Sources and types of light pollution

Light pollution is a relatively recent but rapidly growing threat. As a byproduct of the Industrial Revolution, artificial lighting now serves far more than just safety purposes; it is abundantly used in public and private spaces for leisure, industry, advertising, and even for aesthetic reasons. Typical sources of light pollution include street lighting, factories, greenhouses, urban spaces, sports grounds, electronic advertisements, roads, and other infrastructure (Tiroler Umweltanwaltschaft, 2015b; DarkSky International, 2024c).

Key contributors to light pollution are misdirection of light, upward emission, and over-illumination, which describes the excessive and unnecessary use of artificial light. Another issue is the use of environmentally harmful light, often linked to unnatural colour temperatures (Wallner, 2020). Light pollution appears in different forms. The most common phenomena are "glare", which is excessive brightness that causes visual discomfort up to damage to the eyes; "sky glow" or "light smog", which brightens the night sky like a dome over inhabited areas;

“light trespass” - light falling where it is not intended or needed; and “clutter” - the excessive grouping of bright light sources (DarkSky International, 2024c).

Since the 1930s, outdoor lighting was primarily generated through gas discharge lamps. However, within the last decades, light-emitting diode (LED) technology has become dominant. This bears risks and opportunities. While LEDs are more energy-efficient, they also tend to be used wastefully, potentially worsening light pollution. However, LEDs offer better control and adjustment, which, if managed wisely, can mitigate light pollution while maintaining necessary safety lighting (Tiroler Umweltanwaltschaft, 2015a).

Not all light has the same harmful effects. High-frequency, short-wave light, such as blue or UV light, is more disruptive, while warmer light with longer wavelengths is generally less harmful. The design and positioning of the light source can significantly influence how much light reaches sensitive areas. The intensity and duration of light exposure also play a crucial role in its impact, with stronger and prolonged lighting having more severe effects (Zielinska-Dabkowska *et al.*, 2023).

3.1.2 Scientific basics of light

Light is the portion of the electromagnetic spectrum that is visible to the human eye, and it can be understood as wave and as particle. The wavelengths of visible light range from 380 to 780 nanometres.

- **Luminous flux Φ** refers to the total amount of light emitted by a source over a given period of time that is visible to the human eye, measured in lumens (lm).
- **Illuminance E** describes the luminous flux distributed over a surface area that strikes an illuminated object, measured in lux (lx).
- **Luminous intensity I** refers to the amount of luminous flux emitted in a specific direction within a solid angle, measured in candela (cd), where 1 cd is equivalent to the light from a candle.
- **Luminance L** is the parameter describing the impression of brightness perceived by the human eye. It results from the ratio between luminous intensity and the light emitting area; therefore, the unit is cd/m^2. It can be compared and converted to the astronomical unit for night sky brightness: magnitudes per square arcsecond ($mag/arcsec^2$).
- **Correlated Colour Temperature CCT** quantifies the colour impression of light sources, measured in kelvin (K).

3.1.3 *Methods to monitor light pollution*

Satellite data

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a sensor, which was installed on the polar-orbiting Suomi National Polar-orbiting Partnership, NOAA-20, and NOAA-21 weather satellites. It gathers imagery and radiometric data of the land, atmosphere, cryosphere, and oceans across the visible and infrared bands of the electromagnetic spectrum (NASA Earthdata, 2024). VIIRS is regarded as a primary source of satellite-based observations for capturing top-of-the-atmosphere radiance levels originating from Earth's surface (Wallner, Puschnig and Stidl, 2023).

VIIRS has a spectral sensitivity that starts at roughly 500 nm, which means it may miss light sources emitting significant radiation at shorter wavelengths, such as neutral-white LEDs. This can lead to wrong estimations of light trends depending on the types of lighting used in the specific area. Furthermore, VIIRS data is influenced by atmospheric fluctuations, which can affect the accuracy of the radiance measurements. Even though the data is reduced to moonless and cloudless conditions, atmospheric parameters can still introduce variability. The inhomogeneous sampling of VIIRS monthly means can lead to systematic sampling biases, for example indicating darkening over time (Wallner, 2020; Wallner, Puschnig and Stidl, 2023).

Ground-based measurements

Sky quality meters (SQMs) are instruments which measure the brightness of the night sky to quantify light pollution. Usually, the unit is magnitudes per square arcsecond. These instruments help to standardize the way to monitor light pollution. Meanwhile there are many types of usage. There are handheld devices like the SQM from Unihedron which come in various models, depending on the angle of view, providing an easy tool for one-dimensional photometric measurements of the sky's zenith luminosity (Wallner, 2020). Furthermore, there are instruments used as stationary monitoring devices, e.g. TESS-W or SQM, which gather luminosity data over a long term. To keep track of sky glow, All-sky measurements can be conducted. Images are taken with calibrated digital cameras, either equipping the camera with a fisheye lens, or capturing multiple photos via mosaic imaging. The SQC (Sky Quality Camera) software estimates sky brightness based on image analysis (Wallner, 2020).

Models

VIIRS data has been used by various researchers around the world to model light pollution on the Earth's surface. Probably the best known is the world atlas of light pollution by Falchi et al. The world atlas was created using high-resolution satellite data and ground-based measurements combined in a light pollution propagation software. The researchers employed several constant assumptions, like atmospheric transparency, different light spectra used in different places and the time of observation during one night, in their calculations (Falchi *et al.*, 2016).

Besides models which focus on the macro perspective of light pollution, researchers have started to develop models to map artificial lightscapes in a smaller scale combining inventories of artificial light sources with digital surface and terrain models and ground-based measurements. These light maps serve an ecological purpose by predicting the movement of nocturnal, light-avoiding species between fragmented habitats, helping identify dark corridors that support animal movement in urban settings (Bennie *et al.*, 2014).

Lighting inventory (monitoring of emitting sources)

A lighting inventory is a structured audit of outdoor lighting to assess compliance with the Lighting Management Plan (LMP) of an IDSR. It is necessary to keep track of the direct light emissions within the target area and to identify fixtures needing retrofitting or replacement. Achieving IDSR status requires a full inventory of the core zone lighting, along with a plan to ensure compliance with LMP standards as defined in the "Minimum Requirements for All Reserves." A sample inventory table should include columns for location, fixture type, shielding, purpose, lumen output, correlated colour temperature (CCT), and LMP compliance status (DarkSky International, 2023).

3.1.4 Situation in Austria and worldwide

Light pollution is a growing global issue, with approximately 80% of the world's population living under polluted night skies. 60% of Europeans and nearly 80% of North Americans are hindered from seeing the Milky Way during natural clear conditions. Light pollution continues to rise globally, with a 2,2% annual increase in illuminated areas from 2012–2016 (Falchi *et al.*, 2016; Wallner, 2020).

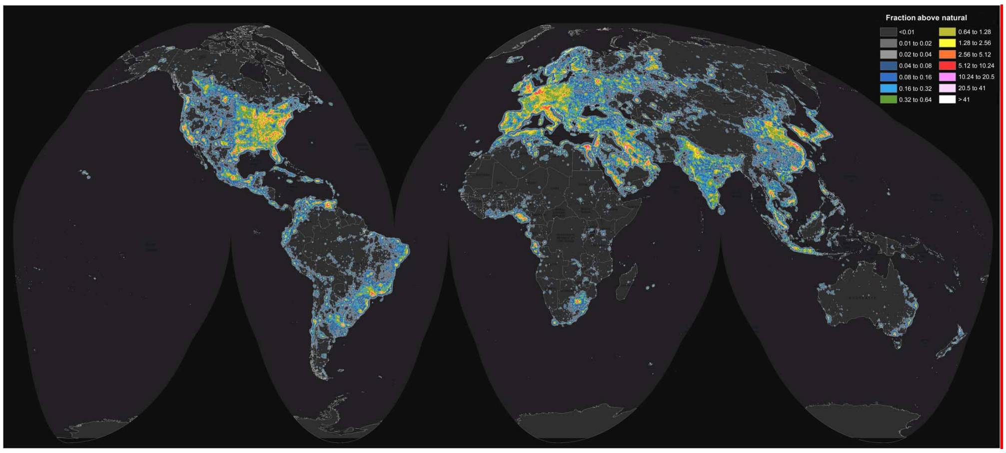


Figure 1: world atlas of light pollution (Falchi et al., 2016)

Austria mirrors global trends in light pollution, with every citizen exposed to at least slight levels of it and an annual radiance increase of 2,53%, slightly higher than the global average. Additionally, one-third of the population is unable to see the Milky Way (Wallner, 2020).

The following graphic (figure 2) shows the artificial night sky brightness across Austria. Large cities like Vienna, Linz, Graz, Salzburg and even Innsbruck show high levels of light pollution. While the darkest regions, indicated in blue, correspond to the Alpine areas. The bottom-left corner hints at the significant light pollution emanating from the Po valley in Northern Italy.

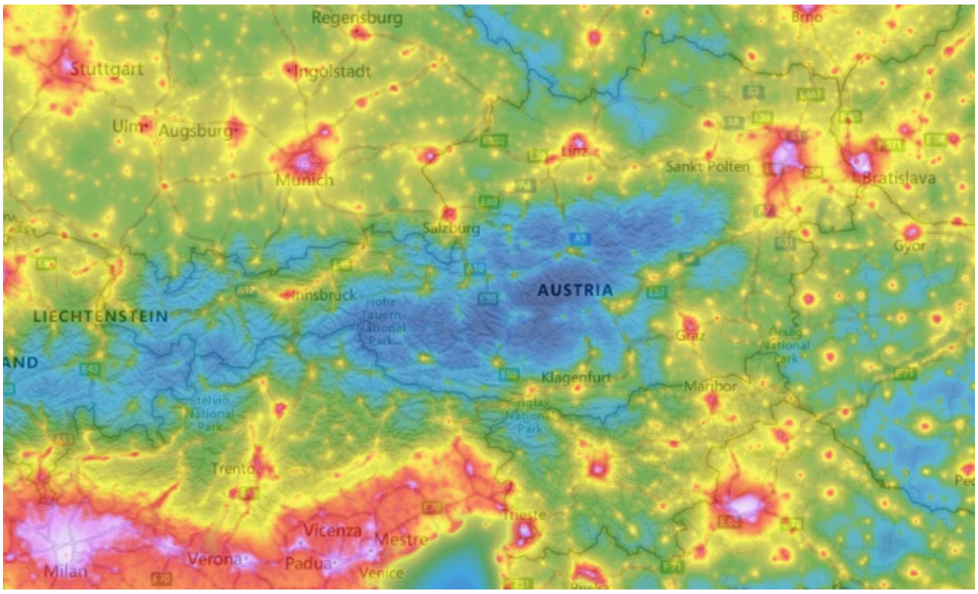


Figure 2: Austria overlaid with the world atlas of light pollution (Falchi et al., 2016; Stare, 2025)

Puschnig et al. studied the long-term trends of light pollution and compared rural, urban and intermediate sites. They found out that light pollution is rising in rural areas at an average rate of 1,7% per year, 1,8% per year in urban places, and 3,7% per year in intermediate regions. These results imply that light pollution would double within 41 years in rural areas, 39 years in urban areas, and 19 years in intermediate areas (Puschnig *et al.*, 2022).

3.1.5 *Effects on environment and species*

However, not only humans are impacted by ALAN. An artificially illuminated night sky affects flora and fauna. Frequently cited examples include the attractiveness of light sources to insects, disturbed flight paths of migratory birds, or changing activity patterns of bats. The day-and-night rhythm and the seasonal changes in day length in our latitudes are important for many species. If they are altered by artificial light during periods of natural darkness, this has unpredictable consequences on ecosystems and its inhabitants. The effects manifest in physiological and behavioural changes of organisms, like orientation, reproduction, communication, foraging, or predator-prey relationships. There have been many studies conducted on the impact of ALAN on single species, their behaviour and physiology (Gaston, Visser and Hölker, 2015). Research shows that light pollution is having a serious impact on the vulnerability of insect species (Suchy and Stoll, 2019). Generally, over 60% of invertebrates are nocturnal and thus are potentially affected by changes in natural light regimes at night (Hölker *et al.*, 2010). The observed and potential effects of artificial night lighting on anuran amphibians were studied (Buchanan, 2006). Da Silva and colleagues have found that light pollution alters the phenology of dawn and dusk singing in common European songbirds (Da Silva *et al.*, 2014). Bennie et al. have studied ecological effects of artificial light at night on wild plants (Bennie *et al.*, 2016).

3.1.6 *Cascading effects and cumulative effects on habitats*

Cascading effects caused by ALAN on a larger ecological level can be expected. Ecosystems are shaped by a natural light-dark cycle which has been stable over geological eras. The recent drastic increase of anthropogenic light pollution disrupts the circadian rhythm and affects the structure and function of multiple levels of biodiversity (Bennie *et al.*, 2015; Hölker *et al.*, 2021). However, until now we understand too little about the cascading effects caused by ALAN on multiple levels of biodiversity and therefore, we cannot yet predict the consequences on a larger ecological scale (Hölker *et al.*, 2021). Figure 3 shows how far-reaching light pollution can be stretching through all levels of biodiversity.

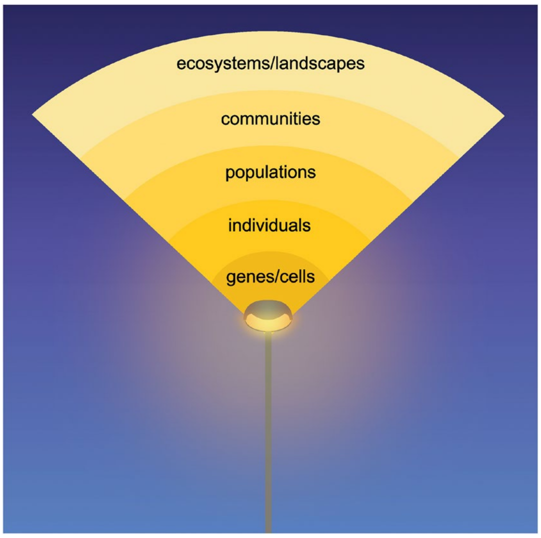


Figure 3: levels of biodiversity (Hölker et al., 2021)

Hölker and colleagues have defined five levels of biodiversity; starting with the microbiological level of genes and cells, to the level of individuals, followed by populations, communities, up to the large level of ecosystems and landscapes. These multiple levels of biodiversity can of course not be regarded as independent from each other. One level of biodiversity may respond in a certain way to light pollution and pass on the influence on other levels. Hölker et al. describe the example that ALAN could impact the gene expression of certain clock genes, which leads to reduced fitness of individuals, resulting in a population decrease and due to a phenological mismatch with other species to a change in the community composition (Hölker *et al.*, 2021).

It can be said that responses to artificial light at night are complex. Multiple forms of light pollution and light sources are impacting several natural cycles and influencing biodiversity on different levels. Other global change stressors are interacting with light pollution and therefore it is difficult to regard it isolated (Caley *et al.*, 2024).

Camacho et al. could show on the example of the Golden Scarab *Chrysina argenteola* that light pollution influences habitat connectivity and metapopulation dynamics. It disrupts inter-patch dispersal and contributes to habitat loss and fragmentation of this species (Camacho, Barragán and Espinosa, 2021).

Bennie and colleagues have studied different ecological mechanisms which might be affected by ALAN. They investigated how the population density of pea aphids *Acyrthosiphon pisum* is affected in an artificial grassland community in the presence and absence of predators and under low-level light of different spectral composition. The scientists found out that physiological effects of light can have measurable effects on the demography of a herbivore who is specialised on a plant species within a diverse plant community (Bennie *et al.*, 2015).

Furthermore, Degen et al. have identified the gap that ALAN is dividing moth habitats but that corridors to avoid the artificial light are missing. The scientists claim that streetlight near hedges or field margins reduces the quality of these for insects' important habitat structures which leads to a decrease in moth mobility (Degen *et al.*, 2016).

Zeale and colleagues designed an experiment where they illuminated hedgerows in different rhythms and with different spectra. They could prove that artificial light at night disrupts the use of major flight routes of the threatened lesser horseshoe bat *Rhinolophus hipposideros* for example. To mitigate the impact of light pollution on bat activity and movement Zeale et al. recommend the preservation of dark corridors (Zeale *et al.*, 2018).

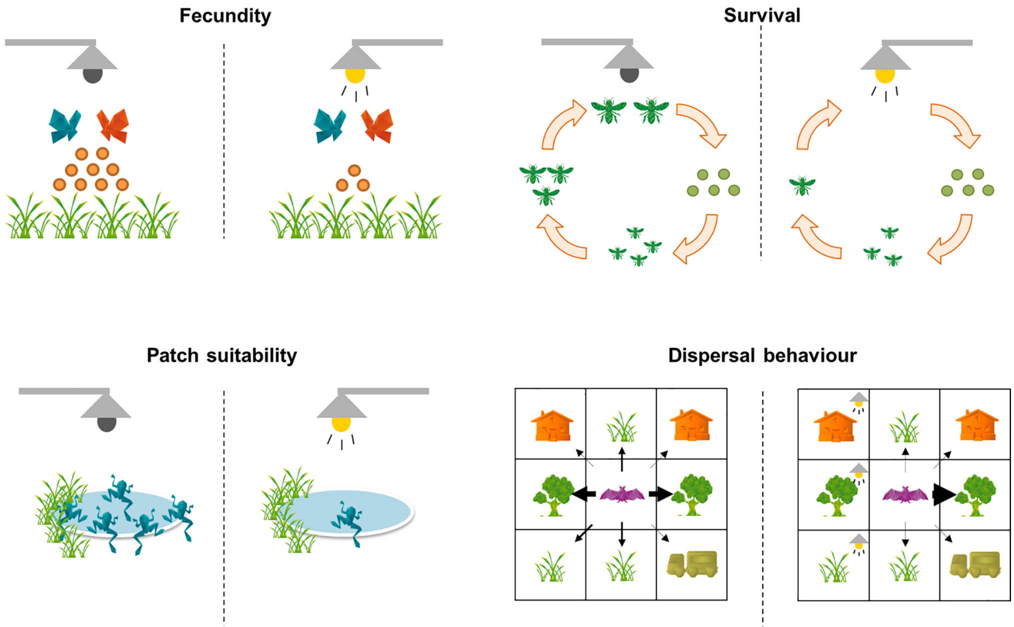


Figure 4: Examples of mechanisms of how ALAN affects biodiversity (Sordello et al., 2022)

To sum up, scientists assume that ALAN has major impacts on habitat suitability and connectivity, species movement, fecundity and survival in general. These mechanisms were visualized by Sordello et al., 2022 in figure 4. Light corridors, like illuminated roads, or light patches, like illuminated gas stations for example, can act as barriers to movement and dispersal of species and can turn former good-quality habitats into population sinks (Degen *et al.*, 2016). There are many other more popular reasons for habitat fragmentation, mainly it is caused by human infrastructure like roads, railways, and settlements etc. disrupting the ability of species to move through landscapes may change foraging and hunting habits, reproductive opportunities; it prohibits the gene flow between populations and alters metapopulation dynamics in general (Camacho, Barragán and Espinosa, 2021; Grubisic and Van Grunsven, 2021). Isolated protected areas are not enough to stop the loss of species. Therefore, it became a priority agenda in nature conservation to create larger networks, corridors, and stepping stones; summarized under the term: green infrastructure. The awareness that light pollution also plays a crucial role for habitat fragmentation is relatively young. The effects of light pollution on green infrastructure are not known yet (Zeale *et al.*, 2018; Camacho, Barragán and Espinosa, 2021; Hölker *et al.*, 2021).

3.1.7 Impacts of ALAN on biodiversity are not well studied

Measuring the impacts of ALAN on larger biological systems and natural processes is still a research challenge. Gaston and colleagues claim in their work that it will be crucial to predict the ecological consequences of ALAN in natural systems reliably. However, much of the available knowledge is based on single study objects, short-term experiments, neglecting response mechanisms such as acclimation, adaptation, physiological, behavioural and even evolutionary compensatory mechanisms linked to environmental context and seasonal timing (Gaston, Visser and Hölker, 2015).

Zschorn has discussed this issue as well, stating that research on the impacts of ALAN on single species is relatively young. She conducted a quantitative literature research using Web of Science filtering for "light pollution" and "ecolog*" for the years 2012 to 2021. Within these 10 years the number of scientific publications per year increased approximately five times (Zschorn, 2024).

In 2021 Hölker et al. published a paper directly addressing the most pressing research questions dealing with light pollution and biodiversity. They have identified fundamental knowledge gaps and summarized it in eleven questions which are necessary to be studied in the near future. The questions deal with the challenge of how to measure light pollution and the impact on nature at the same time, the consequences for biodiversity on several levels and the challenges to develop wise methods of light use (Hölker *et al.*, 2021).

Moreover, it is important to highlight that the impacts of ALAN on biodiversity are difficult to study isolated from other global change drivers, like land use change, direct exploitation, other environmental pollution, climate change or invasive species (Hölker *et al.*, 2021).

3.2 Bats (Microchiroptera)

3.2.1 Characteristics

Bats (Microchiroptera) are members of the order Chiroptera and belong to the class of Mammalia. They exhibit very typical mammal characteristics, like viviparity (live birth), self-regulated body temperature, presence of a mandible or ear conchs. Nevertheless, they are the only mammals who are capable of self-powered flight. Besides that, they have evolved a sophisticated method for orientation and navigation in the dark: ultrasound echolocation. Bats emit ultrasonic sounds in a frequency of 15 to 115 kilohertz and receive the returning echo with its adapted ears. Through that they interpret a detailed map of their surroundings. Another distinctive feature is their ability to actively regulate their body temperature which helps them to save energy (Dietz, Nill and von Helversen, 2016).

3.2.2 Lifestyle

European bats are adapted to the seasonal variation in availability of their prey. They primarily feed on insects and other arthropods. Many different hunting techniques have developed, some capture their prey during flight in open landscape, some prefer to hunt close to vegetation or close to the ground, others over water. Usually, the breeding season starts in May when females gather in maternity roosts. Their ovulation is synchronized with spring temperatures. Most central-European bat species give birth in June to only one young. One to two months later the young bats learn how to fly and start to practice hunting. As soon as the offspring becomes independent the mating season resumes. In autumn male and female individuals gather in so-called swarming roosts to find a partner. They mate before their hibernation period. Females are able to store sperm over the winter and fertilization will only happen in spring upon the female’s ovulation. Many species hibernate near their summer habitats. However, there are several bat species which migrate several hundred kilometres before winter (Dietz, Nill and von Helversen, 2016).

3.2.3 Ecological niche and habitat requirements

Bats have conquered a unique ecological niche. Their nocturnal lifestyle helps them to avoid most of their predators, like birds of prey, foxes or martens. Furthermore, it reduces the competition for food with birds. Probably the usage of caves as roosts helped the bats to adapt to darkness and develop their senses accordingly. As already mentioned, they need places to hide during the day, like caves, tree holes, rock cracks or roof structures of barrens, churches or other human buildings. Especially during the upbringing season and the hibernation period they require safe roosts with minimal disturbance. They emerge at dusk to commute to their hunting grounds. In central Europe many bats are strongly dependent on forests. Some hunt within the forest (e.g., Myotis myotis), some use forests as safe passageways, others prefer the ecotone between forest and open land as ideal hunting ground and some even have their roosts in trees (e.g., *Myotis bechsteinii*). Water bodies like lakes and ponds offer an abundance of food, where species like *Myotis daubentonii* prefer to hunt (Dietz, Nill and von Helversen, 2016).

Table 1 offers an overview of the main pressures and habitat requirements of the investigated species.

Table 1: overview of main pressures and habitat requirements of investigated species (Dietz, Nill and von Helversen, 2016; Stiftung Fledermausschutz, no date)

species	**main pressures**	**roosts & maternity roosts**	**foraging habitats**	**foraging distance from roost**	**foraging habitat size**
Myotis bechsteinii	habitat loss and fragmentation, traffic	trees	broadleaf forest (beech forest)	1- max. 2,5km	10-100 ha
Myotis brandtii	intensive forestry, habitat fragmentation, loss of wetlands	trees, buildings (near the forest!)	forests, water bodies, wetlands	max. 10 km	1-10 ha
Myotis daubentonii	water pollution, loss of roost sites	trees, buildings, bridges	forest, water bodies (also lakes)	female: 6-10 km; male: 3,7km	1-10 ha
Myotis emarginatus	habitat loss, pesticides, traffic	buildings, caves	broadleaf forest, orchards, extensive farms	max. 12,5km	1-10 ha
Myotis myotis	pesticides, intensive agriculture and forestry	buildings	forest, open land	5-15km	1-10 ha
Myotis mystacinus	habitat loss	buildings, trees	mosaic landscape, hedgerows, orchards, forest, wetlands	max. 3km	1-10 ha
Myotis nattereri	habitat fragmentation, pesticides, intensive agriculture	mainly trees	forest, mosaic landscape	max. 4km	1-10 ha
Myotis blythii	intensive agriculture	buildings, caves, bridges	open land, meadows, pastures, extensive farms	4-7 km	10-100 ha
Rhinolophus ferrumequinum	pesticides, roost destruction	buildings, caves	broadleaf forest, hedgerows, orchards, meadows	2-5 km	10-50 ha
Rhinolophus hipposideros	pesticides, habitat fragmentation, urbanization	buildings, caves	primarily forests; close to water bodies	max. 2,5 km	10-50 ha

In general bats are very social and peaceful animals. Gathering in roosts has several advantages to them. They conserve energy by keeping each other warm. Moreover, information sharing is easier in a group, which is crucial for locating good hunting grounds, especially for immature bats. Female bats even synchronize their birthing times to coordinate the time of offspring upbringing. This social way of living might contribute to their relatively high life expectancy (Dietz, Nill and von Helversen, 2016).

3.2.4 Bats in Austria and in the project area

Due to its small-structured landscape and rich habitat diversity Austria has a high number of bat species. 28 out of 55 bat species recorded for Europe and Northwest Africa are native to the small alpine country (Dietz, Nill and von Helversen, 2016; KFFÖ, no date). The project area itself hosts about 20 bat species (Bürger, Hüttmeir and Reiter, 2015; Pysarczuk *et al.*, 2021). Probably the low density of settlements and the mosaic of extensive agricultural land and natural forests fulfil the habitat requirements for many bat species (Dietz, Nill and von Helversen, 2016). Among these native species two genera were selected to be addressed in this scientific work: *Rhinolophus* and *Myotis*.

3.2.5 Threats and protection status

Since the 1960s and 70s central European bat species have experienced a dramatic break-in. One reason for this could have been the industrialization of the agricultural sector, which led to an immense change of landscape and associated habitats. On top of that the increased application of highly toxic pesticides affected bats a lot. They accumulated these toxins mainly through their preys. Also, the loss of natural mixed and broadleaf forests and the therefore reduced deadwood reservoir had impacts on food availability and habitat suitability (Dietz, Nill and von Helversen, 2016).

The prohibition of toxins like DDT and lindane have helped many bat species to recover. Nowadays, bats mainly suffer from habitat loss and habitat fragmentation due to human activity. Infrastructure development such as roads disrupt habitat connectivity, affecting commuting and foraging. Moreover, road traffic counts as a significant threat due to possible collisions. Intensive forestry, intensive agriculture and increased urbanization lead to reduction of suitable roosting sites and loss of foraging habitats. Toxins in the foraging area, like insecticides or herbicides and at the roosts, for instance wood preservatives, lead to poisoning and reduce insect prey availability. Overall, tourism, recreational activities, and increased human presence near roosts and foraging areas cause stress and habitat avoidance. (Biodiversity Information System for Europe, no date)

Bats enjoy several regulations of protection. The different protection states for the analysed species are summarized in table 4 in chapter 4 "Materials and methods". Internationally all European bats are protected under the Bern Convention (except for *Pipistrellus pipistrellus*) and are listed in Annex II of the Bonn Convention which is protecting migrating species. Moreover, the European Union's habitat directive is another strong nature protection instrument. Several bat species, which are also investigated in this study are listed in Annex II, which concentrates all "*animal and plant species of community interest whose conservation requires the designation of special areas of conservation"* (Directive - 92/43 - Habitats Directive - EUR-Lex, no date). Annex IV is listing all "*animal and plant species of community interest in of strict protection"* (Directive - 92/43 - Habitats Directive - EUR-Lex, no date). All species of Microchiroptera are listed there. This special legal protection applies for species with a high risk that populations will disappear, therefore their habitats must not be damaged or destroyed. This species protection applies not only to the NATURA 2000 network of protected areas, but throughout Europe, even if it is not a protected area (Directive - 92/43 - Habitats Directive - EUR-Lex, no date).

3.3 Bats and artificial light at night (ALAN)

All European bat species are nocturnal and therefore are very well adapted to be active in darkness or dim light (Rydell, 1992; Lewanzik and Voigt, 2013). Many studies discuss the possible negative impacts of ALAN and light pollution on bats. Azam et al. even states that the light factor could have a comparable influence on the occurrence of bats as land use and soil sealing (Azam *et al.*, 2016).

The first quantitative study on the significance of increased natural light levels on bats was conducted by Nyholm in 1965. He observed that some *Myotis sp.* constantly avoided their preferred habitats during the bright Nordic midsummer nights. His study did not address areas illuminated by artificial light, which were still rare at that time. However, Nyholm's findings underscored the impact of light for the overall activity and habitat use of bats (Voigt, Azam and Dekker, 2018).

Over time bat experts noticed differences in how various bat species responded to ALAN. These behavioural differences were often linked to specific flight styles, which impacts the ability of a species to evade visually oriented predators, such as birds of prey (Rydell, 1992). If a species is capable of flying faster, it can be more opportunistic towards ALAN compared to slow-flying species. However, their reaction on ALAN is more complex and depends on several additional factors, not only the species (Rowse *et al.*, 2015). The nutritional status, depending on reproductive state, sex and age is an important factor if bats avoid light. Moreover, quality of the habitat, insect availability, presence of competitors and predators play a relevant role too (Voigt, Azam and Dekker, 2018). It can be said that the effect of ALAN on bats is depending on species and context (figure 5) In summary, ALAN likely affects them in most scenarios (Lewanzik and Voigt, 2013).

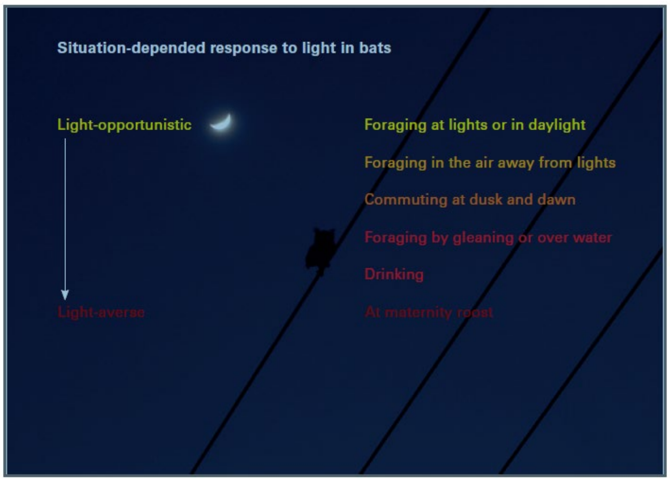


Figure 5: effects of ALAN on bats in different situations (Voigt, Azam and Dekker, 2018)

At the genus level, they can be categorized in averse, neutral and opportunistic behaviour towards ALAN (table 2). Species from the same genus often show similar features, like wing morphology, hunting strategies and habitat requirements, which impacts their reaction to ALAN (Voigt, Azam and Dekker, 2018). Averse bats usually avoid ALAN. If ALAN does not significantly affect the spatial distribution or activity of bats they show neutral behaviour. Some bats exhibit an opportunistic response, which means that they are attracted to ALAN under certain conditions, such as feeding, where the benefit of higher insect density near lights outweighs the increased predation risk (Voigt, Azam and Dekker, 2018).

Table 2: typical ALAN-induced behaviour of European bats (DD… data deficient, n.a. … not applicable)(Schroer et al., 2020; Voigt et al., 2021)

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

[a] "Roosts" include maternity roosts, mating roosts, and swarming sites, excluding temporary night roosts used by a few individuals, as there are no quantitative studies assessing the effect of ALAN on these night roosts.

To simplify the complexity of the potential effects artificial light might have on bats an easy distinction between direct and indirect effects can be made. Direct effects of ALAN on bats describe the direct impact an artificial light source might have on the individual or the colony, such as increased predation risk, or complete abandonment of a roosting site. Effects which are not directly linked but are as impactful are classified as indirect effects. For instance, a decrease in insect availability might lead to reduced foraging success which might affect the growth of the bat's offspring. In most cases of indirect effects ALAN is not the only reason but plays a serious role. Cumulated with other pressures these not-so-obvious effects can become a serious threat.

3.3.1 Direct Effects of ALAN

- **General aversion to light:** Most bat species generally avoid lit areas and prefer darkness for roosting and foraging. However, some species show opportunistic behaviour which can be related to insect accumulation in artificially lit places and decreased competition on prey (Voigt and Lewanzik, 2023).
- **Increased predation risk:** The adaptation to darkness is the main protection mechanism bats have developed to escape predation. Most of their predators, for

instance birds of prey, have a well-developed visual sense, which is dependent on light. Speakman and colleagues even stated that the survival and reproduction rates of bats are often constrained by predation (Speakman, Stone and Kerslake, 1995).

- **Reduced foraging efficiency:** ALAN might disrupt natural foraging patterns, which might be related to changes in the emergence behaviour, reduced insect availability in dark places. It results in a reduced foraging success (Voigt, Azam and Dekker, 2018).
- **Reduced drinking behaviour:** Several studies have investigated the impacts of ALAN on bats and stated in this context that even drinking behaviour of these animals is affected negatively (Zschorn, 2024).
- **Delayed emergence:** Artificial light near the roost entrance can delay the bat's emergence in the evening, reducing the time available for foraging or impacting the frequency of how often females return to feed their offspring during a night. In the worst case, it can lead to starvation, if the illumination totally hinders the bats from emerging (Voigt, Azam and Dekker, 2018).
- **Roost Abandonment:** Persistent artificial light in the near vicinity of roosting sites can lead to the abandonment of a whole colony. Especially maternity roosts are critically sensitive (Voigt, Azam and Dekker, 2018).
- **Habitat fragmentation:** Zeale et al. state that artificial lights restrict major flight patterns of some bats. Changed pathways for transferring might lead to further distances between foraging sites and roosts and loss of good quality foraging sites due to access difficulties (Zeale *et al.*, 2018).
- **Physiological changes:** Due to a lack of data, the physiological impacts of ALAN on bats are not yet well studied (Rowse *et al.*, 2015).

3.3.2 Indirect or cascading effects of ALAN

- **Reduced growth of offspring:** Among other cumulative effects ALAN is mentioned to negatively impact the growth of offspring. Several factors could play a role for the offspring development, for instance reduced foraging success or reduced feeding during one night or increased predation risk for the young while learning how to fly (Voigt, Azam and Dekker, 2018).
- **Reduced insect availability:** Suchy and Stoll (2019) conducted a comprehensive study on the impact of ALAN on nocturnal insects, predicting dramatic changes due to light

pollution. ALAN generally causes attraction of insects leading to high mortality due to the heat of the lamps, reorientation and exhaustion or increased risk of predation (Eisenbeis and Hassel, 2000).

- **Changes in insect availability:** The so-called "vacuum cleaner effect of illumination" accumulates nocturnal insects close to artificial light sources. Therefore, the size and quality of dark foraging habitats shrinks (Manfrin *et al.*, 2018). Light-averse bats are disadvantaged compared to opportunistic species (Voigt, Azam and Dekker, 2018). Continuing this cascading effect, it might lead to a decrease in abundance of certain species, and reducing competition for less sensible bats (Schoeman, 2015).
- **Interspecific competition:** Light-induced changes in circadian activity patterns can alter competition among bats. Light-tolerant species can use illuminated resources, while light-sensitive bat species are excluded. Moreover, ALAN can influence niche partitioning by extending the activity period of diurnal species, leading to increased interspecific competition with nocturnal species, like birds (Voigt and Kingston, 2016).
- **Decrease in bat diversity:** This disadvantage for light-averse species in combination with other pressures like urbanisation or habitat fragmentation might lead to a general shift in bat community composition and furthermore to a less diverse bat fauna (Schoeman, 2015).

This summary mainly focuses on effects of ALAN on light-averse bat species, like *Rhinolophus* and *Myotis*. There might be several other effects related to other species which are regarded as opportunistic towards ALAN, like attraction behaviour or increased food intake (Voigt and Lewanzik, 2023). Overall, both direct and indirect effects are unlikely to appear isolated. In conclusion, ALAN influences multiple aspects of bat life.

3.4 Indicator species concepts

The concept of indicator species focuses conservation efforts on selected species whose protection simultaneously benefits other species and habitats (windfall effect) (Jedicke, 2016). These indicator species, also referred to as target, flagship, keystone, umbrella species, bioindicators, or biomonitors, support the concrete planning, implementation, and evaluation of conservation goals. However, these terms are often used inconsistently or lack clear definitions (Siddig *et al.*, 2016; Zschorn, 2024). Indicator species serve various purposes, such as being characteristic for an ecosystem, demonstrating particular conservation targets, or attractive to the public (Bernhardt, Kropf and Laubmann, 2010; Jedicke, 2016).

In ecological research, indicator species are frequently used to monitor ecosystem or environmental health, assess habitat restoration success, or evaluate the effects of pollution. Most indicator species (50%) are animals, with invertebrates making up 70% of these. Selections are often based on prior research results, ecological significance or conservation status, local abundance, or a combination of several factors (Siddig *et al.*, 2016). Reliable selection criteria include ecological importance, sensitivity to environmental changes, abundance and distribution, demographic stability, habitat specificity, historical data availability, and responsiveness to management actions (Bernhardt, Kropf and Laubmann, 2010; Siddig *et al.*, 2016).

A practical example is the protection of forest-dwelling bats, which also benefits other forest species (Zschorn, 2024). This approach requires less effort since multiple species are indirectly protected and conservation success is easier to measure. Another advantage is its simplicity, which enhances public understanding and acceptance. Furthermore, indicator species can act as an early warning system for environmental changes, simplify complex ecological data, predict future ecological conditions, and focus on specific conservation issues with targeted measures (Jedicke, 2016; Siddig *et al.*, 2016).

Despite these advantages, there are limitations. A single population rarely reflects the full complexity of an ecosystem, and selection criteria are often subjective or lack justification. Additionally, the terminology for indicator species is ambiguous, and the link between an indicator species and environmental contexts may be unclear. Biological interactions at different trophy levels are often difficult to estimate, and methodological challenges, such as detectability or sampling protocols, can bias results. Moreover, the impact of future climate changes on the effectiveness of indicator species remains uncertain, making efficacy assessments challenging (Bernhardt, Kropf and Laubmann, 2010; Siddig *et al.*, 2016; Zschorn, 2024).

The selection of indicator species should align with overarching conservation objectives, ensuring a clear and logical connection to the evaluation's purpose. Moreover, it is important to establish clear scientific criteria for the selection and at the same time consider public acceptance, data availability, and methodological feasibility. By addressing these challenges, indicator species can play a vital role in achieving conservation goals effectively and efficiently (Zehlius-Eckert, 2001; Siddig *et al.*, 2016).

3.5 The potential of dark sky protection

3.5.1 ALAN as a potential threat for protected areas

There is no doubt anymore that ALAN is a serious threat to biodiversity. Several studies mentioned above give evidence to that. At the same time, scientists are measuring that ALAN is increasing with an alarming speed. Worldwide it is rising 2 to 6% per year (Hölker *et al.*, 2021). Referring to the study from Puschnig et al. which shows that ALAN is increasing 1,7% annually in rural areas indicates that light pollution is not only a problem of urban places (Puschnig *et al.*, 2022). Researchers from Beijing found that the percentage of dark protected areas decreased by 35,38% from 1992 to 2012 in China. Especially in rural areas light pollution increases significantly. Therefore, they suggest creating buffer zones for protected areas and establish a large light pollution monitoring system (Jiang, He and Ni, 2017).

Peregrym et al. have studied the level of light pollution affecting strict protected areas of the Republic of Serbia, the Republic of Bulgaria, and Montenegro. They could prove that the increase of ALAN in these areas is still lower than in many other regions in Continental Europe, but there are only a few strictly protected areas in each country where the night sky quality is excellent. Therefore, these places are important for nature conservation and it is a necessity to protect natural darkness there (Peregrym *et al.*, 2020).

Wallner et al. assessed artificial light trends in 47 Austrian nature parks using VIIRS and SQM data. They found that 38 out of 47 nature parks showed significant increases in radiance over a ten-year period, indicating a rise in light pollution levels. This increase was noted to be more than double the average increase across the entire national territory, emphasizing that even areas with low light emissions are not immune to the encroachment of ALAN (Wallner, Puschnig and Stidl, 2023).

To conclude, there is much evidence that increasing light pollution is a serious threat for protected areas and nature conservation sites and there is an urgency to act.

3.5.2 Certification of dark sky areas

In April 2007 the international starlight conference was held on the Canary Island La Palma (`La Palma Declaration, 2007´). Leading stakeholders were the International Astronomical Union (IAU) and the United Nations Educational Scientific and Cultural Organization (UNESCO) to set a first milestone in the battle against light pollution. The Declaration in Defence of the Night Sky and the Right to Starlight, the so-called La Palma Declaration was published afterwards. It creates a basis for dark sky protected areas. Together with UNESCO the organisation Fundacion Starlight developed the concept of certified Starlight sites (Welch *et al.*, 2024). The

NGO DarkSky International, founded in 1988 (previously called International Dark-Sky Association), has been designating Dark Sky Places for several decades already (Hunter, 2023). In 2009 the Dark Skies Advisory Group (DSAG) was founded as a working group of the World Commission on Protected Areas (WCPA) of the International Union for Conservation of Nature (IUCN). It operates as an overarching expert panel and has defined classes for dark sky conservation sites adopting the system of IUCN categories to allow comparisons between different naming styles used by various recognizing bodies (Welch *et al.*, 2024).
There are over 391 certified dark sky places in 34 countries (stand: October 2024), among them are strictly protected areas, astronomical research sites, biosphere reserves and even towns or villages (IUCN Dark Skies Advisory Group, no date).
The DSAG dark sky classes were developed similar to the IUCN categories for PAs to have a worldwide standardized system. However, IUCN categories and dark sky classes are not interconnected, and it is possible that a PA has a higher, lower or even no dark sky class. (Welch *et al.*, 2024)

Table 3: IUCN categories and DSAG dark sky classes (Welch et al., 2024)

IUCN categories for PAs	**DSAG dark sky classes**
I Strict protection: Ia Strict Nature Reserve Ib Wilderness Area **II National Park:** Ecosystem conservation and recreation **III Natural Monument:** Conservation of natural features **IV Habitat or Species Management Area:** Conservation through active management **V Protected Landscape/Seascape:** Landscape/seascape conservation and recreation	1 **Dark Sky Astronomy Site**: containing at least one scientific grade research telescope supporting research, and having a surrounding legally protected area 2 **Dark Sky Park**: legally protected natural area 2a Park, reserve, habitat, natural area or other ecological or geological protection 2b Unpopulated area set aside for traditional or sacred practices related to the sky 2c Rural area, area of outstanding landscape beauty 3 **Dark Sky Heritage Site**: legally protected heritage physical works of mankind 4 **Dark Sky Outreach Site:** 4a Urban or suburban site 4b Rural site

VI Managed Resource Protected Area: Sustainable use of natural ecosystems	5 **Dark Sky Reserve**: legally protected core area and a sustainable development buffer zone of cooperating community, rural and natural area jurisdictions 6 **Dark Sky Community**: a rural municipality, village, town or city 6a City, town or village 6b Populated rural area without a formal PA

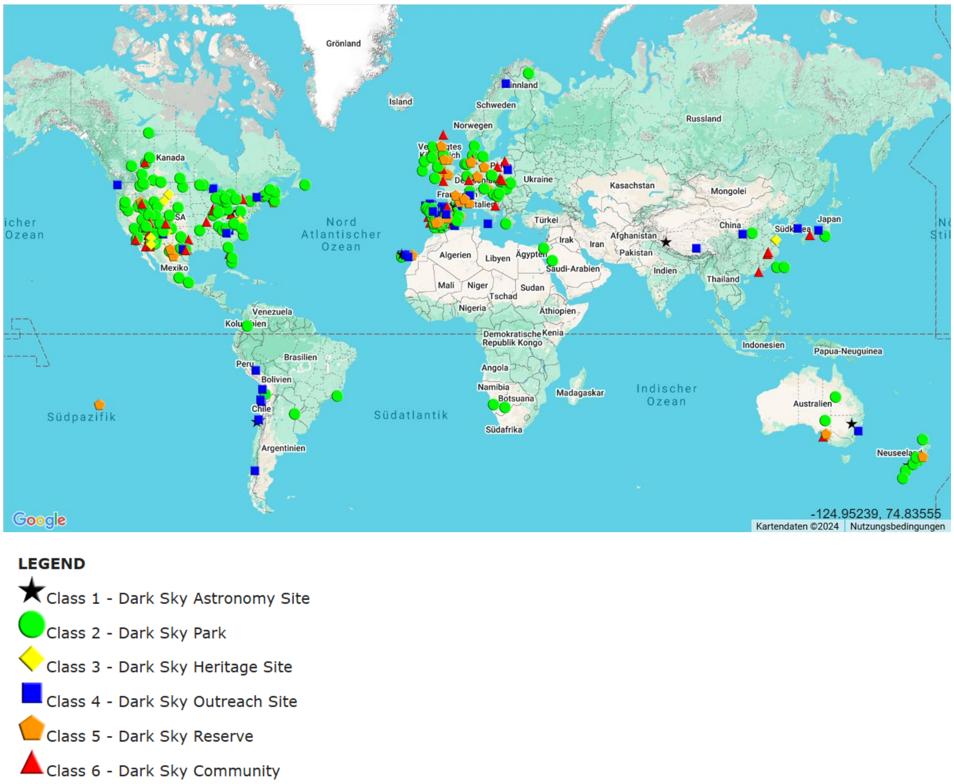


Figure 6: world map showing all certified Dark Sky places classified by the DSAG, October 2024 (IUCN Dark Skies Advisory Group, no date)

Since it was chosen to apply for the International Dark-Sky Reserve (IDSR) certificate from DarkSky International for the target area of this study, the requirements and goals for this certification will be explained in detail. There are five different categories for designation in the framework of DarkSky International. Each category has its own set of guidelines for certification based on land management, sky quality, and size (Welch *et al.*, 2024). The designation flowchart (figure 7) shall help to decide on the right category for a certain area.

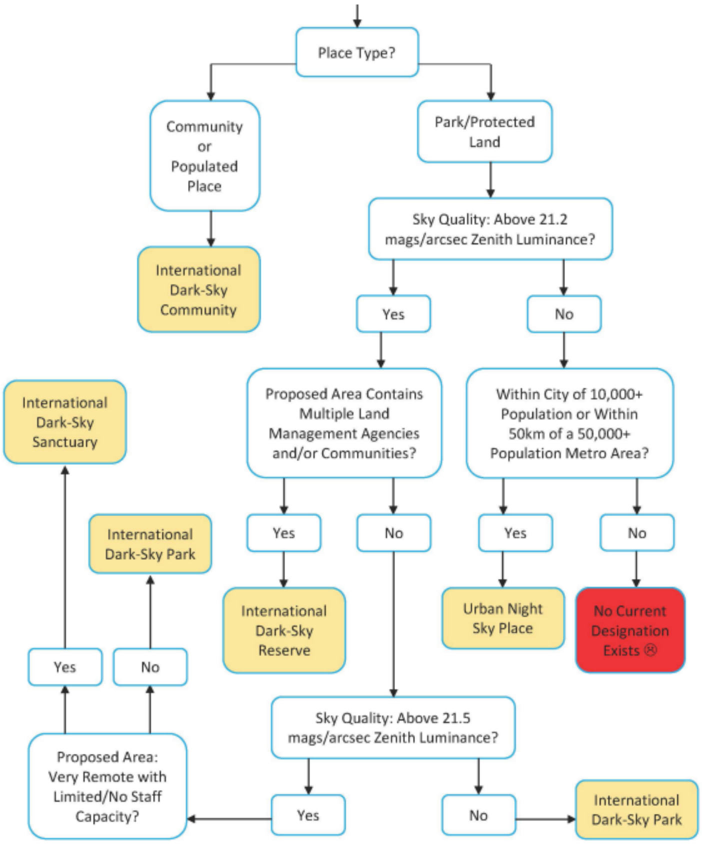


Figure 7: designation flowchart for Dark-Sky categories (DarkSky International, 2018)

An IDSR is a large area of public or private land, covering at least 700 km² (~ 173,000 acres), renowned for its exceptional starry skies and natural nocturnal environment. It is protected for purposes such as scientific research, conservation, education, cultural heritage, and public enjoyment (DarkSky International, 2023).

An IDSR is divided into two zones (DarkSky International, 2023):

- **Core zone:** This area meets strict criteria for sky quality and natural darkness.
- **Peripheral or buffer zone:** Surrounding the core, this zone supports the dark sky values of the core and shares the associated benefits.

The main goals of creating an IDSR are (DarkSky International, 2023):

- Local and international recognition
- Eco- and astro-tourism
- Protection of nocturnal habitats
- Leadership in Environmental Stewardship

3.5.3 *From green and blue to dark infrastructure*

The European Commission has defined "Green Infrastructure" as "a strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity" (*Green infrastructure*, 2023). It is one very important tool to foster connectivity of habitats to achieve an exchange of species, individuals, and genes. Connectivity can be defined as "a measure of how easy it is for species to move between different patches of suitable habitat" (Cayton, 2024). Enhancing connectivity plays a crucial role in reducing the negative impacts of a changing landscape on biodiversity.

It can be differentiated in structural and functional connectivity (figure 8). Structural connectivity is created from a landscape or seascape perspective. It considers habitat size and permeability, and physical structures and barriers. However, it is mainly measured through GIS tools and not directly offering a statement about the ecological effectiveness. In contrast, functional connectivity lays a focus on the species perspective. It is taken into account how species respond to functional elements and built on the species' needs. Some types of green infrastructure are "functional" if they support dispersal and movement and protect ecological processes. The effectiveness can be measured through ecological indicators (Hilty *et al.*, 2020; Cayton, 2024).

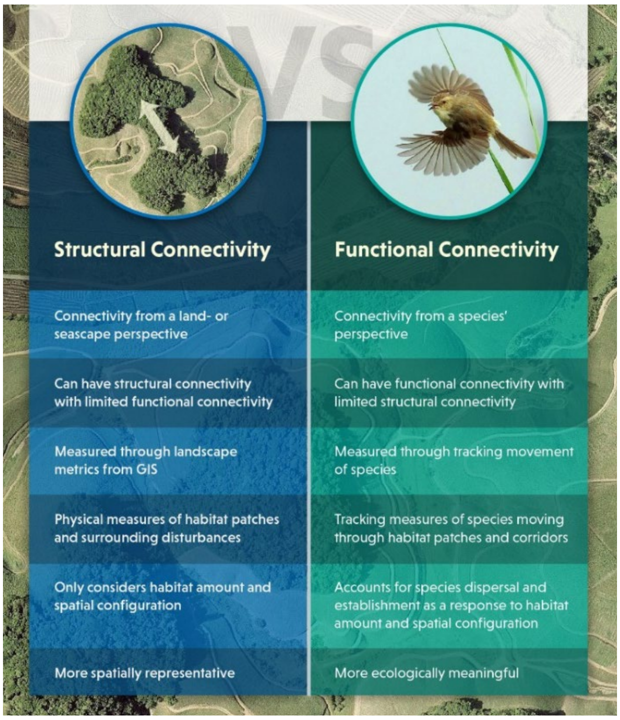


Figure 8: structural vs. functional connectivity (Cayton, 2024)

Not only the International Union for Conservation of Nature (IUCN) recognizes green infrastructure as key spatial planning tool, also several international conventions such as the Ramsar Convention (1971) and the Bern Convention (1979), European agreements (habitats and species directives) are promoting the enhancement of ecological connectivity (Sordello *et al.*, 2022).

Physical barriers like fences, roads or other human infrastructure ALAN have a similar effect on the movement of species that avoid light. The establishment of green infrastructure became a core spatial planning tool to ensure habitat connectivity and to foster biodiversity and genetic exchange. However, the effects of artificial light on species dispersal are mostly not taken into account when planning such measures. Since light pollution is not only affecting the immediate place where it emitted, the planning of such dark corridors is complex (Gaston *et al.*, 2021).

Hölker et al. mentioned that the conservation concept of implementing dark ecological networks consisting of core areas, corridors, and buffer zones to limit the impacts of light pollution on biodiversity at the landscape level is an opportunity for an effective management of ALAN (Hölker *et al.*, 2021). The IUCN has adopted a motion on light pollution during the IUCN world congress held in France in September 2021, which promotes the establishment of dark infrastructure around the world (Hilty *et al.*, 2020).

To tackle this Sordello et al. suggest promoting the integration of darkness quality within the green and blue infrastructure, to recognize dark infrastructure. Dark infrastructure should be identified, preserved and restored at different territorial levels to guarantee ecological continuities where the night and its rhythms are as natural as possible (Sordello *et al.*, 2022).

They propose a 4-steps process to achieve this goal. 1) Mapping of light pollution in all its forms and dimensions in relation to biodiversity, 2) Identifying the dark infrastructure starting or not from the already identified green/blue infrastructure, 3) Planning actions to preserve and restore the dark infrastructure by prioritizing lighting sobriety and not only energy saving, 4) Assessing the effectiveness of the dark infrastructure with appropriate indicators (Sordello *et al.*, 2022). (figure 9)

Furthermore, Sordello et al. introduce several dark infrastructure projects in France and Switzerland which can serve as a blueprint (Sordello *et al.*, 2022).

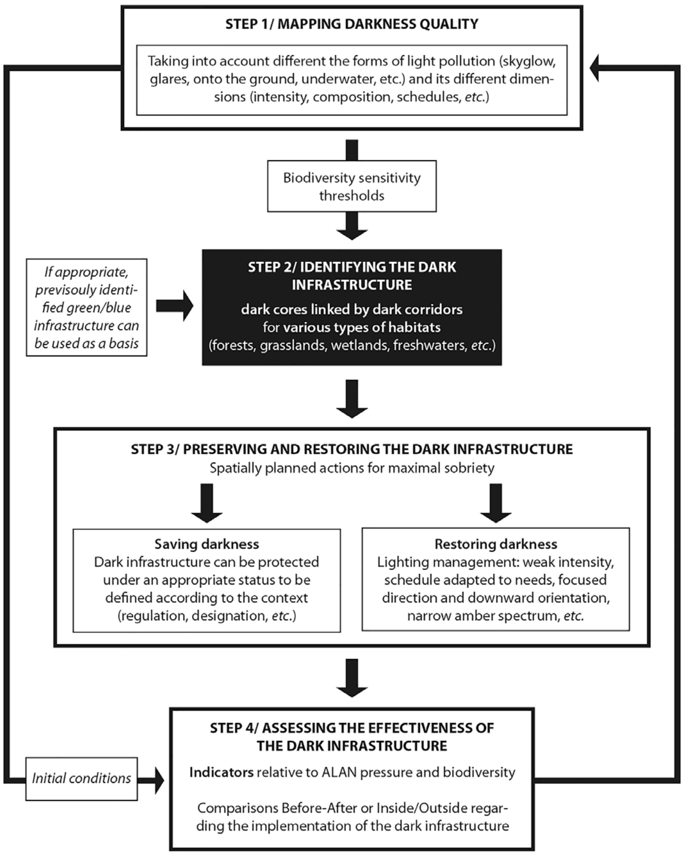


Figure 9: 4-step model (Sordello et al., 2022)

However, Sordello et al. state that the deployment of dark infrastructure raises many operational and methodological questions and stresses some knowledge gaps that still need to be addressed, such as the exhaustive mapping of light pollution and the characterization of sensitivity thresholds for indicator species (Sordello *et al.*, 2022)

4 Materials and methods

4.1 Description of project and project area

In 1991, the Alpine Convention was signed by its contracting parties Austria, Switzerland, Germany, France, Liechtenstein, and Italy. Austria was the first country to ratify it in 1994 (Nitsch, Bindeus and Zwettler, 2015; Alpine Convention, no date). Figure 10 shows a map of the Alps, where the Alpine Convention applies. The Northeastern Limestone Alps around the Styrian Eisenwurzen Nature and Geopark, between the two National Parks Kalkalpen and Gesäuse and the Wilderness Area Dürrenstein-Lassingtal, form a pilot region for the Alpine Convention as a great example for an ecological network (Kreiner, Maringer and Zechner, 2012). Because of its geographical features this area is rich in biodiversity, home of many endemic species and hosts some of the last pristine forests in Austria. Due to its low population density and its distance from larger urban areas it became a valuable area for nature conservation activities. Two national parks, three nature parks, one wilderness area and several UNESCO and Natura 2000 sites have been designated there. These protected areas have established a larger network, called "Netzwerk Naturwald" to collaborate on habitat connectivity between their borders (figure 11). The major goal of the Netzwerk Naturwald is to promote the establishment of green corridors and stepping stones and thus to ensure a sufficiently large gene pool of many species (Nitsch, Bindeus and Zwettler, 2015).

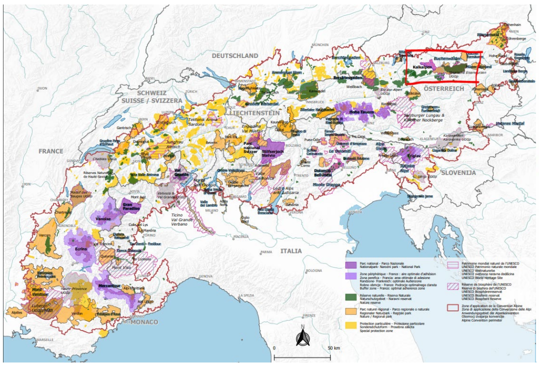


Figure 10: protected areas in the Alps; project area in the north-east (Jean, 2024); project area indicated in red

Figure 11: Netzwerk Naturwald (Nitsch, Bindeus and Zwettler, 2015)

Furthermore, this region in the border triangle between Lower Austria, Upper Austria and Styria has potential to designate a joint dark sky protected area. To become an internationally certified dark sky place, an area must prove low levels of light pollution. Outdoor lighting must be managed under strict standards and the public must be addressed through educational activities about the values of natural darkness (DarkSky International, 2023; DarkSky International, 2024a).

In 2023, a joint project "Sterne über dem Dreiländereck" funded by the state of Austria and the European Union was launched. The aim was to conduct a feasibility study for the project area to apply for the International Dark Sky Reserve certification ('Naturnachtgebiet Eisenwurzen, Dark Sky Reserve Application', 2025). The study area includes a total of 22 municipalities, six large PAs and thus covers an area of 2803,4 km². This master thesis fugues as addition to the feasibility study to investigate especially the value of natural darkness from a nature protection and biodiversity conservation point of view.

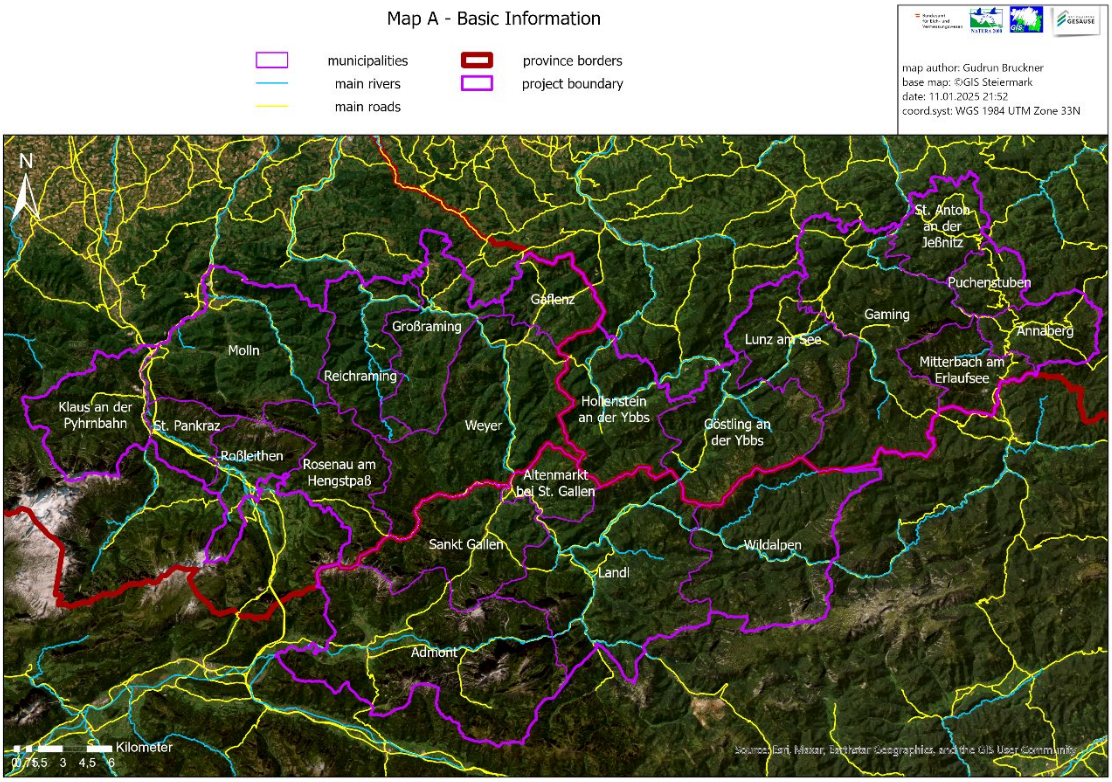


Figure 12: Map A - Overview of project area with basic information

The project area is shown in Map A (figure 12). This map includes the following information: project boundary, municipalities, main rivers, main roads and province borders between Styria, Upper Austria and Lower Austria.

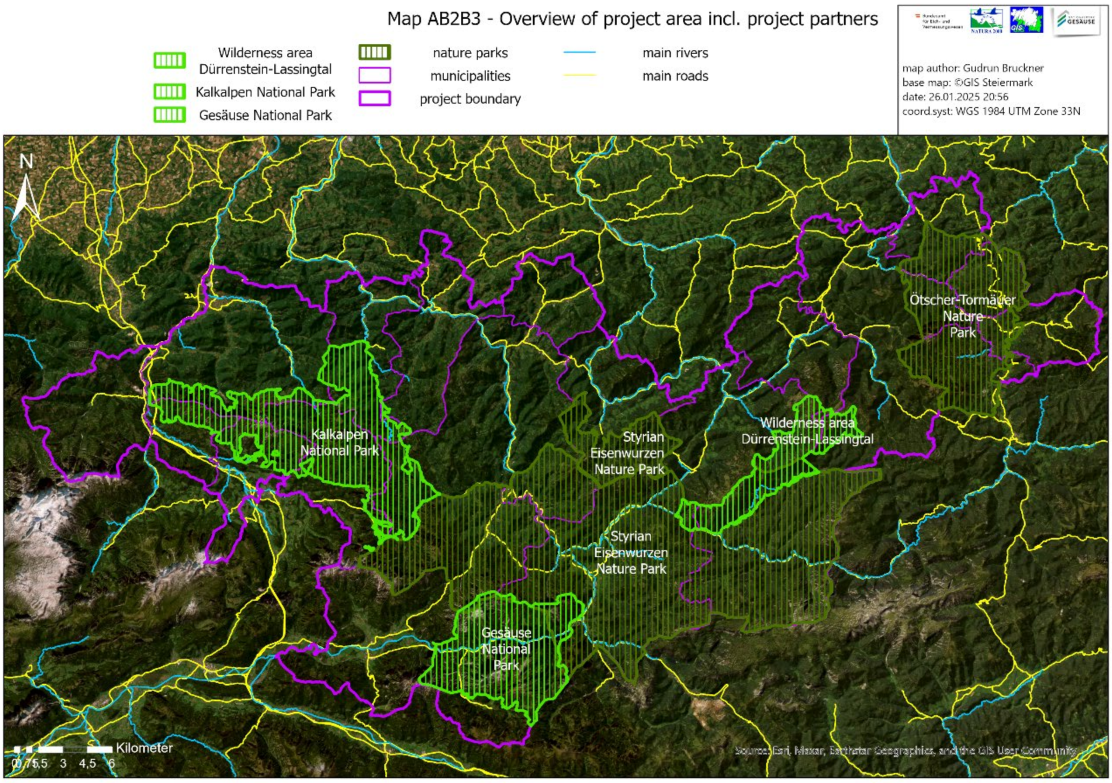


Figure 13: Map AB2B3 - Overview of project area incl. partnering PAs

Partnering protected areas for the nomination of this IDSR include the Styrian Eisenwurzen Nature and Geopark, Ötscher-Tormäuer Nature Park, Lower Austrian Eisenwurzen Nature Park, National Park Kalkalpen and National Park Gesäuse and the Wilderness Area Dürrenstein-Lassingtal (Map AB2B3 – figure 13). The two national parks are IUCN category II and the wilderness area is IUCN category Ib, which makes these three PAs strictly protected areas (Nitsch, Bindeus and Zwettler, 2015).

4.2 Description of the developed zonation of the IDSR

The core zone boundaries should follow natural or logical geographic features and may include a publicly protected area, aiming to fully encompass its boundaries. The peripheral zone must be contiguous, enclose the core, and cover at least 700 km² or a 15-km radius to mitigate 80% of current and future light pollution threats. Both zones should avoid arbitrary exclusions, ensuring they support achieving IDSR status. The core must allow regular public nighttime access and provide an exceptional dark sky resource compared to surrounding communities (DarkSky International, 2023).

The zonation of the planned IDSR was conducted using a GIS-based analysis of geospatial datasets. The goal was to delineate an area with minimal light emission (core zone) and a peripheral zone through spatial operations, analysis, and classification techniques. Key data sources include:

- Municipalities
- Light Pollution Map
- Protected areas
- Settled areas (Corine Land Cover)
- All-sky measurements
- SQM-roadrunner
- Fixed light monitoring stations (permanent photometers)
- Orthophoto basemap ('Naturnachtgebiet Eisenwurzen, Dark Sky Reserve Application', 2025).

The GIS-based analysis for the zonation of the IDSR involved following stages:

1. **Spatial delimitation of the project area**
   The study was limited to 22 municipalities, using a clipping tool to focus on relevant areas and reduce computational effort.

2. **Raster and vector data integration**
   Raster data (e.g., Light Pollution Map) was integrated with vector data (e.g., protected areas, settlements). Overlay analyses like "Union" and "Intersection" helped to identify dark patterns, while weighted overlays and kernel density analysis refined the delimitation of potential core zone parts. Densely populated areas (settlements), derived from the Corine Land Cover dataset, were excluded, ensuring only areas with low light pollution levels were included in the core zone.

3. **Zoning through weighting and classification**
   A combined weighting and classification approach was used adhering the core zone to a brightness threshold of ≥ 21.2 mag/arcsec^2. Ground-based measurements from All-sky measurements, SQM roadrunner, and permanent photometers validated the analysis, refining the zoning by excluding high-lit areas.

4. **Fine delimitation**
   Final boundaries were drawn using natural features (e.g., rivers or ridges) and infrastructure (e.g., roads or settlements) as reference points, supported by high-

resolution aerial imagery. This ensures an ecologically sound and practical zonation ('Naturnachtgebiet Eisenwurzen, Dark Sky Reserve Application', 2025).

The GIS-based stepwise approach provides accurate mapping of different features of planned IDSR. A combination of different data sources and a high spatial agreement between modeled and measured light values ensures a scientifically sound delineation of the zones. The core zone stretches over the darkest and best-protected areas of the project area. It is surrounded by the buffer zone which serves as protective belt to reduce external pressures on the core zone and enhances the implementation of light pollution mitigation measures ('Naturnachtgebiet Eisenwurzen, Dark Sky Reserve Application', 2025).

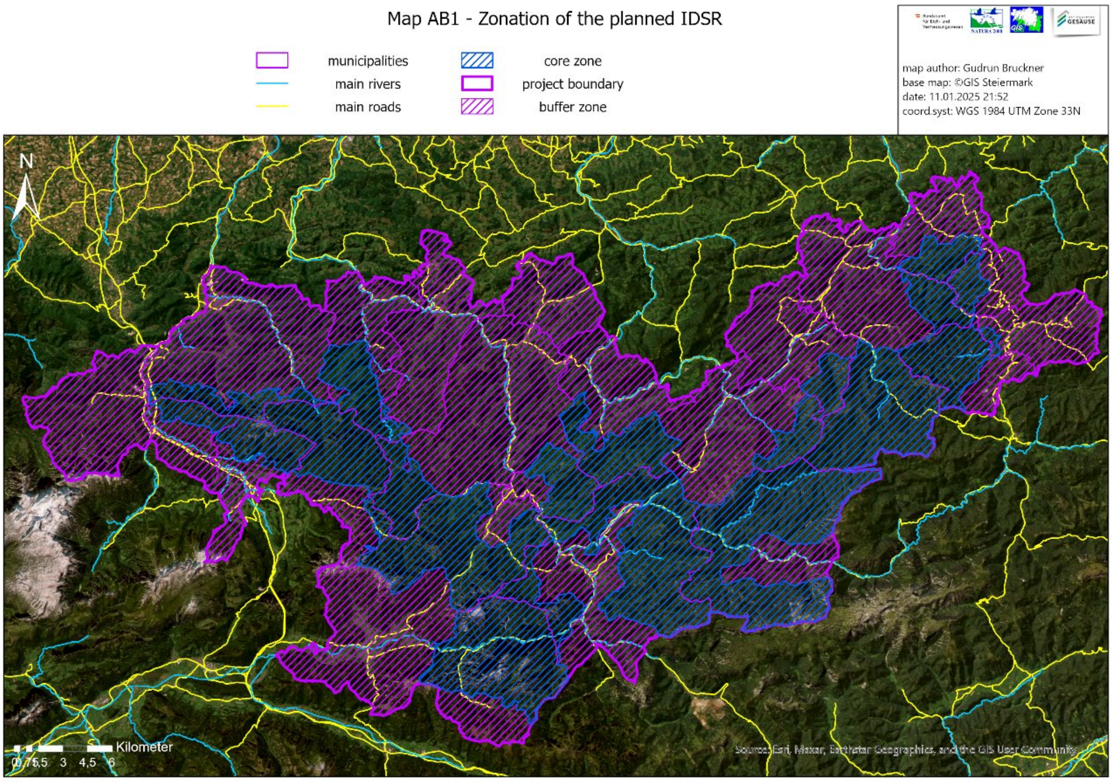


Figure 14: Map AB1 - Zonation of the planned IDSR

Map AB1 (figure 14) includes the proposed zonation of the planned IDSR. The core zone is displayed in the map as blue hatched fill and the buffer zone or peripheral zone as purple hatched fill. The core zone covers an area of 1087,7 km² and the buffer zone extends to a size of 1715,7 km².[1]

[1] Remark: This zonation is just a proposal resulting from a modelling during the joint funding project "Sterne über dem Dreiländereck" (stand: December 2024). It is still possible that size and delineation of the planned IDSR will change.

4.3 Selection of indicator species

There are many approaches to define suitable indicator species. The criteria must be defined according to the purpose of the analysis. In her recent work Zschorn has discussed this concept in regard to light pollution (Zschorn, 2024). She has made a selection of several factual and practical criteria and grouped them in "exclusion criteria", "side criteria", and "further prioritizations". The selection of indicator species for this study is based on Zschorn's work and visualized in figure 15. It was adapted to the requirements of this study, described in detail in the next paragraph. In the scope of this thesis, there was no field data collected nor was the full species spectra investigated. Bats are a very well-studied nocturnal taxonomic order and well-represented in the target area. Therefore, expertise from the KFFÖ (Austrian Coordination Centre for Bat Conservation and Research) was consolidated. Among the light-averse species two genera (*Myotis* and *Rhinolophus*) were selected. As the characteristics and the requirements for different species among one genus are similar and often the distinction of recorded data is not available on species level. Therefore, the selected species were grouped in their genera and the following criteria were assessed mainly on genus level (Voigt, Azam and Dekker, 2018).

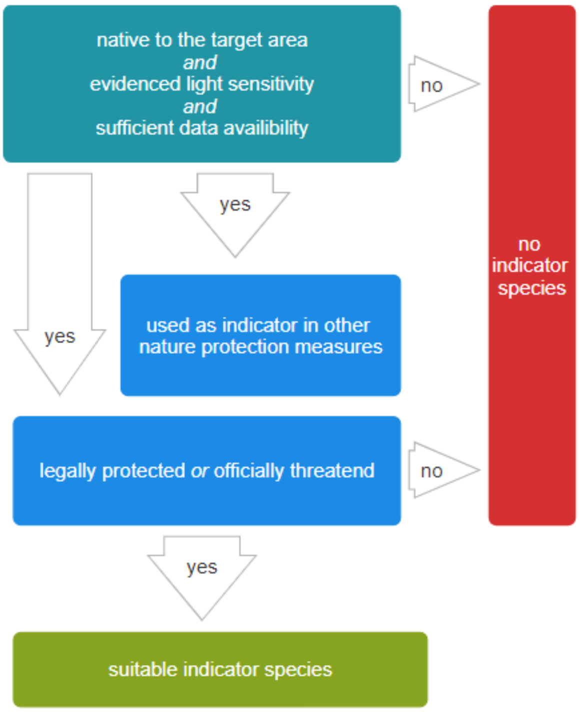


Figure 15: flowchart for selection process; translated and adapted graph taken from Zschorn, 2024

In the following, exclusion criteria, side criteria and further prioritisations for the selected species will be presented in more detail.

Exclusion criteria:

- **Native to the area**

All selected bat species are native to Austria and to the project area.

- **Evidenced light sensitivity**

Zschorn has undertaken comprehensive literature research on the effects of ALAN on bat species occurring in Germany. For *Myotis* and *Rhinolophus* species she has identified following impacts: avoidance behaviour, general population decrease, abandonment of colony, decreased drinking behaviour, delayed foray, extended foray, disturbed flight patterns and reduced growth of offspring (Zschorn, 2024). Moreover, Myotis and Rhinolophus were both used as indicators for a very recent study on the impact of light pollution in the Pyrenees National Park (Fresse, Demoulin and Maingueneau, 2018; Sordello *et al.*, 2022).

A "Web of Science" keyword research was conducted for this thesis on June 16th, 2024. "*Myotis* + light pollution" or "*Rhinolophus* + light pollution". 27 papers were recorded for *Myotis* and 11 were listed for *Rhinolophus*. A deeper insight into the literature on light sensitivity of these species offers chapter 3.3.

- **Sufficient data availability**

Through regular bat counting and monitoring in Austria bats are generally well recorded. As there are several protected areas like national parks or Natura 2000 sites in the target area data availability might be even better. Furthermore, there are several studies discussing the impacts of ALAN on bats and elaborating management measures, for instance the EUROBATS guidelines (Voigt, Azam and Dekker, 2018).

Side criteria:

- **Indicator species in other nature protection measures**

Zschorn has used a slightly different criterion: "target species for other landscape planning projects". As the focus of this thesis is on protected area development and management and not on landscape planning this criterion was slightly adapted. Following species are target species of the regional Natura 2000 sites (figure 16):

- *M. emarginatus*: Ötscher – Dürrenstein, Nationalpark Kalkalpen und Umgebung
- *M. myotis*: Ötscher – Dürrenstein, Nationalpark Kalkalpen und Umgebung

- *R. hipposideros*: Ötscher – Dürrenstein, Nationalpark Kalkalpen und Umgebung, Ennstaler Alpen/ Gesäuse

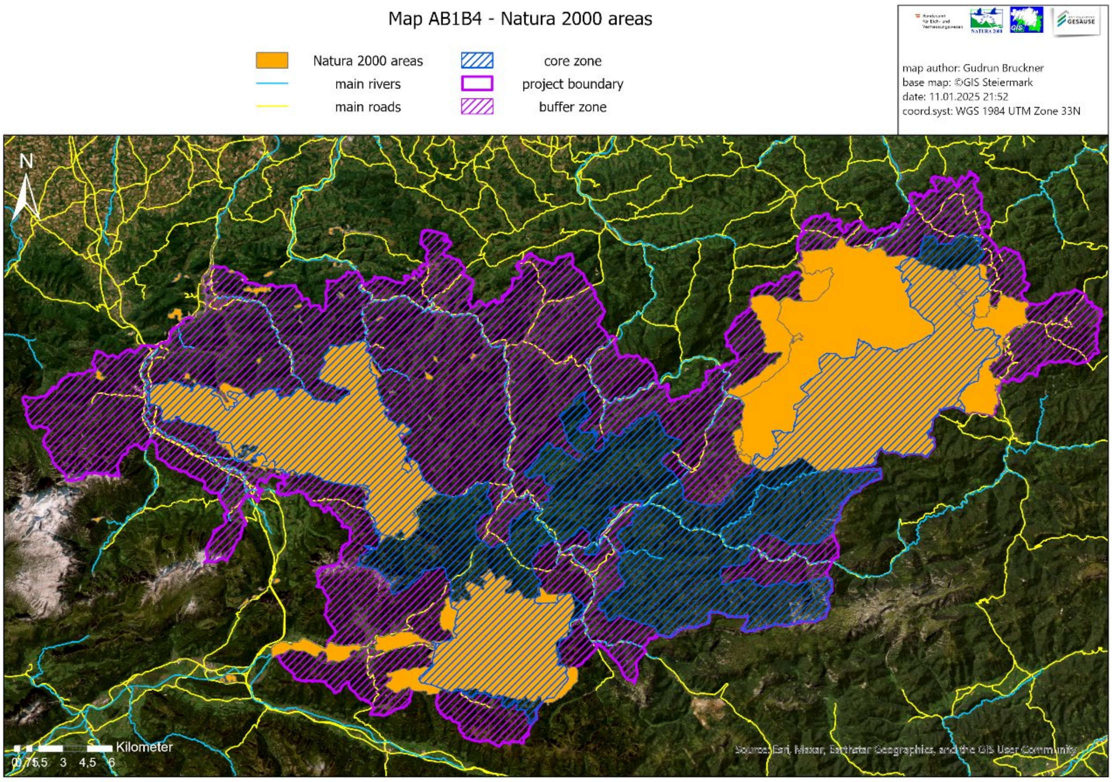


Figure 16: Map AB1B4 – Natura 2000 areas within the project area

- **Threat or protection status**

Table 4 gives an overview on the FFH status and the red list ranking of the bat species (Spitzenberger, F., 2005; Directive - 92/43 - Habitats Directive - EUR-Lex, no date; IUCN red list, no date). Seven out of ten bat species, which were identified in the target area, are vulnerable (VU) or even critically endangered (CR) in Austria. Moreover, all bat species are listed in Annex 4 of the habitats directive and six out of ten are listed in Annex 2.

Table 4: overview of protection status; LC… least concern, NT… near threatened, VU… vulnerable, CR… critically endangered

Species	FFH status (Annex 2 or 4)	IUCN red list	AT red list
Myotis bechsteinii	2 & 4	NT, decreasing	VU
Myotis brandtii	4	LC, stable	VU
Myotis daubentonii	4	LC, stable	LC
Myotis emarginatus	2 & 4	LC, stable	VU
Myotis myotis	2 & 4	LC, stable	LC
Myotis mystacinus	4	LC, unknown	NT
Myotis nattereri	4	LC, increasing	VU
Myotis oxygnathus	2 & 4	LC, decreasing	CR
Rhinolophus ferrumequinum	2 & 4	LC, decreasing	CR
Rhinolophus hipposideros	2 & 4	LC, decreasing	VU

Further prioritisations:

The following points can be regarded as additional information to underline the indicator suitability. They do not have to be fulfilled for each species.

- **Windfall effect**

  Bats feed on insects, which are severely affected by light pollution and therefore usually occur on spots with high insect density. Reducing this thread might lead to an increase in insect availability (Gaston *et al.*, 2013; Stone *et al.*, 2015).

- **Special habitat requirements**

  Bats have a complex lifestyle and therefore very complex habitat requirements. If one habitat or habitat fragment of a population is disturbed, it can be enough to affect the general occurrence of this species in this area. Therefore, bats have turned out as useful indicator species for habitat connectivity (Gutiérrez-Granados and Rodríguez-Zúñiga, 2023).

- **Attractiveness and popularity**

Besides the white-backed woodpecker and the *Rosalia alpina*, *Myotis bechsteinii* was selected as flagship species for the Netzwerk Naturwald. These three species are mainly used for communication purposes (Nitsch, Bindeus and Zwettler, 2015).

Table 5: indicator selection criteria overview

		criterion fulfilled?		Myotis	Rhinolophus	remarks
criteria for exclusion	native to the target area	yes	no. of evidenced species	8	2	M. alcathoe, M. capaccinii and M. dasycneme were not counted due to data deficiency, but might also appear in the target area
	evidenced light sensitivity	yes	avoidance behaviour	yes	yes	Zschorn 2024: annex 1: table A4
			general population decrease	yes	n.s.	
			abandonment of colony	yes	yes	
			decreased drinking behaviour	yes	yes	
			delayed foray	yes	yes	
			extended foray	yes	yes	
			disturbed flight patterns	yes	n.s.	
			reduced growth of offspring	yes	yes	
			Web of Science: no. of papers	27	11	Web of Science: keyword-based search "genus + light pollution"
	sufficient data availability	yes	no. of occurrences	575	179	
			no. of roosts	286	158	
			no. of maternity roosts	7	40	incl. potential maternity roosts
side criteria	indicator species in other nature protection measures	yes	no. of species used as N2000 target species in regional N2000 sites	1	2	3 regional N2000 sites
	threatened	yes	no. of species on AT red list	LC: 2, NT: 1, VU: 4, CR: 1	LC: 0, NT: 0, VU: 1, CR: 1	worldwide only LC and NT (IUCN red list)
	legally protected	yes	No. of species in FFH directive Annex 2	8/8	2/2	
			No. of species in FFH directive Annex 4	4/8	2/2	
prioritisation	windfall effect	yes		yes	yes	
	special habitat requirements	yes		yes	yes	
	attractiveness and popularity	yes		yes	n.s.	

4.4 Species data and development of bat layers

4.4.1 *Description of selected species data (meta data)*

The Austrian Coordination Centre for Bat Conservation and Research (KFFÖ) provided data about the selected species after approval of the data owners (Province of Lower Austria, Province of Upper Austria, Province of Styria, Gesäuse National Park, Kalkalpen National Park, Environmental Umbrella Organisation (Umweltdachverband), Katharina Bürger). The data was geographically restricted to the municipalities of the project area. The data set includes 754 bat records collected between 2000 and 2024. Data acquisition happened either through indirect (acoustic, dropping etc.) or direct evidence (observation or mist netting). Not all recorded locations include a distinct number of individuals nor an identification on species level. All records were logged with an exact location, date, type of observation, abundance estimation and genera or species determination. Most of them also specify the roosting situation. The collection and identification were mainly conducted by KFFÖ staff. As not all records are identified on species level and species from the same genus generally show similar behaviour towards ALAN, the simplification to work on genus level is eligible (Voigt, Azam and Dekker, 2018).

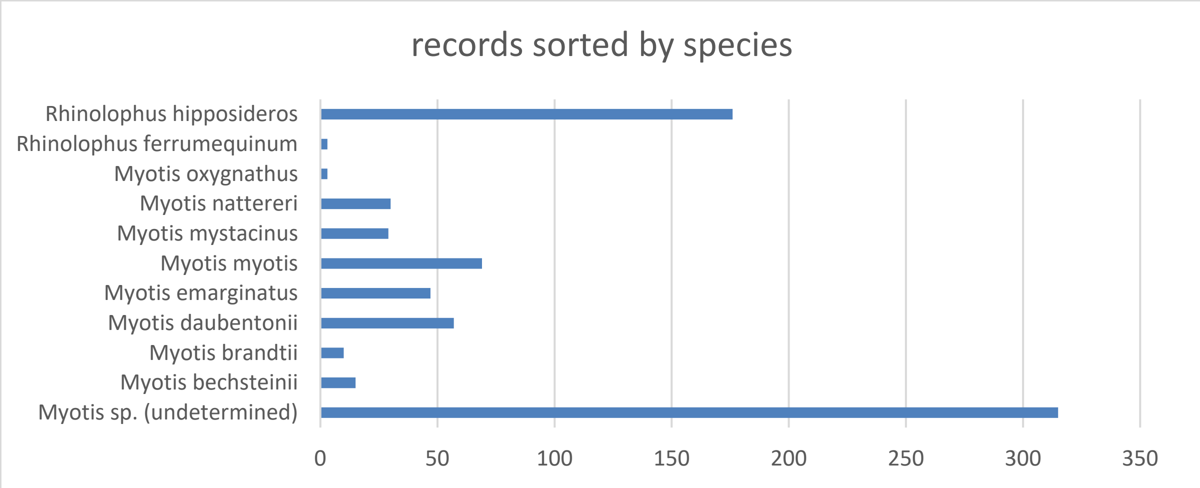
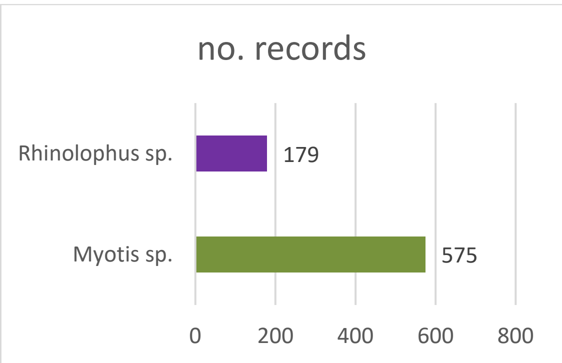


Figure 17: records of bats in the target area sorted by species

Figure 17 displays the number of records per species. *R. hipposideros* and *R. ferrumequinum* can be distinguished in all records. In contrast, most of the *Myotis* records remain undetermined on species level. *M. alcathoe*, *M. capaccinii* and *M. dasycneme* were not identified exclusively, and the target area is not their usual area of distribution. Therefore, these species were disregarded in further analysis.

The following graphs (figures 18-21) present an overview of the available data sorted by genus. Each record represents one geographical data point within the target area. For *Myotis* species more data points were collected compared to *Rhinolophus* species. However, looking at the number of individuals, more individuals of *Rhinolophus* species were counted on less locations. Therefore, a higher abundance of *Rhinolophus* individuals can be deducted. This correlates with the number of maternity roosts, as usually many individuals gather there (Dietz, Nill and von Helversen, 2016).



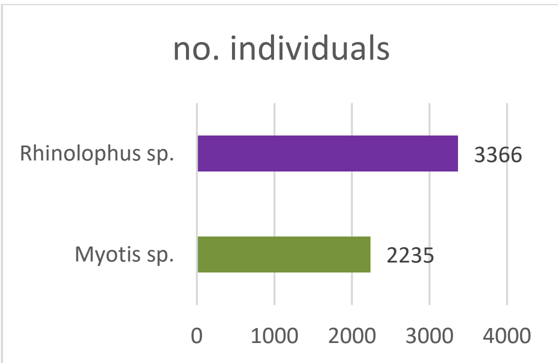
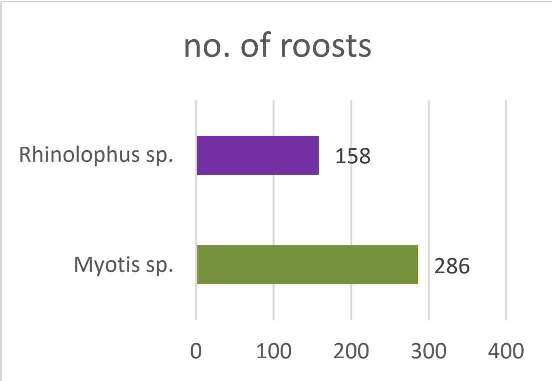


Figure 18: number of records

Figure 19: number of individuals



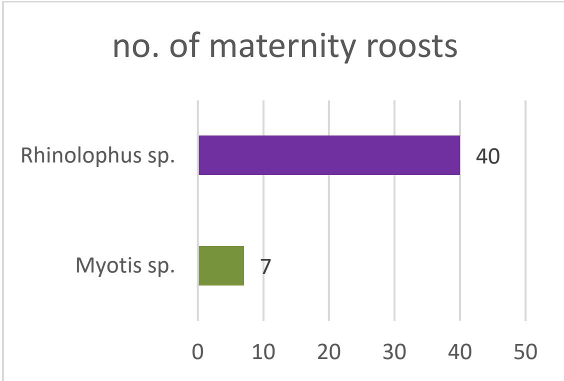


Figure 20: number of roosts

Figure 21: number of maternity roosts

4.4.2 Bat layers and buffer

The layer group C was developed from the bat data provided by KFFÖ. The data was sorted in *Myotis* (Layer C1) and *Rhinolophus* species (Layer C2) and separated in maternity roosts (including potential maternity roosts), other roosts, or other evidence, which is either from foraging or commuting activities.

Maternity roosts are regarded as the most sensible target. The roost exit and immediate surrounding should ensure no artificial light sources (Reiter *et al.*, 2013; Voigt, Azam and Dekker, 2018). Reiter et al. suggest that conservation measures for lesser horseshoe bats should be undertaken near the roost, especially within 2,5 km of the maternity roost. This radius is a recommendable buffer to protect maternity roosts from direct or indirect lighting, and dark corridors must be provided to connect the foraging grounds (Voigt, Azam and Dekker, 2018). Therefore, this radius recommendation was generally applied for all investigated species, considering that *R. hipposideros* count as one of the most sensitive species in terms of light pollution (Fresse, Demoulin and Mainguenea u, 2018; Voigt, Azam and Dekker, 2018).

Table 6: overview of bat layers

C1	all bat records + 2,5km buffer for maternity roosts
C2	maternity roosts of all bats + 2,5km buffer

Layer C1 displays all bat records in the project area: maternity roosts + 2,5km buffer, roosts and other occurrences. Layers C2 visualizes the sensible maternity roosts displayed with a 2,5km buffer.

4.4.3 Limitations of bat field data

The field data used in this analysis was collected over a long period (2006-2023) by different people, which introduces a certain level of uncertainty and the risk of mistakes. One of the main challenges is a detection bias: only what is found can be recorded, and there might be more roosts in the project area which stay unnoticed. To ensure the analysis favours the bats, the author chose not to exclude any uncertain or questionable observations. All data points were treated equally, regardless of the number of individuals observed, the specific date of the observation, or whether the roost was confirmed or only potential.

It is important to remember that each observation is just a snapshot of reality, and results may vary depending on external factors such as season, time, weather, disturbance or other external factors. For example, one site recorded over two consecutive dates showed 26 individuals on one occasion and 41 the next. While it is likely the same colony, the author did not have information to confirm this, so both observations were kept separate, resulting in two roost records. Similarly, a point marked as a potential maternity roost was listed with 0 individuals. Although it is unclear where the roost information originated, it was still included in the analysis due to its potential significance.

For mixed-species roosts, the author counted them separately for each species to retain information for all relevant species (e.g., 3 mixed roosts counted as 6 to represent both species involved).

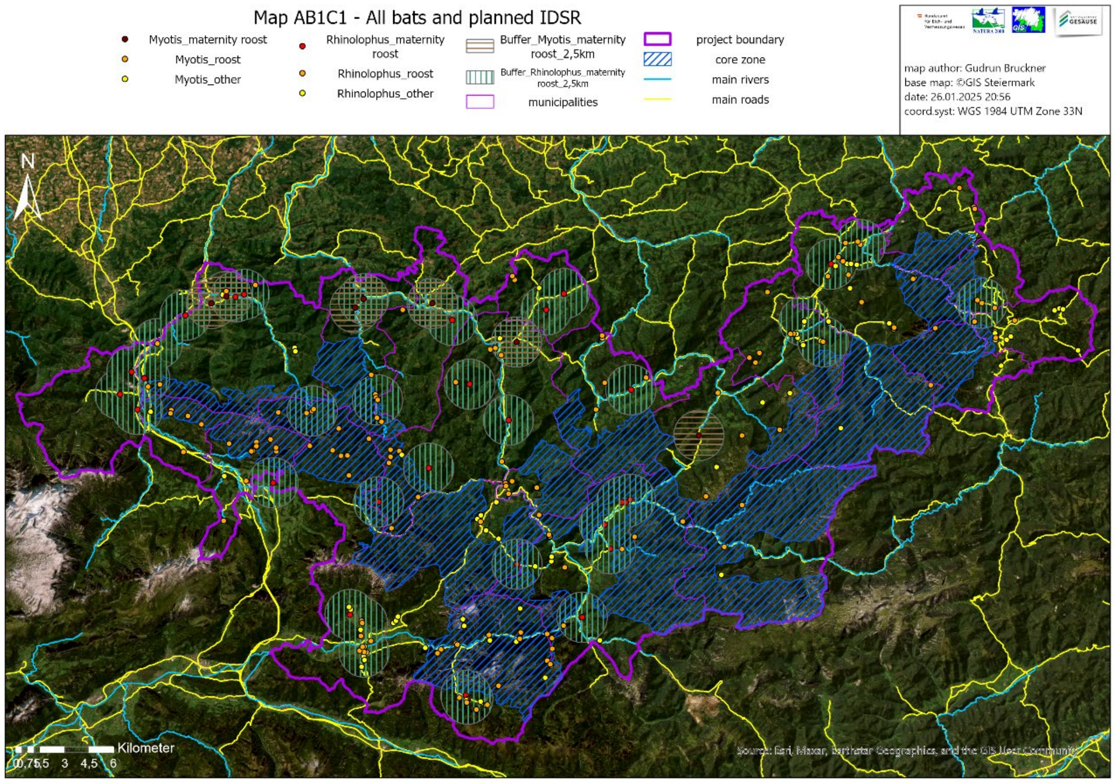


Figure 22: Map AB1C1 - All bats and planned IDSR

Map AB1C1 (figure 22) shows the *Myotis* and *Rhinolophus* distribution data in relation to the zoning of the planned IDSR.

4.5 Light pollution data

The aim was to create a map visualizing the darkness quality of the project area and identifying light pollution hot spots and dark refuges. As discussed and recommended in several studies, the aim was to combine satellite data with on-ground measurements to minimize sampling biases and other monitoring limitations (Hölker *et al.*, 2021; Wallner, Puschnig and Stidl, 2023).

Satellite data (VIIRS 2022)

Satellite data from VIIRS 2022 can be accessed open source on lightpollutionmap.org and was downloaded as TIFF. The VIIRS data is displayed in Map AB1D1D2 and Map AB1D1D3. Falchi et al. have created a model to calculate light pollution values for the whole world called the World Atlas of light pollution (Falchi *et al.*, 2016). Their data is shown in Map AB1D5 (figure 23).

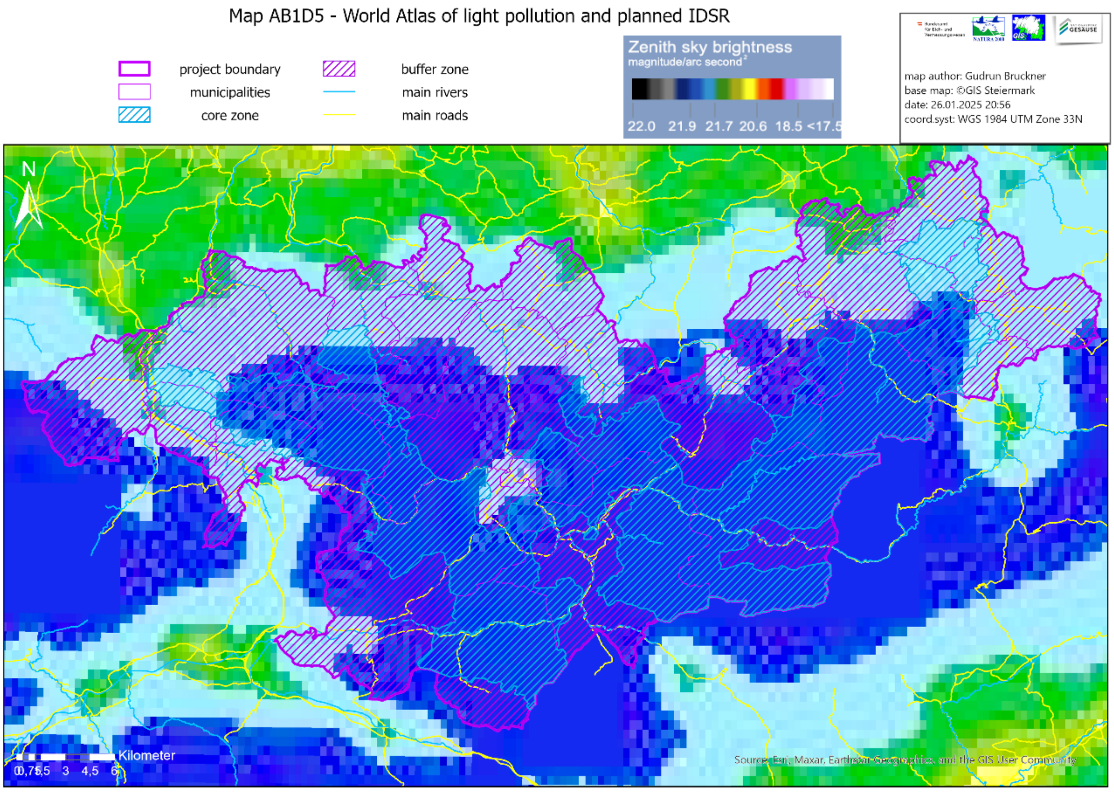


Figure 23: Map AB1D5 - World Atlas of light pollution and planned IDSR

On-ground measurements

To gather detailed on-ground data about night sky brightness a mobile sky quality meter (SQM) was mounted on the roof of a car. While driving along the predefined routes the SQM was measuring zenithal night sky brightness in mag/arcsec². The measurements can start two hours after sunset and must finish two hours before sunrise. New moon and a clear night without overcast are necessary preconditions (Puschnig *et al.*, 2022). With this data a linear layer can be created out of single measuring points giving information about the in-situ night sky of the area. Measuring drives were conducted on 10./11.09.2023, 15./16.09.2023, 17./18.09.2023 and 04./05.11.2024. However, due to the dense forests in the project area the collected data needs to be regarded carefully since surface albedo and vegetation have been described for causing the largest impact on the zenithal night sky brightness (Puschnig *et al.*, 2022). Therefore, large sequences of the data show this measuring error. Map AB1D1D3 (figure 24) shows all captured values starting from 21,0 mag/arcsec². Nevertheless, these NSB-values might still be impacted by vegetation albedo. Comparing it with the NSB-values measured at the All-sky measuring points (Map AB1D1D2), the impression of the NSB is different for each method, although both measured with an SQM. A reason might be that the All-sky photos are usually taken at open spaces where surface albedo does not play a big role. Therefore, it can be assumed for the roadrunner measurements that high values (yellow and green) are indicating good NSB quality, but low values (red) must be regarded carefully as they might be just a result of vegetation albedo.

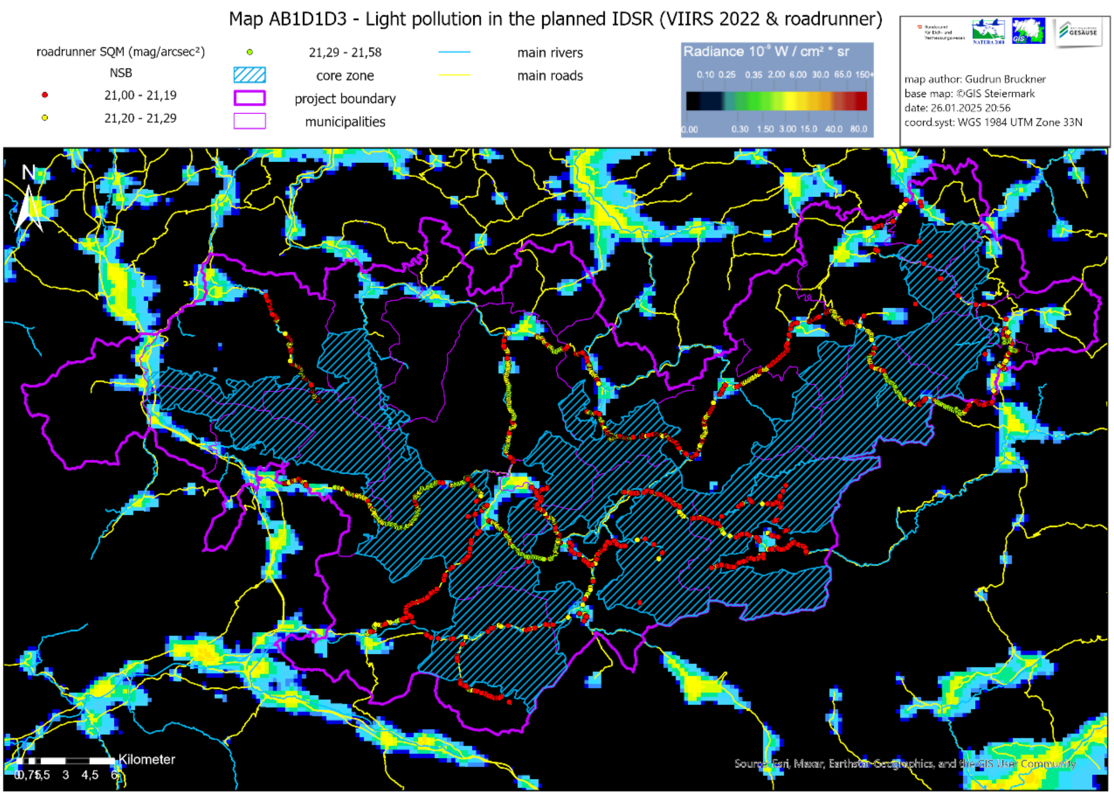


Figure 24: Map AB1D1D3 - Light pollution in the planned IDSR (VIIRS 2022 & roadrunner)

To document edge effects like sky glow from far-away cities, sky quality camera (SQC) pictures were taken on selected spots in the target area on the same days when the mobile SQM measurements took place. For the pictures a Canon EOS 6D Mark II camera with an 8mm sigma fisheye objective was used. Standard settings for the SQC photos are ISO 16000, an open aperture (f/3,5) and an exposure time of 1,5 – 2 minutes. To interpret the photos the SQC software is used, calculating a brightness value per pixel. The result for the village Gstatterboden is shown in figure 26, offering information on the sky brightness and CCT depending on the zenith-angle. A larger angle correlates with increased sky brightness, indicating glare or sky glow. The locations of the measuring points of the SQC are shown in Map ABD1D2 (figure 25) as well as the zenithal night-sky brightness in magnitudes per square arcsecond (mag/arcsec²) measured there. Red pinpoints have measured no sufficient night sky brightness quality regarding the IDSR standards for a core zone. Yellow pinpoints reach the threshold of 21,2 mag/arcsec² for the IDSR core zone. According to a recent study conducted in the French Pyrenees on Rhinolophus and Myotis bats (Sordello *et al.*, 2022), the best darkness quality class starts above 21.3 mag/wearcsec² (indicated with green pinpoints).

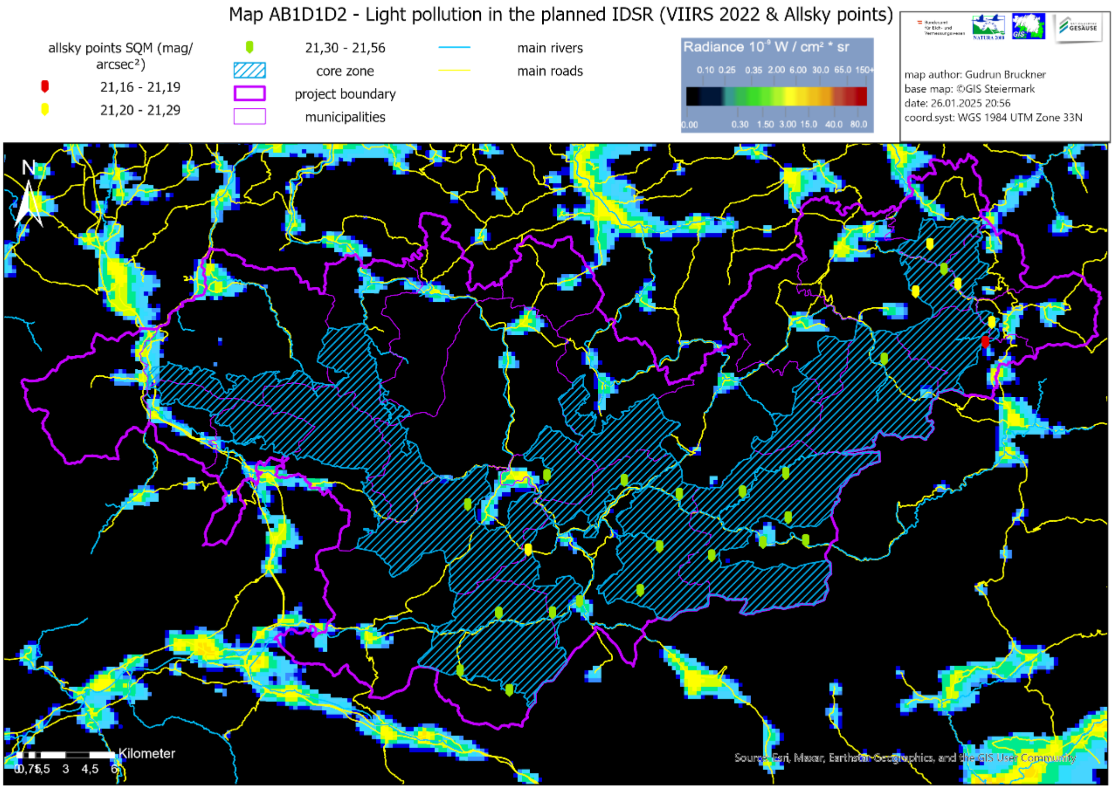


Figure 25: Map AB1D1D2 - Light pollution in the planned IDSR (VIIRS 2022 & All-sky points)

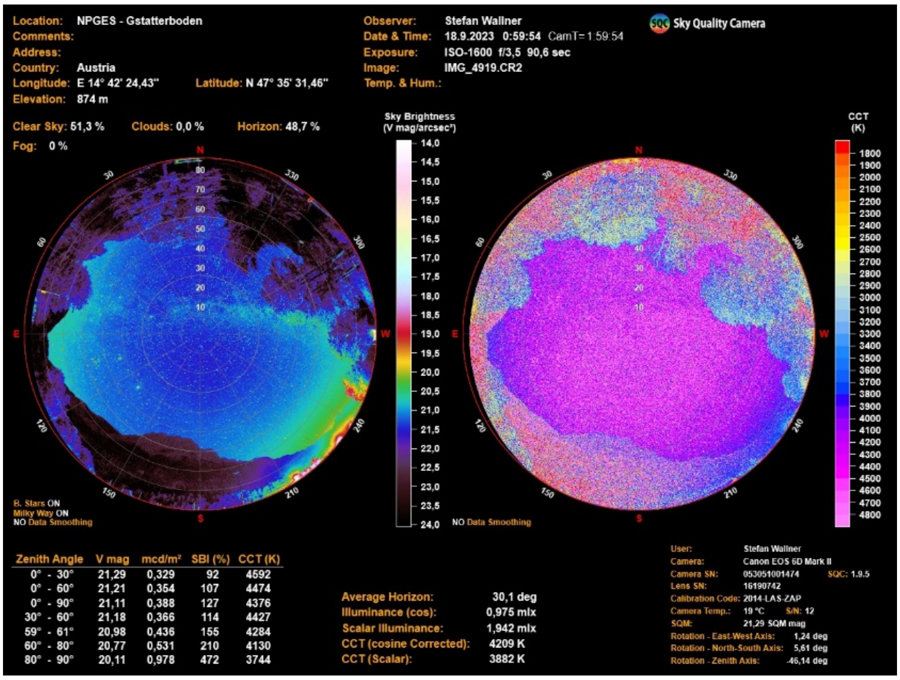


Figure 26: SQC result for Gstatterboden

Furthermore, especially for long-term monitoring, permanent photometers are stationed in the target area. Meanwhile TESS-W devices are preferred to the original SQMs because they provide an open-source automatic evaluation through the Grafana- website. Moreover, TESS devices capture the full visible light spectrum in contrast the SQM has weaknesses capturing higher wavelengths (Wallner, 2020). The locations of the SQC images and the permanent photometers are summarized in Map AB1D1D4 (figure 27).

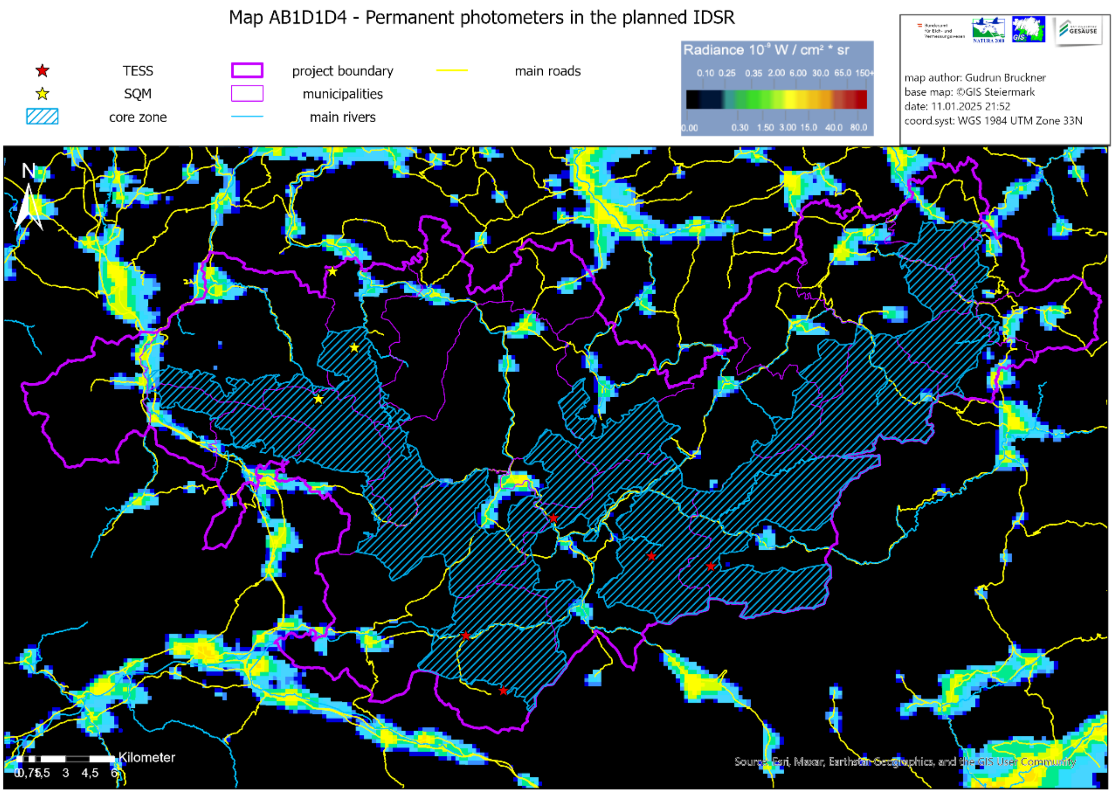


Figure 27: Map AB1D1D4 - Permanent photometers in the planned IDSR

4.6 Landscape data

To incorporate habitat requirements of the target species into the GIS maps, the Corine Land Cover dataset was utilized, with geographic data sourced from data.gv.at on June, 13th 2024. CORINE provides a standardized classification of land cover forms based on satellite imagery. It was used to analyse potential foraging habitats within the target area for specific bat species. Literature sources, such as the handbook of bats (Dietz, Nill and von Helversen, 2016), the Swiss and the Austrian coordination office for bat conservation, and the Biodiversity Information System for Europe (BISE) were reviewed to summarize preferred foraging habitats and key pressures influencing habitat suitability. Based on this information, land cover types were categorized in six foraging habitat suitability classes: no foraging habitat, very little, little, fair, good and very good. Water bodies were also indicated as such. In table 7 the CLC types are listed and the colour scheme for the foraging habitat suitability classes (table 8) was applied.

Table 7: CORINE land cover types with the foraging habitat suitability indication

CLC types indicating foraging habitat suitability	
1.1.1. Continuous urban fabric	2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation
1.1.2. Discontinuous urban fabric	2.4.4. Agro-forestry areas
1.2.1. Industrial or commercial units	3.1.1. Broad-leaved forest
1.2.2. Road and rail networks and associated land	3.1.2. Coniferous forest
1.2.3. Port areas	3.1.3. Mixed forest
1.2.4. Airports	3.2.1. Natural grassland
1.3.1. Mineral extraction sites	3.2.2. Moors and heathland
1.3.2. Dump sites	3.2.4. Transitional woodland shrub
1.3.3. Construction sites	3.3.1. Beaches, dunes, and sand plains
1.4.1. Green urban areas	3.3.2. Bare rock
1.4.2. Sport and leisure facilities	3.3.3. Sparsely vegetated areas
2.1.1. Non-irrigated arable land	3.3.5. Glaciers and perpetual snow
2.2.1. Vineyards	4.1.1. Inland marshes
2.2.2. Fruit trees and berry plantations	4.1.2. Peatbogs
2.3.1. Pastures	5.1.1. Water courses
2.4.2. Complex cultivation patterns	5.1.2. Water bodies

Rhinolophus species typically forage in forests with dense undergrowth, especially deciduous or mixed forests (Dietz, Nill and von Helversen, 2016). Forest edges and riparian zones near rivers are preferred foraging grounds because these areas provide rich insect prey, particularly aquatic insects emerging near water bodies (Russo and Jones, 2003). These bats avoid intensive agricultural areas and urban environments due to lack of prey and high levels of disturbance (O'Mara *et al.*, 2021).

Myotis species are generally forest-bats (except *Myotis blythii*), with many species showing a preference for extensive forests with structural diversity, which provides both foraging habitats and roosting sites in tree cavities or under bark (Dietz, Nill and von Helversen, 2016). *Myotis* species, like *Myotis daubentonii*, are frequently observed foraging near water bodies, as these habitats support abundant populations of aquatic insects, a primary food source (Dietz, Nill and von Helversen, 2016). Extensive agricultural areas with hedgerows, small woods, and patches of natural vegetation can support *Myotis* species if insect abundance is sufficient and roosting options (e.g., barns, trees) are available (Downs and Racey, 2006). *Myotis* species typically avoid highly urbanized areas and intensively farmed monocultures due to a combination of factors:

reduced prey availability, light pollution, and a lack of roosting sites (Biodiversity Information System for Europe, no date)

To summarize, both genera forage in forests and woodlands, preferred mixed and broadleaf forests, wetlands, and rural landscapes with diverse structures like orchards, extensive farms, hedgerows, meadows, pastures and other mosaic landscapes. *Rhinolophus* as well as *Myotis* species tend to avoid intensive agricultural land, urban areas, and treeless landscapes due to habitat fragmentation, disturbance, and decreased prey availability.

Table 8: foraging habitat suitability classes

For Map AB1C1E2 (figure 28) the defined foraging habitat suitability classification (table 8) was used to group CLC types according to these criteria. The map shows that the project area offers abundant good and very good foraging habitats.

foraging habitat suitability classes
no foraging
very little
little
fair
good
very good
water

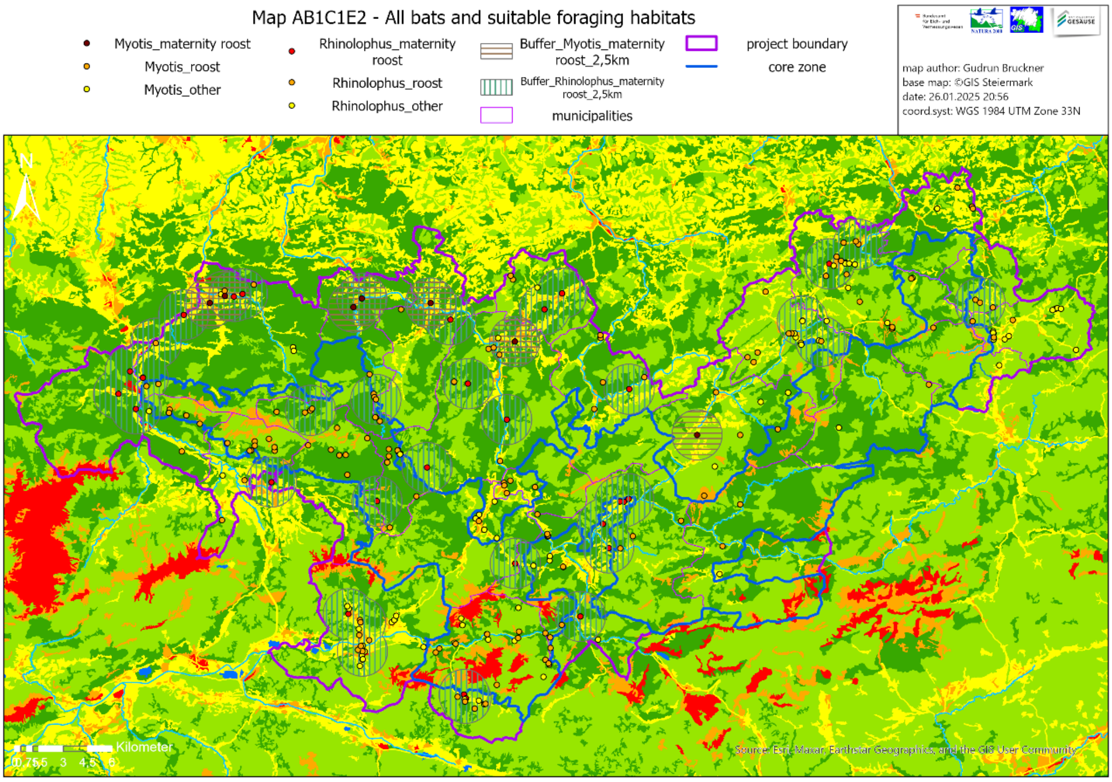


Figure 28: Map AB1C1E2 – All bats and suitable foraging habitats

4.7 Overview of GIS layers and maps

To gain new insights on the bat distribution in relation to light pollution and other landscape parameters several GIS layers were developed and overlaid in different maps. All layers and maps were created with Esri ArcGIS Pro (2023), version 3.2.0, based on three data sources:

1. project-related data ('Naturnachtgebiet Eisenwurzen, Dark Sky Reserve Application', 2025)
2. bat data provided by KFFÖ
3. open-source data (data.gv.at)

Table 9 presents an overview of all layers and information which is displayed in every layer. The maps are listed in table 10. The ID of a map indicates which layers are included. Through this geospatial visualization of light pollution data with geographic and ecological data sensitive areas can be detected and urgent-to-act-places can be identified.

Table 9: Overview of all layers

Layer code	Group layer	Layer
A	basic information	project boundary
		municipalities
		main rivers
		main roads
		province borders
B1	protected areas (PAs)	planned IDSR
B2		strict PAs
B3		nature parks
B4		natura 2000 sites
C1	bats	all bats
C2		maternity roosts
D1	light pollution	VIIRS 20222
D2		all-sky points SQM
D3		roadrunner SQM
D4		permanent photometers
D5		World Atlas
E1	land cover	CORINE Land Cover
E2		foraging habitat suitability
E3		human settlements
F	levels of intervention	Level A
		Level B
		Level C

Table 10: Maps developed from the layers listed in table 09

name	map ID
Basic information	Map A
Overview of project area incl. project partners	Map AB2B3
Zonation of the planned IDSR	Map AB1
Natura 2000 areas	Map AB1B4
All bats and planned IDSR	Map AB1C1
Maternity roosts and light pollution	Map AB1C2D1
Maternity roosts and suitable foraging habitats	Map AB1C2E2
Maternity roosts and human settlements	Map AB1C2E3
All bats and suitable foraging habitats	Map AB1C1E2
Light pollution in the planned IDSR (VIIRS 2022 & Allsky points)	Map AB1D1D2
Light pollution in the planned IDSR (VIIRS 2022 & roadrunner)	Map AB1D1D3
Permanent photometers in the IDSR	Map AB1D1D4
World Atlas of light pollution and planned IDSR	Map AB1D5
Levels of intervention	Map AF

5 Analysis and findings

To test the hypothesis stated above, that the zoning of the planned IDSR is sufficiently protecting nocturnal biodiversity, light-averse bat genera were selected as indicator species based on the procedure developed by Zschorn. Therefore, the research questions were reformulated to practically test them using bats as indicators.

As a result of the GIS-generated maps and overlays following tables could be generated (table 11, 12, 13) to analyse the situation in the target area.

5.1 Q1: Can the proposed core zone of the target area sufficiently protect nocturnal biodiversity?

Can the proposed core zone of the target area sufficiently protect bat habitats (*Myotis* and *Rhinolophus* species) in terms of light pollution?

5.1.1 *Myotis and Rhinolophus records distribution between core and buffer zone*

Table 11: bat records inside and outside of the core zone

	all (counts)	core zone	outside	% in core zone	% outside
Myotis	575	302	273	52,52	47,48
maternity roost	7	0	7	0,00	100,00
roost	279	153	126	54,84	45,16
other	289	149	140	51,56	48,44
Rhinolophus	179	76	103	42,46	57,54
maternity roost	40	4	36	10,00	90,00
roost	119	63	56	52,94	47,06
other	20	9	11	45,00	55,00

This table was generated from the data of Map AB1C1 (figure 22).

For *Myotis* species, a total of 575 records was counted, with 52,52% found in the planned core zone. In contrast, *Rhinolophus* species had 179 records, with only 42,46% in the core zone. Maternity roosts for *Myotis* are entirely outside the core zone, while 10,00% of *Rhinolophus* maternity roosts are in core zone. Overall, other roosts and other records showed a more balanced distribution, indicating potential habitat preferences inside and outside the core zone.

5.1.2 *Distribution of maternity roosts and proximity of potential threats*

Map AB1C2D1 shows the radiance (in Nanowatts per surface) from VIIRS 2022 satellite data and the recorded maternity roosts of the project area. Especially in the north and in the northwest of the project area maternity roosts seem to be more exposed to light pollution.

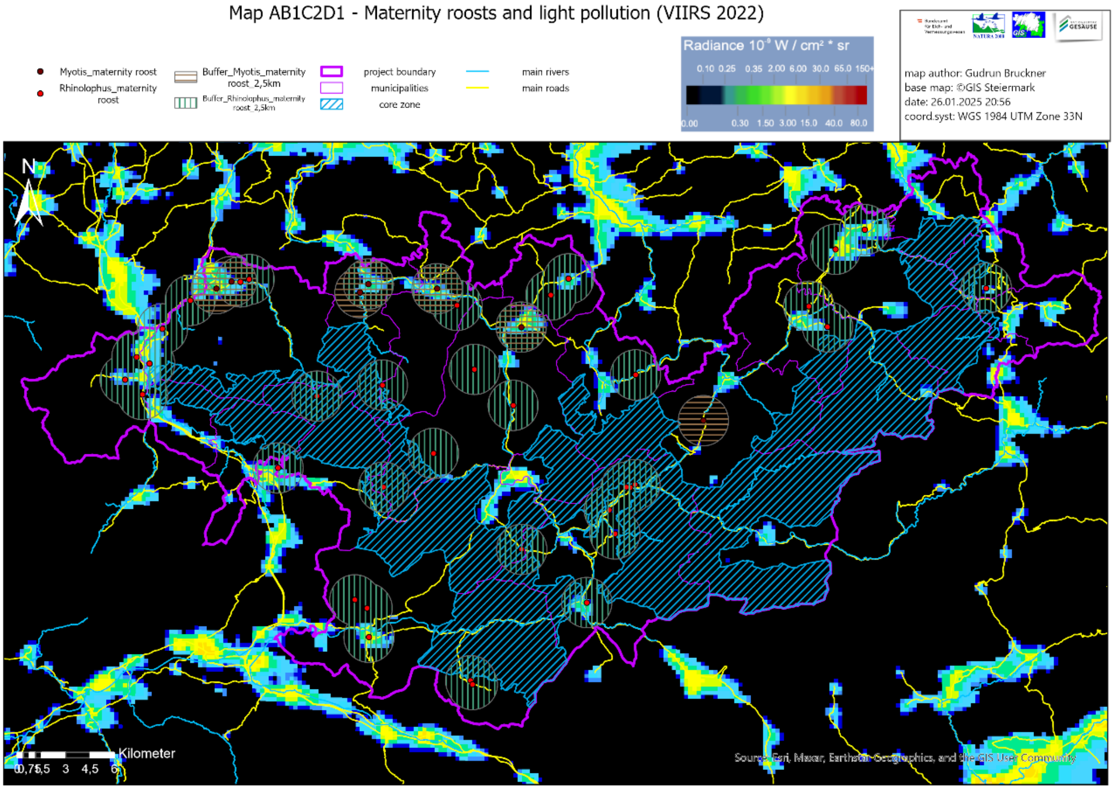


Figure 29: Map AB1C2D1 - Maternity roosts and light pollution (VIIRS 2022)

Literature suggests that human settlements and traffic is a threat to bats (Voigt and Kingston, 2016). Maternity roosts and their surroundings are especially sensitive. Map AB1C2E3 (figure

30) shows the recorded maternity roosts of the project area highlighting human settlements in pink and main roads in yellow.

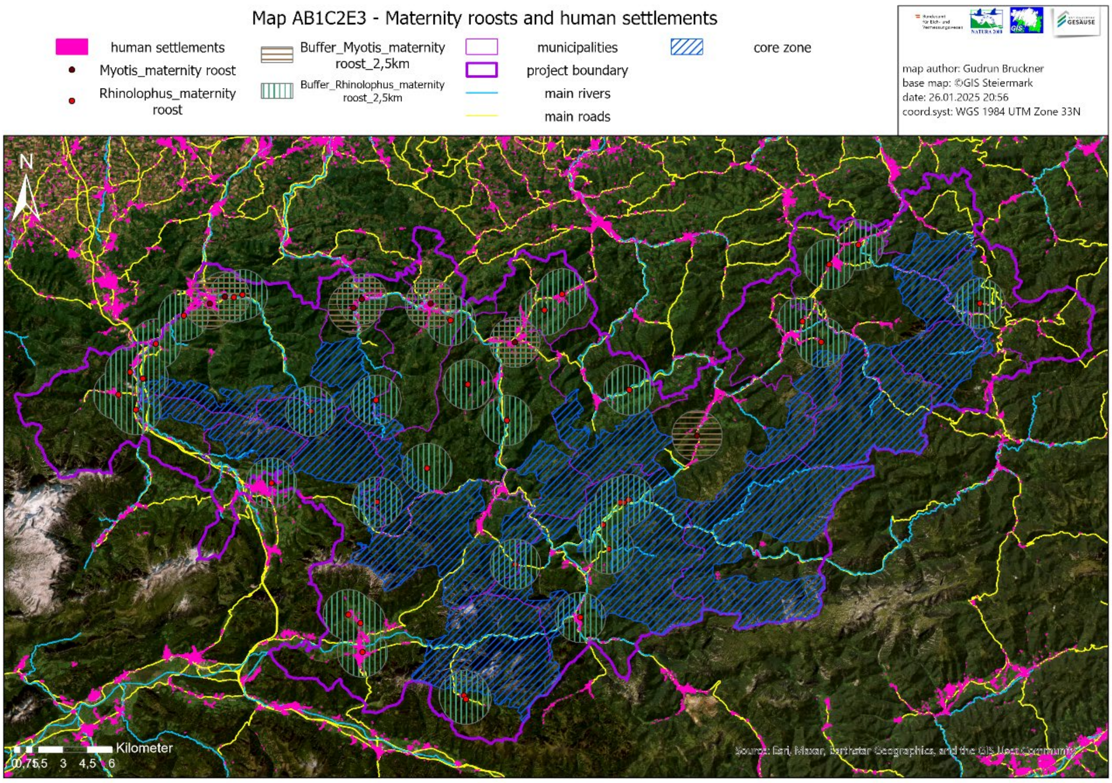


Figure 30: Map AB1C2E3 - Maternity roosts and human settlements (pink); also displaying main roads (yellow) as potential threat

Table 12: Maternity roosts and proximity of potential threats

	Myotis	%	*Rhinolophus*	%	all	%
total no. of maternity roosts	7		40		47	
inside core zone	0	0,00	4	10,00	4	8,51
light pollution - direct	6	85,71	16	40,00	22	46,81
light pollution - within 2,5km	6	85,71	26	65,00	32	68,09
settlement - direct	6	85,71	14	35,00	20	42,55
settlement - within 2,5km	7	100,00	31	77,50	38	80,85
main road - within 2,5km	7	100,00	35	87,50	42	89,36

The results in table 12 and table 13 were generated from MapAB1C2D (vicinity of light pollution) and Map AB1C2E3 (vicinity of roads and settlements). It provides insights into how maternity roosts of *Myotis* and *Rhinolophus* species are influenced by certain environmental conditions. None of the *Myotis* roosts (0%) are located inside the planned core zone, whereas 10% of the *Rhinolophus* roosts are situated within the core zone. Overall, 8,51% (4 out of 47) of all maternity roosts are within the core zone. Direct light pollution affects 85,71% of *Myotis* roosts (6 out of

7) and 40% of *Rhinolophus* roosts (16 out of 40). On average, 46,81% of all maternity roosts are exposed to direct light pollution. Within a 2,5 km radius, 85,71% of *Myotis* roosts and 65% of *Rhinolophus* roosts are affected by light pollution. Across both species, 68,09% of maternity roosts are subject to light pollution within this distance.

85,71% of *Myotis* roosts and 35% of *Rhinolophus* roosts are directly located near settlements, with 42,55% of all maternity roosts overall found near settlements. Within a 2,5 km radius, 100% of *Myotis* roosts and 77,5% of *Rhinolophus* roosts are within proximity to settlements. This represents 80,85% of all roosts being within this radius. All *Myotis* roosts (100%) and 87,5% of *Rhinolophus* roosts are located within 2,5 km of a main road, with 89,36% of all maternity roosts falling within this distance.

Table 13: Comparison of possible threats to maternity roosts inside and outside of the core zone

	inside core zone	%	outside core zone	%
***Myotis* sp.**	0		7	
light pollution - direct	0	0,00	6	85,71
light pollution - within 2,5km	0	0,00	6	85,71
settlement - direct	0	0,00	6	85,71
settlement - within 2,5km	0	0,00	7	100,00
main road - within 2,5km	0	0,00	7	100,00
***Rhinolophus* sp.**	4		36	
light pollution - direct	0	0,00	16	44,44
light pollution - within 2,5km	0	0,00	26	72,22
settlement - direct	0	0,00	14	38,89
settlement - within 2,5km	2	50,00	29	80,56
main road - within 2,5km	3	75,00	32	88,89

None of the *Myotis* maternity roosts are located inside the core zone, while all 7 roosts are found outside. 85,71% of the *Myotis* roosts outside the core zone are directly impacted by light pollution as well as within a 2,5 km radius. Alike, 85,71% of roosts are in direct influence of settlements. All *Myotis* roosts are located within 2,5 km of a main road and of a human settlement.

10% (4 out of 40) of *Rhinolophus* roosts are located inside the core zone, while 90% (36 out of 40) are outside. None of roosts inside the core zone is exposed to direct light pollution, compared to 44,44% outside. Within a radius of 2,5 km, 77,42% of roosts outside the core zone are impacted by light pollution, while still 0% inside are. None of roosts inside the core zone is directly near settlements, versus 38,89% outside. 50% of roosts inside and 80,56% outside of the core zone have human settlements within a radius of 2,5km. A majority of *Rhinolophus* roosts, both inside (75%) and outside (88,89%) the core zone, are located within 2,5 km of a main road.

5.1.3 Key findings

- Only **1/10 of** the recorded **maternity roosts** are **inside** the planned core zone.
- **Other roosts and other records** do **not** have a **significant** majority in- or outside of the planned core zone.
- Almost **half of** all **maternity roosts** are **directly impacted by light pollution** (46,81%) and are 2/3 impacted within a radius of 2,5km (68,09%)
- **80 to 90% of all maternity roosts** have **human settlement and main roads** at least within a 2,5km radius.
- **All *Myotis* maternity roosts** are located **outside** the planned core zone. Therefore, it is very likely that these roosts are in proximity of light pollution, settlements and main roads. (85,71-100%)
- ***Rhinolophus* maternity roosts within** the **core zone** are **not at all impacted** by **light pollution.**
- The percentage of *Rhinolophus* maternity roosts in proximity to human settlements is higher outside of the core zone.
- Main roads have an influence on *Rhinolophus* maternity roosts inside and outside the planned core zone.

5.2 Q2: What needs to be done to ensure a well-connected dark and natural landscape in the whole target area?

How and where can light pollution be effectively reduced or prevented in *Myotis* and *Rhinolophus* habitats in the project area?

The core zone was selected taking darkness quality, protected areas and human infrastructure into account. Moreover, looking at MapAB1C1E2 (figure 28) it provides mainly very good and good foraging habitats, except for a few high mountain ranges. Following the guidelines for IDSR of DarkSky International the core zone should fulfil following nighttime conditions: "A) The Milky Way is readily visible to the unaided eye; B) There are no nearby artificial light sources yielding significant glare; and C) Any light domes present are dim, restricted in extent, and close to the horizon. These conditions correspond approximately to a visual-band zenith luminance of 21.2 magnitudes per square arcsecond (0.4 mcd/m²) and a naked-eye limiting magnitude (NELM) of +6." (DarkSky International, 2023).

Furthermore, the core zone should be buffered through a peripheral zone around it, where light pollution should be managed and mitigated through a Lighting Management Plan (LMP) to not spill in the core zone. (DarkSky International, 2023). The findings from Q1 show that *Myotis* and *Rhinolophus* need more places to be protected, not only the core zone to sustain their populations. Especially the maternity roosts, which count as very sensitive, are mostly in the peripheral zone. In the following paragraphs several methods which could lead to better protection are investigated.

5.2.1 Option 1: Enlarge the core zone and include all most sensitive places in the core zone

The first strategic option would be to include at least the most light-sensitive areas within the IDSR core zone. Under this protection status, these areas would receive special attention, ensuring a mean brightness limit of 21,2 mag/arcsec² during a clear new-moon night, in accordance with DarkSky International program guidelines (DarkSky International, 2023). Since many maternity roosts are recorded, ideally, all of them should be protected. For other known roosts the importance should be evaluated and eventually also included in the core zone. It would be a balancing act to fulfil core zone criteria and reasonably include important bat roosts. Including all known maternity roosts into the planned core zone, might be an unsolvable conflict, due to the strict requirements for the IDSR core zone. An exception could be made for two roosts, which are located very close to the core zone boundary, where the area fulfils the criteria for the IDSR core zone and could potentially be included. One of these two roosts was recorded in 2010 on the southern border of the Gesäuse National Park, located in a building, identified only as a possible maternity roost. The second site was recorded in 2022 in Upper Austria, within a hospitality building. Both roosts are identified as a roost of *Rhinolophus hipposideros*.

The IDSR program guidelines state that "*if the core includes a publicly protected area, such as a national or regional park, it must strive to fully encompass the boundaries of that area*." (DarkSky International, 2023). Therefore, aberration of these borders has to be justified adequately.

5.2.2 Option 2: Protect dark corridors between roosts and core zone, assuming there are the best foraging habitats

In modern nature conservation, it has become standard practice to protect and connect habitats establishing natural corridors. It is a holistic approach to ensure the self-sustaining of populations and ecosystems in the long-term (Hilty *et al.*, 2020).

The core zone of the planned IDSR is characterized by a highly natural environment, with minimal human impact and extensive forests. Two national parks and a wilderness area already provide strict protection to large portions of this core zone. Therefore, it is likely that the core zone offers excellent foraging grounds for the selected bat species. Establishing dark corridors that link their maternity roosts to the core zone could be a viable option, ensuring that at least the transfer to their foraging ground sustains a certain darkness quality until they reach the strictly protected core zone.

Bats require high-quality foraging habitats within a certain proximity from their roosts. Depending on the species and region, suitable foraging grounds need to be within a certain distance from the roost (table 1 chapter 3.2.3). For instance, Reiter et al. recommend that conservation efforts for *Rhinolophus hipposideros* focus on protecting an area within 2,5 km of their maternity roosts, as this is regarded as a preferred foraging range (Reiter *et al.*, 2013). In the target area, *Rhinolophus* roosts have an average distance of 3,18 km from the core zone, while *Myotis* roosts are located at an average distance of 5,90 km. Table 14 shows the distribution of maternity roosts in a certain distance to the core zone.

Table 14: distance from maternity roosts to the core zone

distance to the core zone	no. of maternity roosts
inside	4
< 2,5km	18
2,5 - 5km	10
> 5km	15

Table 15: foraging habitat suitability classes

foraging habitat suitability classes
no foraging
very little
little
fair
good
very good
water

Looking at the distribution and the average distance to the core zone, it can be assumed that not all nursing colonies use foraging grounds inside the planned core zone. However, looking at MapAB1C2E2 (figure 31) it shows that especially northwest in the target area, where maternity roosts are the furthest away from the core zone, bats might find good foraging spots in near proximity and do not need to transfer to the core zone.

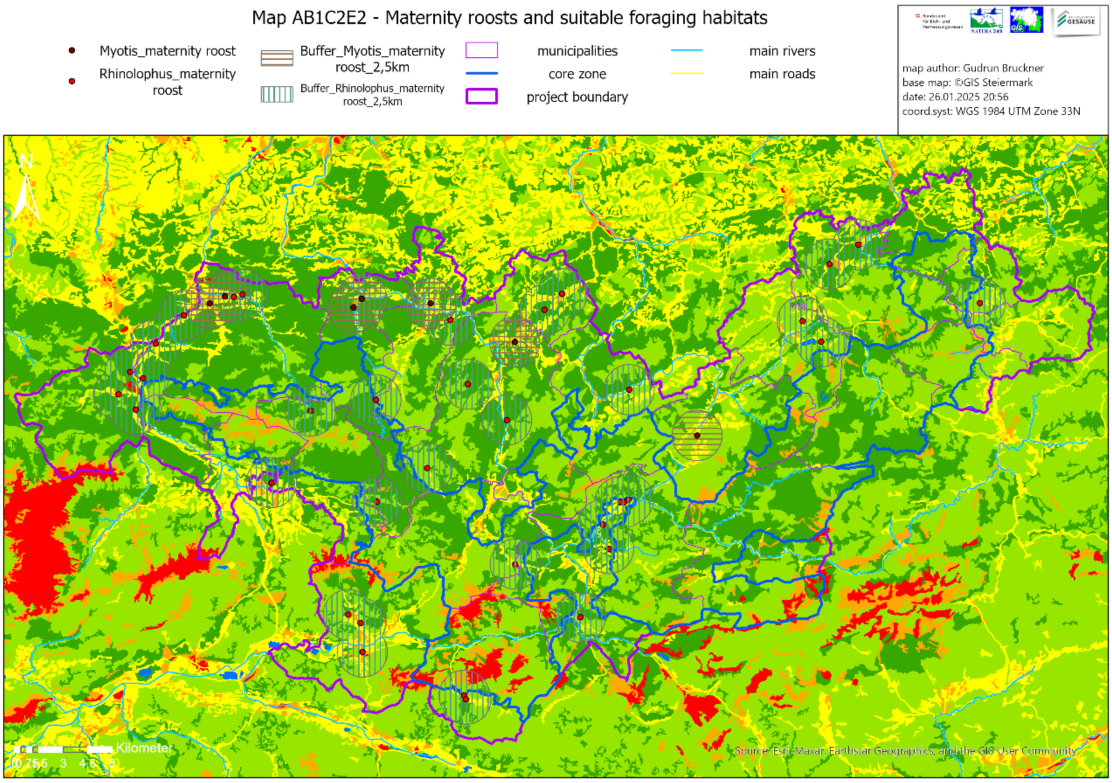


Figure 31: Map AB1C2E2 - Maternity roosts and foraging habitat suitability

5.2.3 Option 3: Coercive application of the ÖNORM O 1052 within the Lighting Management Plan

As stated above, for the peripheral zone an LMP is required. Austrian Standards International has published already the third version of the ÖNORM O 1052 (Light immissions - measurement and assessment) in 2022, which could become the basis for the LMP (ÖNORM O 1052: Lichtimmissionen - Messung und Beurteilung, 2022). This well-elaborated norm groups land use practices in six categories. For each category certain lighting standards are recommended. The categories are described in table 16. In a next step these standards were compared with the Guidelines for consideration of bats in lighting projects (Voigt, Azam and Dekker, 2018)

Table 16: Overview of the land use categories of ÖNORM O 1052 and the related frame conditions for outdoor lighting

Category	Land use practice	Lighting standards			
		Time	max. CCT	Direction max. ULR	Quantity
S	legally designated areas for the protection of nature	No direct outdoor lighting			0,25 lx [a]
G	areas not designated for development such as grassland or recreation areas	No direct outdoor lighting			0,25 lx [a]
A	settled area with sensible objects, e.g. hospitals	06:00-22:00	2700 K	2,5%	1 lx [b]
B	mainly residential areas	06:00-22:00	2700 K	2,5%	1 lx [b]
C	mixed area with stores, apartments, shopping streets	06:00-22:00	3000 K	5%	1 lx [b]
D	commercial and industrial areas	06:00-24:00	4000 K	15%	5 lx [b]
	street lighting and traffic safety lighting in public areas	/	depending on the land use category of the location of the streetlight		3-25 lx [c]
Bats [d]	feeding and commuting areas	Adapt to dawn and dusk; attention on maternity roosts	<2700 K	No light above horizontal	0,1 lx [e]
	roosts	Should not be illuminated at all			

[a] ÖNORM O 1052 does not directly indicate an intensity level for category S and G; In chapter 7 is stated: "nature conservation-sensitive habitats" (e.g. biotope mapping, bodies of water) may not be brightened by more than 0,25 lx by artificial lighting.

[b] Maximum permissible, average vertical illuminance at the window level between 22:00 and 06:00; room brightening due to traffic safety lighting not considered (ÖNORM table 4)

[c] depending on the luminous density L_{ave} on the roadway

[d] thresholds taken from Eurobats Guidelines No.8 (Voigt, Azam and Dekker, 2018)

[e] avoidance of 0,1 lx light trespass on surrounding surfaces from a light emitting object

Category S and Category G generally do not allow artificial light sources' emissions. Exceptions can only be made for compulsory safety standards. In Categories A, B, C and D light emissions and immissions are restricted according to different limits for time, CCT, direction and intensity.

Time

Time restrictions can be an effective solution to reduce light pollution throughout the night. However, for bats, the period two hours before sunrise and after sunset is particularly important due to peak insect availability (Voigt, Azam and Dekker, 2018). Therefore, outdoor lighting should ideally be turned off in alignment with the bats' activity peaks. The French guidelines for dark infrastructure even state that the effectiveness of measures depends above all on the time slot during which the lights are switched off (Sordello, Paquier and Daloz, 2021). Therefore, outdoor lights should be turned on only one hour before sunrise and turned off one hour after sunset, to serve nocturnal and crepuscular species.

Moreover, activity patterns of species change throughout the year. For bats the nursing season in early summer and the swarming or mating season in autumn are very important. Therefore, from spring to autumn special attention should be given to outdoor lighting schedules.

The current ÖNORM standards do not account for these seasonal variations, making them less suitable. Wallner has proposed an amendment to the ÖNORM for nature parks, suggesting that instead of adhering to fixed schedules, lighting should follow the seasonal patterns of sunrise and sunset (Wallner, 2024). This approach is also recommended by Voigt and colleagues in the Eurobats guidelines No.8 (Voigt, Azam and Dekker, 2018). Consequently, timing for lighting in categories A to D should be managed consciously.

CCT and light spectra

Category C and D of the ÖNORM O1052 do not fulfil the spectral recommended maxima for foraging and commuting sites. Eurobats recommends only warm colours below 2700K in these habitats. Some researchers even tend to suggest even lower colour temperatures with a maximum of 2000-2200K (Krop-Benesch, 2018; Zschorn and Fritze, 2022).

Direction

The ÖNORM O 1052 states that the maximum luminous intensity should be within the ideal angle of 70°, to avoid impacts on wildlife and glare of humans. However, the use of "fully shielded" or "full-cut-off" luminaires is not concretely mentioned.

A fully shielded light fixture is designed so that the light source is completely concealed, and all emitted light is directed in a way that no light escapes above the horizontal plane that intersects the lowest light-emitting part of the fixture (DarkSky International, 2023). The Upward Light Ratio (ULR) of a fully shielded luminaire should be 0%. As summarized in table 16 the ÖNORM O 1052 allows an URL up to 15% depending on the category of land use practices. PAs and other near natural lands should not be impacted through any ULR.

Voigt et al. recommend using fully shielded fixtures which emit no light above 90°. Moreover, it is stated that special attention should be given to light trespass and reflecting surfaces creating more illumination (Voigt, Azam and Dekker, 2018).

Quantity

Voigt et al. state that it might not be possible to define an illuminance threshold which complies both with bat conservation and safety standards (Voigt, Azam and Dekker, 2018). There are even studies indicating that some bats reduce their foraging activity during full-moon nights, which have an approximate illuminance of 0,1 lx (Saldaña-Vázquez and Munguía-Rosas, 2013). Habitats with special conservation value (e.g. mapped biotopes, water bodies) should not be illuminated above 0,25 lx according to the ÖNORM O 1052, which would be already too bright for some bats ('ÖNORM O 1052: Lichtimmissionen - Messung und Beurteilung', 2022). However, European safety standards according to EN 13201 for pedestrian pathways and low-traffic roads recommend a minimum of 7,7 to 10 lx and for others even higher (Voigt, Azam and Dekker, 2018).

Consideration of nature and environment in the ÖNORM O 1052

The ÖNORM O 1052 designates one paragraph to the "Illumination of nature and environment". Thresholds should be defined in accordance with the target species or habitat. Areas of special conservation value should not be illuminated above 0,25 lx. Illumination of sleeping or breeding locations of wildlife must be avoided at all. Luminaires with dense closures should hinder insects from entering and its maximum surface temperature should not increase 60°C.

Moreover, the ÖNORM O1052 has an attached Annex A, which elaborates possible measures to reduce the disturbance of nature through ALAN. There several very important points are made but kept very general. To reduce light immissions, the general need and the maximal necessary intensity of lighting should be carefully checked. Light should only be directed at the required areas and controlled by shields or reflectors, ideally with a top-down direction. Low wavelength light sources should be avoided, and low mounting heights are favoured, while the lighting duration should be limited with motion sensors or timers ('ÖNORM O 1052: Lichtimmissionen - Messung und Beurteilung', 2022).

The recommendations listed in Annex A are coherent with the five principles for responsible outdoor lighting jointly developed by DarkSky International and Illuminating Engineering Society. A detailed exploration of these principles is made in chapter 7 – management recommendations.

5.2.4 Option 4: Light pollution protection measures from a bat's perspective

An effective method to protecting bats would be to implement practical measures that directly combat light pollution where it is either proven or assumed that bats have sensible habitats. The aim is to follow a hierarchical approach starting with the strictest measures in the immediate surrounding of maternity roosts and gradually extend these measures throughout the entire area of influence, adapting them to different sensitivity levels (figure 32). For example, areas closer to roosts would have stricter measures, while zones farther away could implement less stringent measures but still contribute to an overall darker environment. A precondition for this hierarchical approach is available data and literature on the target species and a good knowledge of the lighting situation. The following levels of sensitivity are proposed for light-averse bat species.

Figure 32: bats habitats and sensitivity to ALAN

Most sensitive

- **Maternity roosts:** These are considered the most sensitive locations for bat populations as they are crucial for the survival and reproduction of bat communities (Dietz, Nill and von Helversen, 2016; Voigt *et al.*, 2021).
- **Other (permanent) roosts:** Swarming roosts are especially important for conservation since they are essential for maintaining genetic diversity in future generations. Hundreds of bats from a large area gather there to exchange information, and mate. The significance of other summer or transitional roosts varies based on frequency of use and the number of individuals present (Bürger, Hüttmeir and Reiter, 2015; Dietz, Nill and von Helversen, 2016).

Very sensitive

- **Potential roosting habitats:** These areas are particularly crucial for species that do not roost in buildings, such as the forest-dwelling *Myotis bechsteinii*.
- **Flight corridors or transfer routes:** These are important natural structures, including ecotones (habitat boundaries), which bats use for commuting between roosting and foraging areas. Since these structures are often at the edge of a forest, single tree lines or hedge rows the exposure to light pollution is higher compared to inside a forest. For

some *Rhinolophus* as well as *Myotis* species a negative effect of ALAN on flight corridors was documented (Voigt *et al.*, 2021).

- **Drinking sites:** While research on these sites is limited, they should be regarded as sensitive (Voigt *et al.*, 2021). These locations may be scarce and serve also as key foraging grounds due to the abundance of aquatic insects. For narrow-space and edge-space foraging bats decreased drinking behaviour at illuminated water bodies could be observed (Voigt *et al.*, 2021; Zschorn, 2024).
- **Foraging areas**: These areas should ensure minimal disturbance and maintained habitat quality, because they are essential for bats' hunting success. Especially Rhinolophus and Myotis species count as light-averse also during foraging activities (Voigt *et al.*, 2021). Even the seemingly positive effects of ALAN on some bat species' foraging success (mainly *Eptesicus* and *Pipistrellus* species) are likely unsustainable, as more insects may die near luminaires due to exhaustion or increased predation (van Grunsven *et al.*, 2020; Voigt *et al.*, 2021). This fact underscores the hypothesis that even light pollution outside of dark foraging guilds has an impact on the foraging success. This indicates that the impact of ALAN on foraging areas might be complex. From a practical perspective it can be said that good quality foraging grounds are abundant in the project area for the targeted species (figure 28: Map AB1C1E2) and it known that these bat species do not only rely on one foraging spot every night (Dietz, Nill and von Helversen, 2016).

Sensitive

- **Hibernacula**: These are the places where bats spend their winters. While the surrounding area may not be highly sensitive, it is critical to avoid any disturbance inside these roosts (Voigt, Azam and Dekker, 2018). Special attention on hibernacula must be given in commercial caves or historical buildings (Dietz, Nill and von Helversen, 2016).
- **Migration routes:** Migration distances vary from a few kilometres (*M. bechsteinii*) up to more than 100 km (*M. myotis*), for most *Rhinolophus* and *Myotis* species it is below 100 km (Dietz, Nill and von Helversen, 2016; Stiftung Fledermausschutz, no date). While ALAN's disruptive potential on animal migration is recognized, evidence for its impact on migratory bats, as seen in birds, remains scarce (Voigt *et al.*, 2021).

5.2.5 Key findings

- **Enlarging the planned core zone** to include maternity roosts and other important roosts would be a sufficient protection measure. However, it **might bear some difficulties** to realize that.
- The **average distance between maternity roost and core zone** in the target area is **above the average distance taken from literature** between maternity roost and foraging area.
- **Not all nursing colonies might use foraging grounds inside the planned core zone** due to far distances and closer foraging possibilities.
- The **ÖNORM O 1052** provides a **structured approach to lighting management**. These guidelines help manage light pollution across the whole target area, including the peripheral zone.
- Bats require **lighting schedules that adjust to seasonally changing natural light patterns** rather than follow strict, year-round timelines. Modifying the ÖNORM and incorporating these variations is reasonable, particularly during nursing periods.
- Different aspects of lighting, like **spectral composition, direction, and intensity, require careful management** in bat habitats.
- The ÖNORM O 1052 includes recommendations to **avoid illuminating habitats critical for conservation** (e.g., roosting sites, water bodies), enforcing light limitations in such areas.
- A **hierarchical approach based on bat sensitivity** is reasonable. This hierarchy fosters **targeted management** that reduces unnecessary light in sensitive areas.

6 Discussion of findings and key take-aways

6.1 Q1: Can the proposed core zone of the target area sufficiently protect nocturnal biodiversity?

Can the proposed core zone of the target area sufficiently protect bat habitats (*Myotis* and *Rhinolophus* species) in terms of light pollution?

6.1.1 Limited protection of maternity roosts within the core zone

The analysis reveals several important challenges in the conservation of bat maternity roosts in the target area, particularly in relation to the planned core zone. Only 10% of recorded maternity roosts are located within the planned core zone, which suggests that most bat roosts remain outside the most protected areas. This indicates that the core zone, as it is currently planned, may not be sufficient to safeguard a significant portion of bat populations, particularly *Myotis* species, which have no roosts within the core zone at all. However, these findings must be taken with a pinch of salt.

The data reveals that the recorded *Myotis* maternity roosts are limited to just three or four species: *Myotis emarginatus*, *Myotis myotis*, and either *M. mystacinus* or *M. brandtii*. However, figure 17 shows records of eight different Myotis species in the project area. Given the large size of the area, it is unlikely that the other species - *Myotis bechsteinii*, *Myotis daubentonii*, and *Myotis nattereri* - are only passing through or foraging. *Myotis blythii*, with only three records, is the exception, as it seems not to be abundant to the project area.

Since *Myotis bechsteinii*, *daubentonii*, and *nattereri* are typically forest-dwelling species that mainly roost in trees, where they are difficult to be observed, this suggests a distortion of reality due to a sampling bias. The current data only reflects maternity roosts in human-made structures, with no known records of tree-roosting bats. This is supported by the fact that all recorded maternity roosts are located in buildings (table 17). Some of these bat species would also use caves as maternity roosts, but in central Europe buildings and other human structures have proven as suitable because the caves there are too cold for raising their offspring (Berková, Pokorný and Zukal, 2014). It remains unclear whether *Myotis bechsteinii, daubentonii*, *nattereri* or *blythii* are only hibernating in the project area or if they are also present for mating and nursing.

Table 17: overview of location types for recorded maternity roosts in the target area

alpine hut	monastery
farmhouse	farm
single-family house	outbuilding
hospitility building	vicarage
tool shed	barn
hunting lodge	castle
church	other building

Why focus solely on maternity roosts when including all roost-types records might better reflect the diversity of bat habitats? The reason is practical: maternity roosts are more stable and consistent compared to summer or night roosts, which frequently change (*Bat Conservation Trust*, no date). Additionally, other roost types often record only few individuals, making their protection less impactful for the overall species. While winter roosts generally house many bats, they typically don't forage during hibernation, so disturbances of the surroundings are less impactful. Only direct disturbance should be avoided (Voigt, Azam and Dekker, 2018). Moreover, maternity roosts are widely considered the most vulnerable and critical for bat conservation, making them a central target for protection measures (Reiter *et al.*, 2013; Voigt, Azam and Dekker, 2018).

Additionally, it's important to consider why the recorded maternity roosts are primarily found in human structures, despite the impact of light pollution and other disturbances. While we have already acknowledged that the data on maternity roosts is insufficient, another factor could be the complex habitat requirements of bats. They need suitable infrastructure for their roosts, which they often find in suburban or rural settled areas (Zagmajster, 2014).

Due to human colonisation and the loss of natural cave habitats, many bat species have adapted to buildings as alternative habitats. Buildings offer stable and warmer temperatures, which are ideal for the development of offspring. Caves in Central Europe are often too cool, which can affect the growth of young bats. Many bat species have adapted to living near humans over centuries, as caves are less available in the cultivated landscape (Dietz, Nill and von Helversen, 2016).

Species like *Myotis emarginatus, Myotis myotis, M. mystacinus*, and both *Rhinolophus* species are known to prefer buildings such as barns, churches, or attics for their nurseries (Dietz, Nill and von Helversen, 2016). The data suggests that these species rely heavily on such structures for maternity roosts, and the planned core zone does not provide the same conditions for nursing. While high-quality roosting sites might outweigh the negative effects of light pollution, it doesn't mean that these areas are less sensitive to ALAN. In fact, studies indicate that these areas can be even more vulnerable to light pollution (Zeale *et al.*, 2016; Voigt, Azam and Dekker, 2018). Looking at the Map AB1C2D1 (figure 29) the Map AB1C2E3 (figure 30) in chapter 5.1.2, there seems to be a pattern: the larger the settlement and the higher the light pollution, the fewer maternity roosts and overall bat records. This highlights the need for stronger efforts to protect natural darkness, both inside and outside the planned core zone.

6.1.2 Impact of light

Nearly half (46,81%) of all maternity roosts are directly affected by light pollution, and this number increases to 68,81% within a 2,5 km radius. This demonstrates the extensive reach of artificial light. It is concerning that Rhinolophus maternity roosts outside the core zone are twice as exposed to light pollution as those inside, highlighting the need for better protection strategies in these areas. A comparison for Myotis maternity roosts is not possible, as all recorded roosts are located outside the core zone. As mentioned earlier, this could be the result of an observer bias, with roosts within the core zone simply remaining undiscovered. It is highly likely that these unknown roosts experience less human disturbance and light pollution compared to those outside the core zone.

This thesis does not investigate the presence or absence of bats due to artificial light at night, but rather the level of light pollution to which the recorded maternity roosts in the target area are exposed. Whether roosts have been abandoned or otherwise impacted by light pollution goes beyond the scope of what the available data can reveal. Additionally, we lack information on the bats' activity patterns in the area. It would be valuable to explore whether light pollution affects the timing of their emergence at dusk for hunting or if they take energy-consuming detours to avoid illuminated areas while reaching their preferred foraging grounds.

Satellite data offers valuable insights into light pollution from a space-based perspective. The World Atlas of Artificial Night Sky Brightness, on the other hand, provides modelled artificial light levels at sea level, based on a calculation by Falchi echyt al. (2016). Using the perspective from the earth's ground to measure the degree of light pollution is a great added value generated through this model. Although this model is somewhat limited – with a resolution of around 10 km, it is not very precise and furthermore it relies on data from 2015. Given the rapid increase in light pollution, more recent and frequent data is crucial for accurately tracking this emerging threat.

For the analysis, the author chose to use the satellite data from VIIRS 2022 to provide an updated perspective and supplemented it with ground-based measurements collected in 2023. However, these on-site measurements were taken only once and lack the temporal and spatial coverage needed for detailed conservation planning and monitoring. Regular, comprehensive ground-based assessments are essential. More consistent measurements, such as all-sky photos (e.g. in the vicinity of maternity roosts) and a denser network of TESS (Telescope Encoder and Sky Sensor) devices, are needed. Currently, there are only few permanent SQM or TESS devices contributing to open-source data in the area, which is insufficient to provide a robust dataset for long-term monitoring. Expanding this network to measure NSB would improve accuracy and support better-informed conservation strategies.

6.1.3 Proximity to settlements and roads

The fact that almost 90% of maternity roosts are within 2,5 km of human settlements and main roads suggests that urbanization and infrastructure are pervasive threats to bat habitats. Roosts in these areas may experience higher disturbance levels due to noise, traffic, and increased exposure to predators and the risk of collision.

Considering maternity roosts as the most sensitive target for protection, an analysis was conducted to assess how the maternity roosts of *Myotis* and *Rhinolophus* species are influenced by environmental factors such as light pollution, human settlements, and roads. Both light pollution and traffic pose significant threats to these species, particularly in the immediate vicinity of their maternity roosts (Voigt and Kingston, 2016). However, the impact of settlements requires further discussion. In the project area, settlements are predominantly rural, which may actually benefit bats. Research indicates that some bat species can even thrive in rural settlements, which often provide suitable roosting opportunities. Nonetheless, when settlements undergo urbanization, the negative effects—such as increased light pollution and habitat disturbance—may begin to outweigh the benefits. (Starik, Gygax and Göttert, 2024).

The maternity roost data reveals that all 47 recorded roosts are located within some form of human infrastructure, such as barns, churches, abandoned houses, alpine cabins or attics. However, this does not necessarily imply that these roosts are situated in densely populated human settlements. The settlement layer was derived from the CORINE Land Cover dataset, which, although based on remote sensing data and not perfectly precise, provides a fairly accurate representation of areas where human settlements are concentrated. When considering all bat records, **227 out of 754** were recorded in direct proximity to human infrastructure, highlighting a connection between bats and man-made structures in the region.

6.1.4 Landcover & habitat suitability

According to the European Biodiversity Information System (BISE) 9 out of 10 selected species have listed "forest" as suitable habitat (Biodiversity Information System for Europe, no date). Most of them forage there and use natural landscape features like tree lines or hedgerows to commute, some even need natural forests for roosting.

Map AB1C2E2 (figure 31) reveals that most of the maternity roosts, although inside human settlements, have an abundance of very good foraging habitat (dark green colour) within their 2,5km radius. Looking at MapAB1C1E2 (figure 28); it is interesting that a higher density of bat occurrences is recorded in Gesäuse National Park despite its rough environment. Two possible reasons can be assumed: it might have to be dealt with an observer bias, as the national park is usually better investigated compared to its surroundings. Also, the Kalkalpen National Park shows more records. However, it offers very great habitat possibilities compared to Gesäuse National Park. Another assumption could be that the bats still find the best darkness conditions there.

Fresse et al. could show in her study conducted in the Pyrenees that the presence of *Rhinolophus hipposideros* increases with more wooded areas, as it prefers to hunt in forests. These areas must be interconnected with roosts through hedges or tree rows for movement. In contrast, the presence and activity of *Rhinolophus ferrumequinum* decreases as the wooded area increases, probably due to its preference hunting along forest edges, hedgerows, or open pastures. There is a strong positive relationship between forest cover and activity of *Myotis* species, as these bats mainly hunt in forests, leading to more frequent movement in such areas (Fresse, Demoulin and Maingueneau, 2018).

6.1.5 Differences in genera

Moreover, it remains unclear how different bat species in the target area respond to light pollution. While many studies confirm that these species are generally light-averse due to their "slow flying" nature, it is uncertain whether their tolerance thresholds for brightness and illumination are uniform, or if some species are more sensitive and require stricter protection measures.

A recent study conducted in the French Pyrenees examined the effects of light pollution on *Rhinolophus* and *Myotis* bats. The results indicated that the impact of light pollution varies by species. For *Myotis* bats, light pollution significantly affects their presence, while for *Rhinolophus ferrumequinum*, intermediate light levels (19,8 mag/arcsec²) increase the probability of detection by up to 50%, with activity dropping to zero at higher light levels (18,0 mag/arcsec²). Although *Rhinolophus hipposideros* is highly sensitive to artificial light, the study did not find a clear pattern, likely due to limited data. Despite these variations, all species showed reduced activity when light pollution exceeded certain thresholds, suggesting that management measures can be based on the species with the highest light sensitivity. (Fresse, Demoulin and Maingueneau, 2018).

The differences between species in terms of roosting habits and habitat preferences have been discussed above. It is important to emphasize that several *Myotis* species are tree-roosters, making them more challenging to locate and monitor at their roosting sites. These differences should be considered when designing monitoring strategies.

6.1.6 Key take-aways

- Only **1/5 of maternity roosts** are located **in the planned core zone**, suggesting inadequate protection for most bat species.
- The data mainly reflects maternity roosts in human structures, **missing tree-roosting species** like *Myotis bechsteinii*, *Myotis daubentonii* or *Myotis nattereri*, indicating a sampling bias.
- The **focus on maternity roosts is practical**, as they are more stable and critical for species conservation, unlike summer or night roosts.
- Some *Myotis* and *Rhinolophus* species favour human-made structures for roosting, despite risks from light pollution and human disturbances.
- **Larger settlements and higher light pollution correlate with fewer roosts**, underscoring the need for better protection of natural darkness.
- The study focuses on the level of light pollution affecting recorded roosts but **does not address whether ALAN influences the presence or absence** of these bat species.
- **Satellite data is a good basis** to visualize the degree of light pollution in a larger area. However, it faces **some limitations**.
- **Greater** temporal and spatial **coverage of light pollution measurements and bat monitoring are needed** for accurate conservation planning and tracking of light pollution's effects.

- **Rural settlements**, as long as they do not become too urban, **may offer suitable roosting sites**, benefiting some bat species.
- **All 47 recorded maternity roosts** are found **in human-made structures**, such as barns and churches, demonstrating a strong link between bats and man-made infrastructure.
- **Easy access to natural forests** is crucial for the studied bat species.
- Strict **protected areas might be beneficial** for the bats.
- Despite species differences, all bats exhibited reduced activity when light pollution exceeded certain thresholds, suggesting that **conservation efforts should focus on the most sensitive species**.

6.1.7 Summary

The core zone provides great habitat quality for bats in terms of land cover, darkness level and little human disturbance. Although it seems proper facilities for maternity roosts are not abundant or not known by the protected area management.

In the cause of this study, it could be assumed that *Myotis* species are more affected by light pollution, settlements, and proximity to roads as all recorded maternity roosts are located outside the core zone. However, looking at the available data (table bats), *Myotis* species cover more records (575 out of 754) but less maternity roosts are recorded. This underlines the hypothesis that a majority of their maternity roosts are not known, because they are located in the forests and therefore difficult to monitor (Schwab *et al.*, 2024). *Rhinolophus* maternity roosts benefit somewhat from being inside the core zone, with reduced exposure to light pollution and settlements compared to those outside the core zone. This result is a first indication that an IDSR core zone can serve as protection from outside threats. Therefore, it is generally recommended to incorporate targets of protection in the zonation of a new IDSR. While the core zone ensures strict protection, it is not sufficient to fully safeguard these species from the impacts of ALAN across their entire range. The reasons for this might be diverse; it can be assumed that the size of the core zone is not large enough or that some bat species do not find all habitat types they need within a lifecycle inside the core. Therefore, to protect *Rhinolophus* and *Myotis* bats from ALAN, measures would need to be expanded. This could involve either extending the core zone or implementing other protective measures across the entire target area.

6.2 Q2: What needs to be done to ensure a well-connected dark and natural landscape in the whole target area?

How and where can light pollution be effectively reduced or prevented in *Myotis* and *Rhinolophus* habitats in the project area?

6.2.1 *Option 1: enlarge the core zone and include all most sensitive places in the core zone*

Practically it is not feasible to include all known maternity roosts into the planned core zone, due to various constraints, such as settlements, infrastructure, and already elevated night sky brightness. Furthermore, maternity roosts and drinking sites which are unknown remain unprotected. The two "border roosts", where the location would fulfil core zone requirements, could be included but would bear the potential of creating disadvantages instead of improvement of the conservation situation. Due to the good conditions of the location of each roost and the immediate vicinity to the core zone, the protection level is already good. Changing the borders of the core zone might lead to complications for the future management of the IDSR due several reasons, like different landowners, or municipalities. Experience from Gesäuse National Park has shown that differences in border lines can make research and management agendas more complex (Zimmermann, 2023).

A 2,5 km buffer around maternity roosts located on or near the core zone boundaries already includes significant portions within the core zone, which is highly beneficial. In contrast, maternity roosts situated further away are more problematic, as they lack proximity to the protected core. Due to these reasons, it would be difficult to sufficiently justify this exception towards the Dark Sky Places Committee.

6.2.2 *Option 2: Protect dark corridors between roosts and core zone, assuming there are the best foraging habitats*

Creating corridors between roosts and the core zone, based on the assumption that the best foraging habitats for bats are found within the core zone, presents several limitations:

- **Distance:** It is very likely that some colonies don't forage in the core zone just because it is too far away. Depending on the species, *Myotis* bats commute 1 up to 15 km every night between their roost and their foraging grounds. *Rhinolophus ferrumequinum* commute 2 to 5 km and *Rhinolophus hipposideros* on average 2,5 km per night. (Dietz, Nill and von Helversen, 2016; Stiftung Fledermausschutz, no date)

- **No single pathway:** There is never just one fixed route that bats will take, making it difficult to establish definitive corridors.
- **Colony differences and lack of data in the target area:** Different bat colonies may behave differently, and there is insufficient data on how far or where the bats in the target area fly each night. To better understand their flight patterns, preferred transfer routes, and foraging grounds, additional field studies, such as telemetry or ringing, are necessary. The available data is not sufficient: while some records do not have a certain roosting situation, it can be suggested that these records were taken, where bats might be foraging or transferring between areas. However, they do not provide a full picture of their behaviour. For instance, we don't know if the bats' preferred foraging grounds are even inside the core zone, leading to the next limitation.
- **Anthropocentric assumptions:** When modelling corridors to the core zone, they could be based on factors like land cover and foraging habitat suitability classes (as described in chapter 5.2.2), and light pollution along these corridors could also be analysed. However, it is uncertain whether bats actually use the core zone or prefer to hunt closer to their roosts.
- **Solely structural connectivity:** The approach of connecting roosts with the core zone is a rather structural conservation strategy. For instance, Poiani et al. emphasize that without functional connectivity, structural corridors may fail to support critical ecological processes, such as gene flow and dispersal, ultimately limiting biodiversity outcomes (Poiani *et al.*, 2000).
- **Multiple foraging grounds:** Furthermore, literature shows that bats often visit multiple foraging areas in a single night (Dietz, Nill and von Helversen, 2016), which complicates the corridor concept and raises doubts about its overall effectiveness.

6.2.3 Option 3: Coercive application of the ÖNORM O 1052 through the Lighting Management Plan

The ÖNORM O 1052 is a good standard to mitigate and avoid light pollution. Category S and G already ensure good conditions for nocturnal biodiversity. Only lowering the recommended maximal luminous intensity from 0,25 lx to 0,1 lx could be considered for category S ang G areas in the peripheral zone. With this measure the maximum would be similar to natural full-moon conditions. Category A to D define the measures for inhabited areas. There, it is difficult to comply with the needs of wildlife and nature with human needs. However, thresholds for luminous intensity and spectral composition in sensitive habitats could be reconsidered and made even stricter. Moreover, timing should not be attached to a certain time but to the natural cycle of light and darkness.

To ensure bat protection in a respective area where the ÖNORM is applied some additional measures would be senseful. Especially the time issue and the colour issue could be adapted relatively easily. If there are roosts in categories A to D special protection measures need to be planned as well. We can assume that foraging grounds, drinking sites and forest-roosting bats' habitat are protected with the ÖNORM, as they are mainly in category S or G. It is crucial to also protect bat habitats within category A to D, which are mainly roosts or maternity roosts. Another very sensitive protection target are the immediate roost surroundings and the "first mile" of the transfer route to the foraging ground, which are not protected enough if within categories A to D.

On top of that it is foreseen that the Lighting Management Plan is implemented only by 80% of the project area, which would mean that not all municipalities are obliged to follow the ÖNORM. To properly protect bats in the target area it is highly important to ensure implementation of measures within 100% of the target area. Leaks in measures must be ecologically wisely selected or even avoided.

6.2.4 Option 4: Light pollution protection measures from a bat's perspective

Integrating top-down policies that structurally protect large landscapes with bottom-up processes that adapt to local species' needs can create a well-connected network for biodiversity conservation. Therefore, not neglecting the bats' perspective and start implementing measures not only considering geographic landscape features and habitat models, but also regarding the bats' needs, is a necessary task to ensure long-term protection. In effective conservation strategies, both approaches are crucial. Structural connectivity can help provide a framework to identify potential corridors and areas for large-scale conservation and restoration, while functional conservation measures can guide management practices to ensure that these areas meet the ecological needs of the species they aim to support. Ultimately, a holistic approach that integrates both structural and functional connectivity is essential for successful conservation outcomes. "Option 4: Light pollution protection measures from a bat's perspective" serves as the functional addition to the structural approach of the ÖNORM or the 4-step model for dark infrastructure developed by Sordello et al.

A good starting point is to focus on sensitive habitats which are already mapped, prioritizing areas where measures are needed most. Tasks for the future IDSR management include developing a comprehensive monitoring plan, selecting a set of indicator species, initiating an inventory, and establishing long-term monitoring protocols. A similar approach should be applied to cataloguing artificial light sources within the target area. A smart standard which can be used when defining measures for each sensitivity level are the five principles for responsible outdoor lighting, further elaborated in chapter 8. Meanwhile, the ÖNORM O 1052, supplemented with additional restrictions, can serve as an effective tool protecting habitats and species that lack in data or are challenging to study. Later, it should not be substituted with the concept of sensitivity levels but complemented with them. This bottom-up approach enables the immediate implementation of protection measures and at the same time an overtime improvement. Through long-term monitoring changes can be easily detected and with adaptive management reacting with appropriate measures is always possible.

Furthermore, differentiating between necessary and non-necessary lighting is crucial in each sensitivity level. Necessary lights, such as those for traffic safety or emergency indications, should comply with recommended measures as long as they do not compromise safety or hinder their intended purpose. For non-essential lighting, such as advertisements, cultural monuments, or building facades, lighting should be turned off when not in use or when the location is closed. Otherwise, these lights must strictly adhere to the recommended measures to minimize their environmental impact. Voigt et al. state that there is no such thing as a "bat-friendly" lamp (Voigt, Azam and Dekker, 2018).

Moreover, option 4 is a complete approach to implement measures within 100% of the target aera disregarding the municipality borders or other human-drawn lines.

6.2.5 Key-takeaways

- An **enlargement of the core zone to improve the situation** for *Myotis* and *Rhinolophus* species is **hardly feasible** due to practical reasons.
- **Creating corridors** between the maternity roosts and the core zone might have **several limitations.**
- **More actual data** to better understand **bats' flight patterns** is necessary.
- The ÖNORM O 1052 provides a robust basis for managing light pollution with **categories S and G**, which **support nocturnal biodiversity** by limiting light exposure in sensitive natural areas.

- Slight adjustments, like **reducing maximum luminous intensity to 0,1 lx in sensible habitats**, could better align artificial light with natural conditions, similar to full-moon levels.
- **Enhanced measures for categories A to D** (residential and commercial areas) to ensure better protection of bats' habitats.
- The **timing and colour of outdoor lighting** could be **adapted to ecological needs** relatively easily.
- **Integrating structural measures** (strategies for large landscapes) **with functional measures** (species-specific habitat needs) results in better connectivity and conservation outcomes.
- **Required versus non-necessary lights**: There is **no bat-friendly lamp**, and therefore, natural darkness will always be the best option.
- To **ensure long-term protection**, targeted measures should be incorporated into the **management agenda** of the IDSR.
- Achieving **full implementation (100%)** of measures across the target area is crucial. Partial compliance risks leaving gaps in protection, particularly in municipal areas not bound by the LMP or the ÖNORM standard.

6.2.6 *Summary*

After examining four possible options, it's clear that a mixed approach is most effective for reducing or preventing light pollution in habitats of *Myotis* and *Rhinolophus* bat species within the project area. Focusing solely on the core zone or on establishing corridors is insufficient on its own. Instead, using well-established standards like the ÖNORM O 1052 provides a strong foundation for implementing protective measures across the entire project area, including the peripheral zone. Additional measures guided by the model of sensitivity levels are also essential. This model, developed in this work specifically for light-averse bat species, draws on best-practice examples and provides a framework for identifying and protecting areas of high sensitivity to ALAN.

Examples from other regions underscore the value of this approach. In Douai, France, a bat activity map was created using 80 bat recorders in the whole project area, and sensitivity thresholds were identified to aid dark infrastructure planning (Sordello, Paquier and Daloz, 2021; Sordello *et al.*, 2022). Meanwhile, the Pyrenees National Park has designated a "Dark Grid" within its large green and blue Infrastructure network. Here, light-sensitive bats serve as umbrella species for preserving nocturnal biodiversity. By analysing two years of acoustic data, the park could identify areas where light pollution disrupts bat activity. In a next step collaboration with municipalities was enforced to adjust lighting and enhance wildlife mobility. Priority is given to zones where light pollution intensity falls between 19,8 and 18,0 mag/arcsec², with adjustments refined by ongoing data analysis (Fresse, Demoulin and Maingueneau, 2018; Sordello *et al.*, 2022).

Sordello et al. have streamlined an approach towards dark infrastructure within a 4-step model, including the testing of methods to safeguard habitats based on several classifications: optimal dark zones, which should be preserved; moderately impacted zones, which should be restored; and urban planning that incorporates ALAN as a critical parameter (Sordello *et al.*, 2022). Similarly, Zschorn proposes a three-step process for the integration of darkness into landscape planning: 1. analysing and measuring current light pollution; 2. evaluating impacts on species and biotopes to identify sensitive areas; and 3. conducting a gap analysis to align lighting concepts with ecological needs. By comparing illuminated areas with light-sensitive zones, conflicts can be identified and targeted measures implemented (Zschorn, 2024).

To ensure long-term protection, concrete thresholds and measures should be incorporated into the management agenda of the IDSR. A "Nocturnal Species Management Plan" could be a chapter of the general management plan or a document on its own. This would prioritize the needs of the bats, focusing on their natural behaviour and ecological requirements, rather than relying on a human perspective of how a bat corridor should look or where measures are easily implementable. By involving the species in the planning process, the IDSR can create a habitat that supports the bats' survival while maintaining natural darkness. An example of how this "Nocturnal Species Management Plan" could look like, was elaborated in chapter 8. Moreover, it should not remain using only bats as indicator species but applying the same concept to a wisely selected set of indicator species.

7 Conclusion

This thesis underscores the complexity of achieving holistic and sustainable nature conservation. Effective strategies cannot rely on the expertise of a single field alone but require input from diverse disciplines, including zoology, ecology, astronomy, metrology, geospatial and landscape planning, as well as strategic and adaptive management. The collaboration of biologists, physicists, landscape planners, and policymakers must be institutionalized through dedicated platforms or transdisciplinary working groups to address these multifaceted challenges comprehensively.

The findings emphasize that the ecological impacts of artificial light at night (ALAN) are highly dependent on species-specific behaviour, habitat types and quality, and other cumulative environmental effects. While this study reflects the current status-quo based on the best available data of *Myotis* and *Rhinolophus* species, gaps in data density and coverage remain significant. To enhance the effectiveness of management measures, more targeted and regular monitoring is strongly recommended. Studying flight patterns and emergence time or conducting a light inventory around maternity roosts are just some examples.

Although bats serve as indicator species in this study, they alone cannot represent overall nocturnal biodiversity. The same approach and procedure should be expanded to other taxa, such as insects and birds. Developing a broader indicator set would allow more comprehensive understanding of nocturnal biodiversity and light pollution mitigation measures can be streamlined not only for a single species but for a whole ecosystem. Nevertheless, mitigating light pollution at least for bats creates a windfall effect: other species, including additional bat populations and insects, also benefit, aligning with Lotka-Volterra ecological interdependencies (Bunin, 2017).

Furthermore, the spectral composition of light remains a critical issue, as different wavelengths have varying impacts on organisms. Similarly, while humans perceive light visually based on subjective "lumen" values, other organisms notice different wavelengths, interpreting visual and non-visual emissions is a complex and species-specific challenge. For instance, light emissions that are invisible to humans may still significantly disrupt animals or plants (Voigt, Azam and Dekker, 2018). More research is needed to fully understand these effects.

The broader debate on light and safety—particularly its role in traffic safety and crime prevention—must also be carefully balanced with ecological needs. Other challenges such as the rebound effect emerging from the usage of energy-efficient LED lighting further complicate conservation efforts. While LEDs offer lower energy consumption, their widespread adoption may increase overall light emissions.

Prominently, light pollution is different from other anthropogenic pollutants in that it cannot be captured or neutralized—the only solution is to reduce or stop emissions at the source. Even widespread and persistent forms of light pollution, like skyglow or glare, can only be eliminated through simply turning off the light.

Finally, when comparing ALAN with other forms of anthropogenic pollution, the thesis highlights the need for an integrated perspective. By addressing light pollution holistically, we will not only safeguard specific species but also enhance the overall health of humans and ecosystems. An interdisciplinary and adaptive approach can be a vital step towards balancing human needs and biodiversity conservation.

This thesis demonstrates that even with limited or incomplete data, concrete conservation strategies and actions can still be formulated. The growing number of guidelines and frameworks addressing light pollution mitigation further underscores that this issue is gaining increasing attention and recognition on both scientific and policy levels. In summary, this work shows that, while challenges remain, tackling light pollution on a strategic, transdisciplinary level can harvest significant benefits for species and ecosystems.

8 Nocturnal Species Management Plan - Bats

Several guidelines, recommendations, and position papers were reviewed to develop practical measures for preserving and restoring a well-connected, natural landscape for *Myotis* and *Rhinolophus* species across the target area, encompassing both the core and peripheral zones of the IDSR. Key references include the Austrian ÖNORM O 1052, Austrian Outdoor Lighting Guide (Leitfaden Österreichische Außenbeleuchtung), "Mindful use of light" - guiding principles for outdoor lighting (Leitbild Naturpark Vulkanland), International Dark Sky Reserve Program Guidelines, "Helle Not" - Tyrol Competence Center on Light Pollution and Dark Skies, Eurobats - Guidelines for consideration of bats in lighting projects , IUCN - the world at night and the "Guide trame noire" (Office français de la biodiversité). Sordello et al. emphasize the importance of focusing on specific taxa when planning dark infrastructure measures (Sordello *et al.*, 2022). Consequently, the conservation efforts of this plan are directed toward the indicator species identified in this research.

Based on the key takeaways of this study, a management recommendation has been developed to improve the situation for bats concerning light pollution in the project area. The current status is favourable for bats and nocturnal biodiversity in general, with the area being one of the largest relatively dark places in Austria. It also hosts several strictly protected areas and is moving towards becoming an International Dark Sky Reserve (IDSR). However, to ensure mitigation of light pollution in this area, a well-structured procedure is recommended, focusing on the preservation of nocturnal biodiversity using bats as indicator species. Additionally, this strategy could be expanded to address other key indicator species beyond bats. The focus should lay on selecting areas for intervention based on ecological necessity rather than prioritizing easy feasibility.

Three critical steps are outlined:

1. **MEASURE:** Define what needs to be measured to mitigate light pollution within a certain Level of intervention. Which variables are necessary to measure?
2. **MITIGATE:** Set target conditions and thresholds, which are necessary to protect bats from light pollution. Establish concrete actions to achieve these thresholds.
3. **MAINTAIN:** Develop a long-term strategy to ensure sustained protection. This includes public awareness raising, monitoring of the effectiveness of the actions, and conducting periodic reviews to adapt and improve actions and strategies.

8.1 Levels of intervention

The measures should be tailored to the varying sensitivity levels of bat habitats, as described in Chapter 5.2.4 (refer to figure 32: "Bat habitats and sensitivity to ALAN"). Based on these sensitivity levels, three distinct levels of intervention have been established, visualized in figure 33. These interventions account for practical conservation needs, incorporating slight adaptations and generalizations where necessary. For example, drinking sites for bats, such as standing waters and rivers, are less sensitive compared to roost entrances. However, water bodies are generally critical habitat features for many bats (Voigt, Azam and Dekker, 2018). They serve not only as drinking sites, but also as foraging habitat and guiding structures for commuting. To address these concerns, water bodies have been included in Level A interventions, with a designated buffer of 20 meters. Foraging habitats are not exclusively considered within the levels of intervention. They are protected with very strong measures (Level A and B) for drinking sites, potential roosting habitats and within the 2,5km buffer around maternity roosts. Moreover, Level C measures should be sufficient for foraging areas inside of forests, since a dense forest canopy is naturally shielding ALAN. The approach considers available knowledge regarding landscape features, light pollution, and bat distribution to ensure effective and context-specific conservation actions.

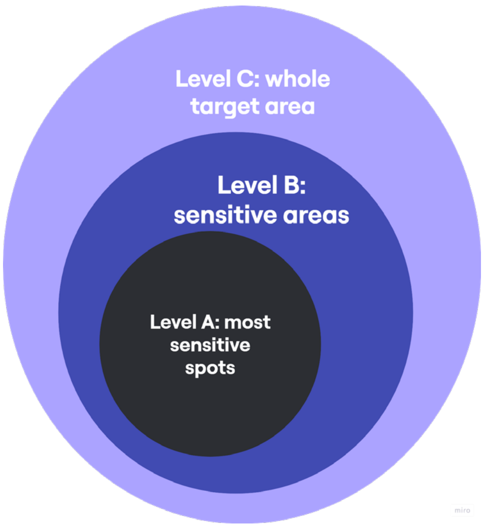


Figure 33: Levels of intervention

Level A: most sensitive spots

- exits and entrances of maternity roosts and other (permanent) roosting sites
- the direct vicinity/ entrance lanes of maternity roosts and other (permanent) roosting sites
- drinking sites (and all water bodies in general)

Level B: sensitive areas

- 2,5 km radius around maternity roosts
- potential flight corridors and commuting features (ecotones)
- potential roosting habitats (especially for forest dwelling species)

Level C: whole target area

- The whole project area for the planned IDSR hosts possible foraging habitats in and outside the core zone and measures on a landscape level have an impact on transferring and migrating of bats.

The information on the locations for Level A, B and C which is available (by 12/2024) is summarized and visualized in Map F (figure 34). Information is missing especially on maternity roosts of forest-dwelling bat species, on flight corridors and commuting features and therefore not displayed on the map. Rivers also function as commuting features and for potential roosting habitats all broadleaf and mixed forests were taken from the CLC (CLC types 3.1.1 and 3.1.3).

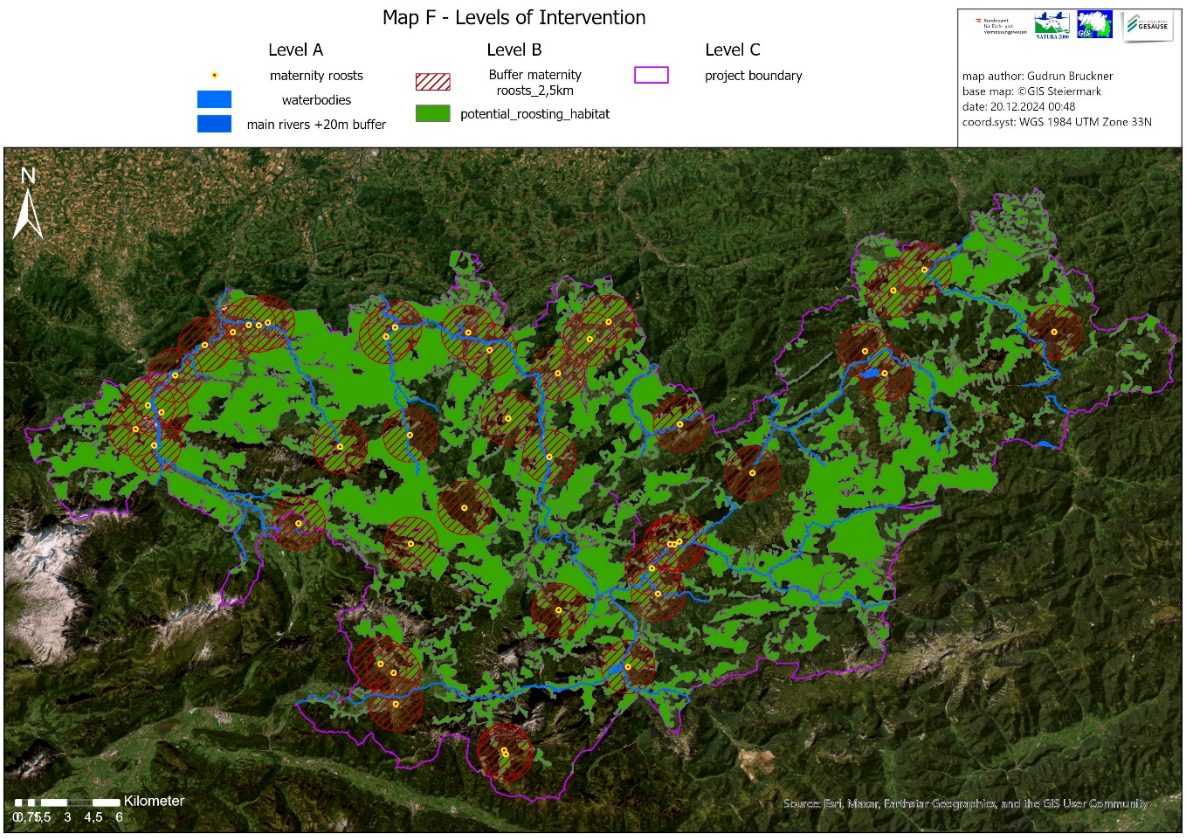


Figure 34: Map AF - Levels of intervention

The following list reflects what is recommended to measure, including examples for possible methods. Secondly, mitigation measures based on DarkSky International's principles are formulated for each level. Finally, strategies on how to maintain natural darkness and a good conservation status of the indicator species are elaborated.

8.2 What to MEASURE?

Level A:

- Up-to-date maternity roost inventory
- Mapping of all water bodies
- All-sky image at the maternity roost entrances
- Illuminance measurement (luxmeter) at the maternity roost entrance and in the direct vicinity of water bodies

Level B:

- Assessment of potential flight corridors: e.g. telemetry or special GIS-based modelling
- Identification of green infrastructure which is used by bats as commuting features; for instance, ecotones, edges of forests or hedge rows: GIS analysis
- Assessment of potential roosting habitats of forest-dwelling species: e.g. acoustic monitoring within suitable CLC types (forests)
- Light inventory 2,5km around maternity roosts (illuminance, spectral composition, direction) and along identified commuting features, and in potential roosting habitats.

Level C:

- Assessment of potential migration routes: e.g. telemetry
- Identification of suitable foraging grounds: e.g. acoustic monitoring or GIS -based modelling
- Documentation of observations
- Light inventory of all outdoor luminaires (illuminance, spectral composition, direction)
- Permanent photometers (SQM, TESS) distributed over the whole target area

A strong understanding of bats, their flight patterns and habitat use within the target area is essential. However, additional data collection and continuous monitoring are urgently needed to enhance conservation efforts.

8.3 How to MITIGATE?

These mitigation measures should be based on the "Five Lighting Principles for Responsible Outdoor Lighting" jointly published by DarkSky International and Illuminating Engineering Society. Several guidelines were screened and the recommended thresholds mentioned are listed in table 18.

1. **Useful**
2. **Targeted (Direction)**
3. **Low level (Quantity)**
4. **Controlled (time)**
5. **Warm coloured (Spectral composition)**

Figure 35: Five Lighting Principles for Responsible Outdoor Lighting

Table 18: Different guidelines assessed according to the Five Lighting Principles for Responsible Outdoor Lighting (Tiroler Umweltanwaltschaft, 2015a; Voigt, Azam and Dekker, 2018; 'Österreichischer Leitfaden-Außenbeleuchtung', 2018; 'ÖNORM O 1052: Lichtimmissionen - Messung und Beurteilung', 2022; Sordello, Paquier and Daloz, 2021; DarkSky International, 2023; Wallner, 2024; Welch et al., 2024)

Different Guidelines	**5 Lighting Principles for Responsible Outdoor Lighting**				
	1. Useful	**2. Targeted**	**3. Low level**	**4. Controlled**	**5. Warm-coloured**
ÖNORM O 1052	The need for lighting should be clarified.	0 - 15% ULR tolerated depending on the area type	0,25 lx (in ecologically sensitive areas) up to 25 lx at window level (depending on area type, daytime and purpose of the light)	depending on the area type 6:00 to 22:00 or 24:00 o'clock	ecological sensitive: 2700K, intermediate: 3000K, everywhere else: 4000K
Austrian Outdoor Lighting Guide (Leitfaden Österreichische Außenbeleuchtung)	Before planning a lighting project, the necessity should be scrutinized!	full cut-off luminaires are preferred.	The lighting level should be lowered during the night based on the changing parameters in accordance with ÖNORM 1055.	ÖNORM O 1052	max. 3000K + blue filter in case of luminaire aging)
Mindful use of light - guiding principles for outdoor lighting (Leitbild Naturpark Vulkanland)	Lighting only there, where and when it is needed.	All outdoor lighting fixtures >1000 initial lamp lumens must be fully shielded. For public lighting a beam angle of max. 70° and for private max. 90° are recommended.	Calculation of minimum lighting levels depending on road situation (ÖNORM 1055)	ALAN only from one hour before local civil sunrise until one hour after local civil sunset	ecological sensitive: 1800K, intermediate: 2400K, everywhere else: 3000K

International Dark Sky Reserve Program Guidelines	only prescribed when it is strictly needed, where it is needed, and in the appropriate amount for a specific task. […] specifically, to ensure public safety.	All outdoor lighting fixtures >500 initial lamp lumens must be fully shielded.	[…] in the appropriate amount for a specific task.	[…] make appropriate use of timers and motion sensors.	max. 3000K
Helle Not - Tyrol Competence Centre on Light Pollution and Dark Skies	Roads, footpaths and cycle paths are linear elements, they dominate the landscape and fragment habitats - all the more so if they are illuminated at night. Outside inhabited areas they should not be illuminated.	This so-called fully shielded luminaire type has a maximum beam angle of 70° and ensures optimum light distribution. Streetlight poles should be max. 6 m high (reduction of distant effects).	Cycle paths and footpaths should be assigned to general lighting class P (ÖNORM EN 13201, ÖNORM 1055). […] These correspond to the minimum average horizontal illuminance of **3 lx** during operation until midnight.	With night-time shutdown, night-time reduction and intelligent control systems, lighting can be adjusted to suit requirements.	amber (2200K) or warm-white (max.3000K) LEDs
Eurobats - Guidelines for consideration of bats in lighting projects	ALAN should be avoided wherever possible!	use fully shielded luminaires that have no light emitted above the horizontal. […] light flux only toward the area that needs to be lit. Correcting luminaire's hight can help […]	Illuminance levels caused by distant lights must be below 0,1 lx at the roost entrances, exits and along the emergence corridors outside the roost.	part-night lighting schemes at landscape features where bats commute and forage should be adapted to dawn and dusk.	max. 2700K
IUCN - the world at night	remove rather than replace; only for public safety and navigation	no light upwards; low enough so that it does not shine beyond the target surface	least amount of light necessary	[…] used only while people are present […] use automatic timers and motion detectors.	should not emit blue and violet spectral components; no higher than 2700K, […] and preferably 2200K
Guide trame noire (Office français de la biodiversité)	Avoid or eliminate unnecessary streetlamps.	Lighting should be directed downward and shielded to minimize light scattering into the sky and natural habitats.	emit the smallest possible amount of light; thresholds that apply are those 'outside built-up areas' (i.e. 25 lm/m² for road lighting).	Timers and motion sensors are recommended to ensure lighting is used only, when necessary, especially in urban and peri-urban areas.	with the narrowest possible spectrum, in amber: In PAs the colour temperature may not exceed 2400K.
Level A	ALAN should be avoided wherever possible!	no luminaires at all	max. 0,1 lx	no luminaires at all	no luminaires at all
Level B	remove rather than replace; only for public safety and navigation	All outdoor lighting fixtures >500 initial lamp lumens must be fully shielded. For public lighting a beam angle of max. 70° and for private max. 90° are recommended.	least amount of light necessary; ecologically sensitive areas max. 0,25 lx; streetlights in accordance with ÖNORM 1055 minimum values	ALAN only from one hour before local civil sunrise until one hour after local civil sunset; except street and safety lighting where it is necessary	1800-2400K
Level C	The need for lighting should be clarified.	All outdoor lighting fixtures >1000 initial lamp lumens must be fully shielded.	The lighting level should be lowered during the night based on the changing parameters in accordance with ÖNORM 1055.	Timers and motion sensors are recommended to ensure lighting is used only when needed; night-time shutdown and intelligent control systems	max. 3000K

Level A:

- ALAN should be **avoided wherever possible**.
- Elimination of all luminaires at these spots.
- Maximum allowed light level: **0,1 lx** (caused by scattering of distant light sources).

Level B:

- Reduce lighting impacts while **ensuring public safety** and essential navigation.
- Luminaires should be removed rather than replaced, wherever possible.
- All outdoor lighting fixtures emitting >500 initial lamp lumens must be **fully shielded** (0% ULR!) to direct light downward and avoid light spills. For public safety lighting, which deviates from the defined operating times, a beam angle of max. 70° is recommended and for private lights max. 90° are eligible if conforming operating times are respected.
- Use the **least amount** of light **necessary** for the intended purpose.
- Ecologically sensitive habitats may not be brightened by ALAN more than **0,25 lx**.
- Calculation of minimum lighting levels for street lights depending on the road situation (minimum values of ÖNORM 1055).
- Artificial light should be turned on only **from one hour before** local civil **sunrise** and **until one hour after** local civil **sunset**. An exception is street and safety lighting, where it is really necessary.
- Implement **part-night lighting schemes** near landscape features where bats commute and forage. These schemes should be **adapted to dawn and dusk**, minimizing disturbances during peak bat activity.
- Use warm-coloured lighting with **1800–2400K** to reduce blue light emissions, which are more disruptive to bats and other wildlife.

Level C:

Evaluate the need for lighting and apply measures that minimize its ecological impact on a landscape level.

- The necessity for lighting in these areas should be **carefully clarified**.

- All outdoor lighting fixtures emitting **>1000 initial lamp lumens** must be **fully shielded**.
- The lighting level should be lowered during the night based on the changing parameters in accordance with ÖNORM 1055.
- Timers and motion sensors are recommended to ensure lighting is used only during the time needed. Night-time shutdown and intelligent control systems should be installed to easily adjust to different lighting requirements.
- Use lighting with a maximum colour temperature of **3000K**.

Furthermore, a contrasting idea is that light could also be intentionally used to guide bats away from hazardous flight paths (e.g. high traffic roads) toward safer crossing points. While this approach has been implemented, its effectiveness remains untested and could potentially intensify the barrier effect. Evaluating this strategy is crucial, not only for bat protection but also for other wildlife, as many species actively avoid light. (Voigt and Kingston, 2016)

8.4 How to MAINTAIN?

Level A:

- Keep track of the maternity roost situation: Are new maternity colonies formed or do some roosts get abandoned? Putting it in context with the location-specific circumstances.
- In case roosting situations are changing, adopt mitigation measures.
- Inform local population and property owners directly about the special sensitivity of maternity roosts and involve them in conservation activities.

Level B:

- Keep track of the bat activity through a well-elaborated, constant monitoring program.
- Regular controls of the lighting situation within Level B areas: repeating the light inventory in regular intervals to keep track of changing or new light sources.
- Conduct a before-and-after assessment of bat populations to measure the effectiveness of the measures.
- Educating the local population how to use environmentally friendly lights at night following the Five Lighting Principles for Responsible Outdoor Light
- ing.

Level C:

- Use permanently stationed photometers (TESS or SQM) to determine if the areas are overall darker after implementing the measures.
- **Identify critical thresholds** within the continuous bat monitoring framework to establish an "early warning system" for potential declines. (Alignment with the Natura2000 controlling of the favourable conservation status and the prohibition of deterioration)
- Include the bat conservation status in the **annual reporting** to DarkSky International
- When NSB is constantly falling below the threshold of **20,5 mag/arcsec²** (Fresse, Demoulin and Maingueneau, 2018), the cause must be evaluated, and stricter mitigation measures are recommended.
- Keep a "No net loss of darkness" approach (Voigt, Azam and Dekker, 2018).

8.5 Desired results

Miradi is a tool for conservation managers to visualize conservation goals and all related factors. It helps to implement adaptive management measures. Miradi was used to picture the desired results of the management recommendations formulated for the conservation target light-averse bats.

Table 19: definition of Miradi terms (Miradi Glossary, no date)

Activity	A specific action or set of tasks undertaken by project staff and/or partners to reach one or more objectives.
Conservation Target	An element of biodiversity (species, habitat, or ecological system) at a project site on which a project has chosen to focus. All targets should collectively represent the biodiversity of concern at the site.
Goal	A formal statement detailing a project's desired impact, such as the desired future status of a target.
Objective	A formal statement detailing a desired outcome of a project, such as reducing a critical threat. A good objective meets the criteria of being *specific*, *measurable*, *achievable*, *results-oriented*, and *time-limited* (SMART). If the project is well-conceptualized and -designed, the realization of a project's objectives should lead to the fulfilment of the project's goals and ultimately its vision.

Result	A desired change from the current context resulting from successful implementation of conservation actions.
Strategy	A set of activities with a common focus that work together to achieve specific goals and objectives by targeting key intervention points, optimizing opportunities, and limiting constraints. A good strategy meets the criteria of being: *linked, focused, feasible*, and *appropriate.*

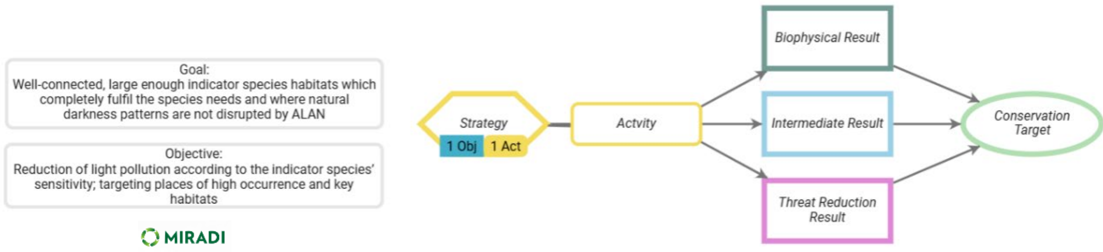


Figure 36: template for a Miradi result chain

The goal of these conservation efforts is to create well-connected, large habitats for indicator species that remain unaffected by ALAN, fulfilling species-specific needs. The objective is to reduce light pollution based on the sensitivity of these species, particularly in places of high occurrence and key habitats. Light-averse bats as indicator species are the conservation target of the formulated strategy: "Integration of the ecological perspective in the IDSR management agenda". This strategy feeds into three main activities applied within a defined level of intervention (Level A, B and C): measure, mitigate, and maintain. Each activity is linked to specific results:

- **Biophysical Results**: Positive ecological impacts.
- **Intermediate Results**: Progress in achieving immediate conservation goals.
- **Threat Reduction Results**: Decrease in threats such as light pollution (Miradi Glossary, no date).

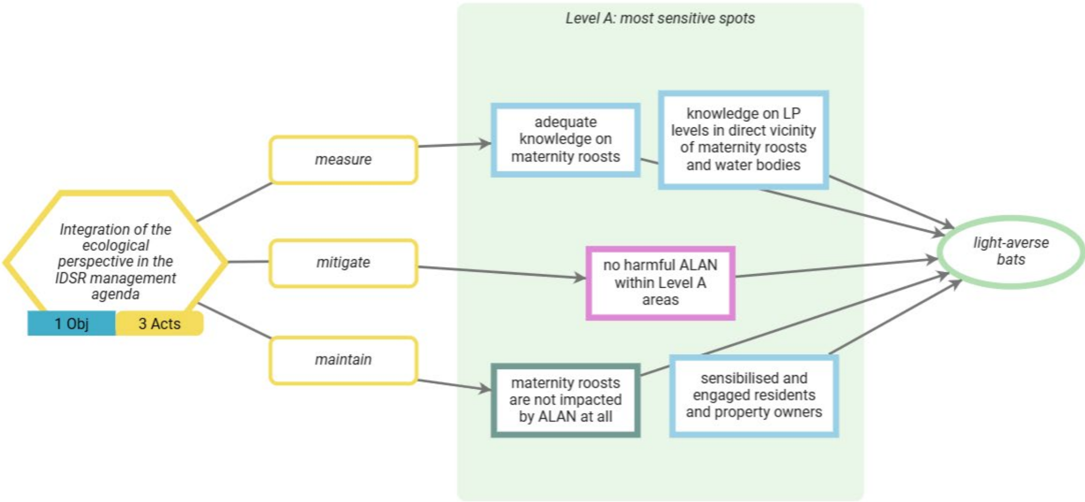


Figure 37: Miradi result chain for Intervention Level A

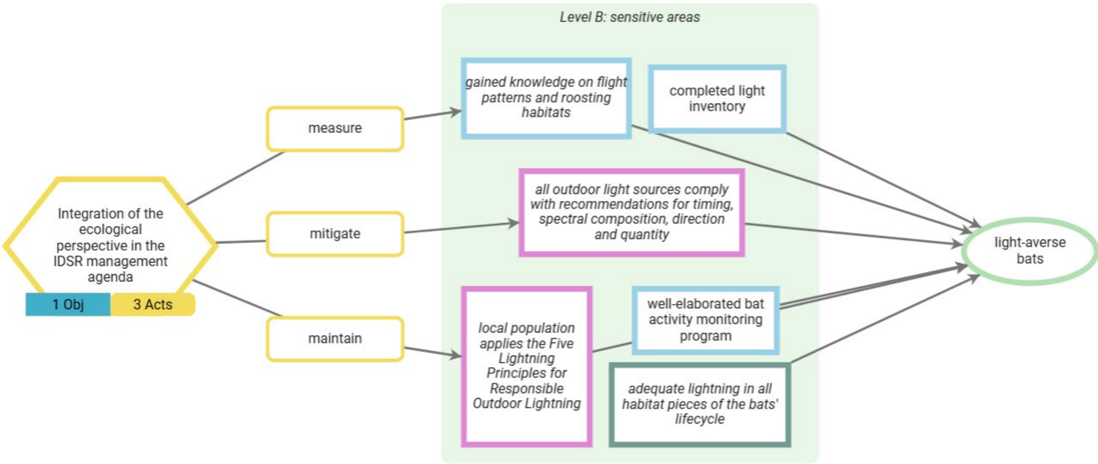


Figure 38: Miradi result chain for Intervention Level B

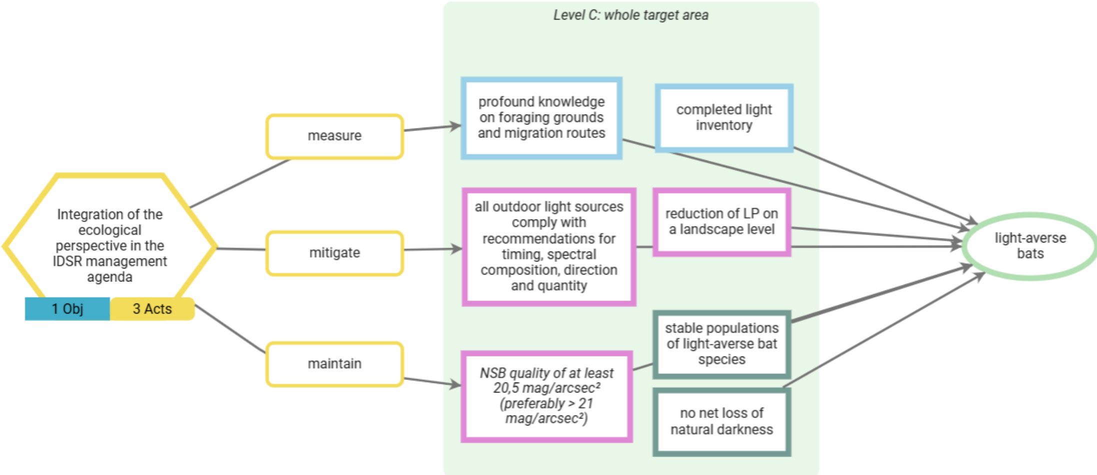


Figure 39: Miradi result chain for Intervention Level C

9 References

9.1 Publication bibliography

Alpine Convention (no date). Available at: https://www.alpconv.org/en/ (Accessed: 6 December 2024).

Azam, C. *et al.* (2016) 'Disentangling the relative effect of light pollution, impervious surfaces and intensive agriculture on bat activity with a national-scale monitoring program', *Landscape Ecology*. Available at: https://doi.org/10.1007/s10980-016-0417-3.

Bat Conservation Trust (no date). Available at: https://www.bats.org.uk/about-bats/where-do-bats-live/bat-roosts/what-is-a-roost (Accessed: 17 October 2024).

Bennie, J. *et al.* (2014) 'Mapping artificial lightscapes for ecological studies', *Methods in Ecology and Evolution*. Edited by R. Chisholm, 5(6), pp. 534–540. Available at: https://doi.org/10.1111/2041-210X.12182.

Bennie, J. *et al.* (2015) 'Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 370(1667), p. 20140131. Available at: https://doi.org/10.1098/rstb.2014.0131.

Bennie, J. *et al.* (2016) 'Ecological effects of artificial light at night on wild plants', *Journal of Ecology*. Edited by N. Swenson, 104(3), pp. 611–620. Available at: https://doi.org/10.1111/1365-2745.12551.

Berková, H., Pokorný, M. and Zukal, J. (2014) 'Selection of buildings as maternity roosts by greater mouse-eared bats (Myotis myotis)', *Journal of Mammalogy*, 95(5), pp. 1011–1017. Available at: https://doi.org/10.1644/13-MAMM-A-102.

Bernhardt, K.-G., Kropf, M. and Laubmann, D. (2010) 'Das Zielartenkonzept als Naturschutzinstrument - eine kritische Betrachtung'.

Biodiversity Information System for Europe (no date). Available at: https://biodiversity.europa.eu/ (Accessed: 15 October 2024).

Buchanan, B.W. (2006) 'Observed and potential effects of artificial night lighting on Anuran amphibians.' Island Press 192–200.

Bunin, G. (2017) 'Ecological communities with Lotka-Volterra dynamics', *Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel* [Preprint].

Bürger, K., Hüttmeir, U. and Reiter, G. (2015) 'Fledermäuse in Niederösterreich 2012-2015'.

Caley, A. *et al.* (2024) 'Antagonistic Effects of Light Pollution and Warming on Habitat-Forming Seaweeds', *Ecology and Evolution*, 14(10), p. e70420. Available at: https://doi.org/10.1002/ece3.70420.

Camacho, L.F., Barragán, G. and Espinosa, S. (2021) 'Local ecological knowledge reveals combined landscape effects of light pollution, habitat loss, and fragmentation on insect populations', *Biological Conservation*, 262, p. 109311. Available at: https://doi.org/10.1016/j.biocon.2021.109311.

Cayton, H. (2024) *Connectivity 101 - Conservation Corridor.* Available at: https://conservationcorridor.org/the-science-of-corridors/ (Accessed: 16 October 2024).

Da Silva, A. *et al.* (2014) 'Artificial night lighting rather than traffic noise affects the daily timing of dawn and dusk singing in common European songbirds', *Behavioral Ecology*, 25(5), pp. 1037–1047. Available at: https://doi.org/10.1093/beheco/aru103.

DarkSky International (2018) *IDSP-Designation-Flowchart*. Available at: https://darksky.org/app/uploads/2021/12/IDSP-Designation-Flowchart-2018.pdf (Accessed: 22 January 2025).

DarkSky International (2023) 'International Dark Sky Reserve Program Guidelines'.

DarkSky International (2024a) *DarkSky International*. Available at: https://darksky.org/ (Accessed: 15 January 2025).

DarkSky International (2024b) *Light pollution harms wildlife and ecosystems*. Available at: https://darksky.org/resources/what-is-light-pollution/effects/wildlife-ecosystems/ (Accessed: 15 January 2025).

DarkSky International (2024c) *What is light pollution?* Available at: https://darksky.org/resources/what-is-light-pollution/. (Accessed: 30 August 2024).

Degen, T. *et al.* (2016) 'Street lighting: sex-independent impacts on moth movement', *Journal of Animal Ecology*. Edited by J. Chapman, 85(5), pp. 1352–1360. Available at: https://doi.org/10.1111/1365-2656.12540.

Dietz, C., Nill, D. and von Helversen, O. (2016) *Handbuch der Fledermäuse - Europa und Nordwestafrika*. Kosmos.

Directive - 92/43 - Habitats Directive - EUR-Lex (no date). Available at: http://data.europa.eu/eli/dir/1992/43/oj (Accessed: 8 August 2024).

Downs, N.C. and Racey, P.A. (2006) 'The use by bats of habitat features in mixed farmland in Scotland', *Acta Chiropterologica*, 8(1), pp. 169–185. Available at: https://doi.org/10.3161/1733-5329(2006)8[169:TUBBOH]2.0.CO;2.

Eisenbeis, G. and Hassel, F. (2000) 'Zur Anziehung nachtaktiver Insekten durch Straßenlaternen-eine Studie kommunaler Beleuchtungseinrichtungen in der Agrarlandschaft Rheinhessens.', *Natur Und Landschaft*.

Falchi, F. *et al.* (2016) 'The new world atlas of artificial night sky brightness', *Science Advances*. Available at: https://doi.org/10.1126/sciadv.1600377.

Fresse, E., Demoulin, J. and Maingueneau, J. (2018) 'Elaboration d'une Trame Sombre par la mise en place d'un protocole sur les chiroptères au sein du Parc national des Pyrénées (65)'.

Gaston, K.J. *et al.* (2013) 'The ecological impacts of nighttime light pollution: a mechanistic appraisal', *Biological Reviews of the Cambridge Philosophical Society*. Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall, TR10 9EZ, U.K. Available at: https://doi.org/10.1111/brv.12036.

Gaston, K.J. *et al.* (2021) 'Pervasiveness of Biological Impacts of Artificial Light at Night', *Integrative and Comparative Biology*, 61(3), pp. 1098–1110. Available at: https://doi.org/10.1093/icb/icab145.

Gaston, K.J., Visser, M.E. and Hölker, F. (2015) 'The biological impacts of artificial light at night: the research challenge', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 370(1667), p. 20140133. Available at: https://doi.org/10.1098/rstb.2014.0133.

Green infrastructure (2023). Available at: https://environment.ec.europa.eu/topics/nature-and-biodiversity/green-infrastructure_en (Accessed: 18 October 2023).

Grubisic, M. and Van Grunsven, R.H. (2021) 'Artificial light at night disrupts species interactions and changes insect communities', *Current Opinion in Insect Science*, 47, pp. 136–141. Available at: https://doi.org/10.1016/j.cois.2021.06.007.

van Grunsven, R.H.A. *et al.* (2020) 'Experimental light at night has a negative long-term impact on macro-moth populations', *Current Biology*. Available at: https://doi.org/10.1016/j.cub.2020.04.083.

Gutiérrez-Granados, G. and Rodríguez-Zúñiga, M.T. (2023) 'Bats as indicators of ecological resilience in a megacity', *Urban Ecosystems*, in press. Available at: https://doi.org/10.1007/s11252-023-01462-5.

Hilty, J. *et al.* (2020) *Guidelines for conserving connectivity through ecological networks and corridors*. Edited by C. Groves. IUCN, International Union for Conservation of Nature. Available at: https://doi.org/10.2305/IUCN.CH.2020.PAG.30.en.

Hölker, F. *et al.* (2010) 'Light pollution as a biodiversity threat', *Trends in Ecology & Evolution*, 25(12), pp. 681–682. Available at: https://doi.org/10.1016/j.tree.2010.09.007.

Hölker, F. *et al.* (2021) '11 Pressing Research Questions on How Light Pollution Affects Biodiversity', *Frontiers in Ecology and Evolution*, 9, p. 767177. Available at: https://doi.org/10.3389/fevo.2021.767177.

Hunter, T. (2023) *The birth of DarkSky (IDA) and a lifelong mission fighting light pollution | DarkSky International.* Available at: https://darksky.org/news/the-birth-of-ida-and-a-lifelong-mission-fighting-light-pollution/. (Accessed: 30 August 2024).

IUCN Dark Skies Advisory Group (no date) 'Dark skies and nature conservation – Dark Sky Parks'. Available at: https://darkskyparks.org/dark-skies-and-nature-conservation/ (Accessed: 9 January 2025).

IUCN red list (no date). Available at: https://www.iucnredlist.org/en (Accessed: 8 August 2024).

Jean, M. (2024) *Alparc*. Available at: https://alparc.org/discover-the-apa.

Jedicke, E. (2016) 'Zielartenkonzepte als Instrument für den strategischen Schutz und das Monitoring der Biodiversität in Großschutzgebieten', *Raumforschung und Raumordnung | Spatial Research and Planning*, 74(6). Available at: https://doi.org/10.1007/s13147-016-0448-x.

Jiang, W., He, G. and Ni, Y. (2017) 'Assessment of light pollution on protected areas in China', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W7, pp. 1307–1312. Available at: https://doi.org/10.5194/isprs-archives-XLII-2-W7-1307-2017.

KFFÖ (no date) *Fledermausschutz Österreich*. Available at: http://www.fledermausschutz.at/ (Accessed: 9 January 2025).

Kreiner, D., Maringer, A. and Zechner, L. (2012) 'ECONNECT – Improving connectivity in the Alps Implementation in the pilot region Northern Limestone Alps', *eco.mont (Journal on Protected Mountain Areas Research)*, 4(1), pp. 41–46. Available at: https://doi.org/10.1553/eco.mont-4-1s41.

Krop-Benesch, D.A. (2018) 'Die Auswirkung künstlicher Beleuchtung bei Nacht auf Fledermäuse'.

'La Palma Declaration' (2007). STARLIGHT INITIATIVE LA PALMA BIOSPHERE RESERVE / INSTITUTO DE ASTROFÍSICA DE CANARIAS / GOVERNMENT OF THE CANARY ISLANDS / SPANISH MINISTRY OF THE ENVIRONMENT / UNESCO - MaB. La Palma, Canary Islands, Spain.

Lewanzik, D. and Voigt, C.C. (2013) 'Lichtverschmutzung und die Folgen für Fledermäuse', *In: Held, M., Hölker, F. & Jessel, B. (2013) Schutz der Nacht - Lichtverschmutzung, Biodiversität und Nachtlandschaft. - BfN-Skripten*.

Manfrin, A. *et al.* (2018) 'Dietary changes in predators and scavengers in a nocturnally illuminated riparian ecosystem', *Oikos*. Available at: https://doi.org/10.1111/oik.04696.

Miradi Glossary (no date). Available at: https://help.miradishare.org/hc/en-us/articles/6273565415323-Glossary. (Accessed: 17 January 2025).

NASA Earthdata (2024) *VIIRS*. Earth Science Data Systems, NASA. Available at: https://www.earthdata.nasa.gov/data/instruments/viirs (Accessed: 15 January 2025).

'Naturnachtgebiet Eisenwurzen, Dark Sky Reserve Application' (2025).

Nitsch, C., Bindeus, E. and Zwettler, K. (2015) 'Planungskonzept zum Schutzgebietsverbund Nationalpark Kalkalpen, Nationalpark Gesäuse und Wildnisgebiet Dürrenstein'.

O'Mara, M.T. *et al.* (2021) 'Bats use topography and nocturnal updrafts to fly high and fast', *Current Biology*, 31(6), pp. 1311-1316.e4. Available at: https://doi.org/10.1016/j.cub.2020.12.042.

'ÖNORM O 1052: Lichtimmissionen - Messung und Beurteilung' (2022). Austrian Standards International.

'Österreichischer Leitfaden-Außenbeleuchtung' (2018). Land Oberösterreich.

Peregrym, M. *et al.* (2020) 'Is Artificial Light at Night Dangerous for the Balkan Strict Protected Areas at Present?', *Water, Air, & Soil Pollution*, 231(2), p. 90. Available at: https://doi.org/10.1007/s11270-020-4452-y.

Poiani, K.A. *et al.* (2000) 'Biodiversity Conservation at Multiple Scales: Functional Sites, Landscapes, and Networks', *BioScience*, 50(2), p. 133. Available at: https://doi.org/10.1641/0006-3568(2000)050[0133:BCAMSF]2.3.CO;2.

Puschnig, J. *et al.* (2022) 'Long-term trends of light pollution assessed from SQM measurements and an empirical atmospheric model', *Monthly Notices of the Royal Astronomical Society*, p. stac3003. Available at: https://doi.org/10.1093/mnras/stac3003.

Pysarczuk, S. *et al.* (2021) 'Fledermäuse im Nationalpark Gesäuse 2019-2020'.

Reiter, G. *et al.* (2013) 'Impact of landscape fragmentation on a specialised woodland bat, Rhinolophus hipposideros', *Mammalian Biology*, 78(4), pp. 283–289. Available at: https://doi.org/10.1016/j.mambio.2012.11.003.

Riegel, K.W. (1973) 'Light Pollution: Outdoor lighting is a growing threat to astronomy.', *Science*, 179(4080), pp. 1285–1291. Available at: https://doi.org/10.1126/science.179.4080.1285.

Rowse, D., E.G.,. Lewanzik *et al.* (2015) 'Dark Matters: The Effects of Artificial Lighting on Bats', *Bats in the Anthropocene: Conservation of Bats in a Changing World*. School of Life Sciences, University of Bristol, Bristol, UK; Gareth.Jones(at)bristol.ac.uk: Springer. Available at: https://doi.org/10.1007/978-3-319-25220-9_7.

von Ruschkowski, E. (2009) 'Causes and Potential Solutions for Conflicts between Protected Area Management and Local People in Germany'.

Russart, K.L.G. and Nelson, R.J. (2018) 'Artificial light at night alters behavior in laboratory and wild animals', *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, 329(8–9), pp. 401–408. Available at: https://doi.org/10.1002/jez.2173.

Russo, D. and Jones, G. (2003) 'Use of foraging habitats by bats (Mammalia: Chiroptera) in a Mediterranean area determined by acoustic surveys: conservation implications', *Ecography*, 26, pp. 197–209.

Rydell, J. (1992) 'Exploitation of Insects around Streetlamps by Bats in Sweden', *Functional Ecology*. Available at: https://doi.org/10.2307/2389972.

Saldaña-Vázquez, R.A. and Munguía-Rosas, M.A. (2013) 'Lunar phobia in bats and its ecological correlates: A meta-analysis', *Mammalian Biology*, 78(3), pp. 216–219. Available at: https://doi.org/10.1016/j.mambio.2012.08.004.

Schoeman, M.C. (2015) 'Light pollution at stadiums favors urban exploiter bats: Selected urban exploiter bats hunt insects at stadiums', *Animal Conservation*. School of Life Sciences, Westville Campus, University of KwaZulu-Natal, Durban, South Africa; schoemanc(at)ukzn.ac.za: Wiley. Available at: https://doi.org/10.1111/acv.12220.

Schroer, S. *et al.* (2020) *Analyse der Auswirkungen künstlichen Lichts auf die Biodiversität*. Bundesamt für Naturschutz.

Schwab, N.A. *et al.* (2024) 'Roost characteristics and fidelity of silver-haired bat maternity colonies in a floodplain cottonwood forest', *Conservation Science and Practice*, 6(11), p. e13243. Available at: https://doi.org/10.1111/csp2.13243.

Secretariat of the Convention on Biological Diversity - Target 3 (no date). Secretariat of the Convention on Biological Diversity. Available at: https://www.cbd.int/gbf/targets/3 (Accessed: 15 January 2025).

Siddig, A.A.H. *et al.* (2016) 'How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in Ecological Indicators', *Ecological Indicators*, 60, pp. 223–230. Available at: https://doi.org/10.1016/j.ecolind.2015.06.036.

Sordello, R. *et al.* (2022) 'A plea for a worldwide development of dark infrastructure for biodiversity – Practical examples and ways to go forward', *Landscape and Urban Planning*, 219, p. 104332. Available at: https://doi.org/10.1016/j.landurbplan.2021.104332.

Sordello, R., Paquier, F. and Daloz, A. (2021) 'Trame Noire - Méthodes d'élaboration et outils pour sa mise en oeuvre'.

Speakman, J.R., Stone, R.E. and Kerslake, J.L. (1995) 'Temporal patterns in the emergence behaviour of pipistrelle bats, Pipistrellus pipistrellus, from maternity colonies are consistent with an anti-predator respose', *Animal Behaviour*, 50(5), pp. 1147–1156. Available at: https://doi.org/10.1016/0003-3472(95)80030-1.

Spitzenberger, F. (2005) *Rote Liste der Säugetiere Österreichs (Mammalia). In: Zulka, K. P. (Red.): Rote Listen gefährdeter Tiere Österreichs. Checklisten, Gefährdungsanalysen, Handlungsbedarf. Teil 1: Säugetiere, Vögel, Heuschrecken, Wasserkäfer, Netzflügler, Schnabelfliegen, Tagfalter. Grüne Reihe des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft Band 14/1 (Gesamtherausgeberin Ruth Wallner).* Böhlau, Wien.

Stare, J. (2025) *Light pollution map (v2.8.26)*. Available at: https://www.lightpollutionmap.info/#google_vignette (Accessed: 15 January 2025).

Starik, N., Gygax, L. and Göttert, T. (2024) 'Unexpected bat community changes along an urban–rural gradient in the Berlin–Brandenburg metropolitan area', *Scientific Reports*, 14(1), p. 10552. Available at: https://doi.org/10.1038/s41598-024-61317-7.

Stiftung Fledermausschutz (no date) *Einheimische Fledermausarten im Überblick*. Available at: https://fledermausschutz.ch/arten (Accessed: 6 December 2024).

Stone, E.L. *et al.* (2015) 'The impacts of new street light technologies: experimentally testing the effects on bats of changing from low-pressure sodium to white metal halide', *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. School of Biological Sciences, University of Bristol, Life Sciences Building, 24 Tyndall Avenue, Bristol BS8 1TQ, UK; emma.stone@bristol.ac.uk: Royal Society. Available at: https://doi.org/10.1098/rstb.2014.0127.

Suchy, S. and Stoll, S. (2019) 'Lichtverschmutzung und die Vulnerabilität nachtaktiver Insekten'. Jahrbuch des Vereins zum Schutz der Bergwelt (München), 84. Jahrgang 2019, S. 203–226.

Tiroler Umweltanwaltschaft (2015a) *Helle Not - Gewusst wie*. Available at: https://hellenot.org/gute-beleuchtung/gewusst-wie/ (Accessed: 15 January 2025).

Tiroler Umweltanwaltschaft (2015b) *Helle Not - Kunstlicht Historie*. Available at: https://hellenot.org/themen/kunstlicht-historie/ (Accessed: 15 January 2025).

Voigt, C., Azam, C. and Dekker, J. (2018) *Guidelines for consideration of bats in lighting projects*. Bonn: UNEP/EUROBATS (EUROBATS Publication Series, No. 8).

Voigt, C.C. *et al.* (2021) 'The Impact Of Light Pollution On Bats Varies According To Foraging Guild And Habitat Context', *BioScience*, 71(10), pp. 1103–1109. Available at: https://doi.org/10.1093/biosci/biab087.

Voigt, C.C. and Kingston, T. (eds) (2016) *Bats in the Anthropocene: Conservation of Bats in a Changing World*. Cham: Springer International Publishing. Available at: https://doi.org/10.1007/978-3-319-25220-9.

Voigt, C.C. and Lewanzik, D. (2023) 'Evidenzbasierter Fledermausschutz bei Beleuchtungsvorhaben im Außenbereich', in C.C. Voigt (ed.) *Evidenzbasiertes Wildtiermanagement*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 199–230. Available at: https://doi.org/10.1007/978-3-662-65745-4_8.

Wallner, S. (2020) 'Measuring and Modelling Night Sky Brightness - The Impact of Light Pollution'.

Wallner, S. (2024) 'Leitbild zur nachtgerechten und energieeffizienten Nutzung von Außenbeleuchtung zum Schutz des natürlichen Nachthimmels'.

Wallner, S., Puschnig, J. and Stidl, S. (2023) 'The reliability of satellite-based lighttrends for dark sky areas in Austria', *Journal of Quantitative Spectroscopy and Radiative Transfer*, p. 108774. Available at: https://doi.org/10.1016/j.jqsrt.2023.108774.

Welch, D. *et al.* (2024) 'The world at night: Preserving natural darkness for heritage conservation and night sky appreciation.' IUCN WCPA Good Practice Guidelines Series No. 33, Gland, Switzerland: IUCN.

Zagmajster, M. (2014) 'The influence of external lighting on bats. In: Mohar ., . Zagmajster, . Veronik, B. Bota kaerne (2014:) Nature-friendlier lighting of objects of cultural heritage (churches) – Recommendations. Dark-Sky Slovenia: 15-19.'

Zeale, M.R.K. *et al.* (2016) 'Mitigating the Impact of Bats in Historic Churches: The Response of Natterer's Bats Myotis nattereri to Artificial Roosts and Deterrence', *PLOS ONE*. Edited by D. Russo, 11(1), p. e0146782. Available at: https://doi.org/10.1371/journal.pone.0146782.

Zeale, M.R.K. *et al.* (2018) 'Experimentally manipulating light spectra reveals the importance of dark corridors for commuting bats', *Global Change Biology*, 24(12), pp. 5909–5918. Available at: https://doi.org/10.1111/gcb.14462.

Zehlius-Eckert, W. (2001) 'Möglichkeiten und Grenzen der repräsentativen Auswahl von Arten im Naturschutz'.

Zielinska-Dabkowska, K.M. *et al.* (2023) 'Reducing nighttime light exposure in the urban environment to benefit human health and society', *Science*, 380(6650). Available at: https://www.science.org/doi/epdf/10.1126/science.adg5277 (Accessed: 15 January 2025).

Zimmermann, T. (2023) 'Wiederholung der Bestimmung des Erhaltungsgrades der Moore und Moorwälder (7110, 7140, 7150, 7230, 91D0) im Natura 2000-Gebiet Ennstaler Alpen / Nationalpark Gesäuse.'

Zschorn, M. (2024) *Lichtverschmutzung - Methodenentwicklung zur Analyse und Bewertung für die vorsorgende Landschaftsplanung*. Technische Universität Dresden.

Zschorn, M. and Fritze, M. (2022) 'Lichtverschmutzung und Fledermausschutz', *Naturschutz und Landschaftsplanung*, pp. 16–23.

9.2 List of abbreviations

LP…. Light Pollution

ALAN… Artificial Light At Night

IDSR… International Dark Sky Reserve

LMP… Lighting Management Plan

LED… Light Emitting Diode

SQM… Sky Quality Meter

SQC… Sky Quality Camera

NSB… Night Sky Brightness

CCT… Correlated Colour Temperature

ULR… Upward Light Ratio

PA/PAs… Protected Area/ Protected Areas

NP… National Park

WA… Wilderness Area

IUCN… International Union for the Conservation of Nature

DSAG… Dark Sky Advisory Group

CLC… Corine Land Cover

9.3 List of figures

9.4 List of tables