The environmental impact of artificial lighting in urban settings: gaps, challenges, and sustainable lighting design

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Declaration of Independence

Herewith I certify that I have prepared and written my thesis independently and that I have not used any sources and aids other than those indicated by me.

Table of Contents

Thesis outline

This thesis outlines the personal process of constructing a comprehensive narrative for a lighting practice that urgently needs ecological awareness. The work engages theoretical and empirical tasks at the intersection of ecology and lighting design. Additionally, it draws upon insights from various domains, including physics, ecology, science communication, and design. The thesis consists of three published manuscripts and one manuscript in preparation to be submitted to the Journal of Limnology. Each manuscript represents a thesis chapter and contains an introduction, methodology, results, discussion, conclusion, and bibliography section. Chapter 1 introduces the general context of the thesis. Chapters 2 to 4 comprise three peer-reviewed published articles. Chapter 5 comprises a submitted manuscript. Chapters 2 and 3 are literature reviews. Chapters 4 and 5 are experimental studies. Chapter 6 closes with a general discussion, conclusions, and recommendations.

Summary

Artificial light has significantly impacted the value and perception of the night in individuals who apply it, those who develop technologies to supply it, those who assess its environmental impact, and those who use and benefit from it. The unnatural illumination of nightscapes has become seamlessly integrated into society's fabric, making night-time bright and over-illuminated across landscapes where the natural light (e.g. emitted by the moon and stars) is masked by Artificial Light At Night (ALAN). In this way, ALAN has become a pollutant, known as light pollution (LP), that has emerged with the exponential increase of unnatural brightness and the change in spectral composition induced by improperly managed lighting technologies.

ALAN has been shown to alter light environments of nocturnal terrestrial and aquatic habitats, which can impact many organisms' physiological processes, body functions and behaviour, affecting multiple intra- and interspecific interactions and even ecosystem processes. Current technological advances in outdoor lighting have the potential to develop light pollution reduction strategies that balance conflicting societal needs and environmental concerns. However, this potential remains largely untapped due to insufficient communication between ALAN researchers and lighting practitioners. The problem of reducing LP remains complex as it involves the active collaboration between ALAN researchers and lighting practitioners and a lingua franca between experts involved to transfer and translate research into practice. This thesis addresses the environmental impact of artificial lighting in urban settings, including existing communication and knowledge gaps, challenges posed by artificial light in aquatic realms and future perspectives towards sustainable lighting design.

To mitigate the communication gaps between ALAN researchers and lighting practitioners, I propose a transdisciplinary framework between the experts in the practice, research, production, policy-making and planning of light and lighting. In collaboration with experts from ALAN research and the lighting practice, I suggest a four-step process to aid in establishing collaboration between the domains involved.

Moreover, to set a shared understanding between ALAN research and the lighting practice, I propose a collaborative systematic review to aid in the transfer of diverse responses of plants, arthropods, insects, spiders, fish, amphibians, reptiles, birds, and non-human mammals (including bats, rodents, primates, and ungulates) when exposed to ALAN. As well, a mutual agreement on key terms set by representatives from both domains. The systematic review is based on finally 216 studies reporting behavioural and physiological responses across six relevant organism groups. To transfer the results between the research and the lighting practice, collaborative discussions between the experts of each domain resulted in establishing an ALAN lingua franca on key terminologies and definitions related to natural and artificial light as knowledge both domains should acquaint. The collaborative discussions also included a common language on relevant radiometric and photometric parameters that ALAN researchers must consider in their research and lighting practitioners in their day-to-day lighting practice. Also, the discussions led to the proposal of two communication strategies: a communication framework and a knowledge infrastructure scheme to set an ecological ceiling of awareness (responses to avoid) and a lighting foundation (essential knowledge to gain) for a better flow of information between the domains involved. The findings of this study also indicated that aquatic organisms and their realms remain understudied and that further studies on the impact of ALAN on aquatic habitats and their inhabiting biodiversity are needed.

Furthermore, I explored the potential implications of bridge illumination on a river transect to confront the existing knowledge gap on the potential impact of ALAN on riverine systems with illuminated bridges. The light field of a river was quantified from a research vessel considering seven illuminated bridges. The results indicated that LP was induced by surrounding illumination and bridge illumination. Via a conceptual model, the unnatural light scenarios at illuminated bridges and their potential impact on the life history of two migrating fish species, Atlantic salmon and European silver eels, were addressed.

Additionally, at the same river transect and illuminated bridges, patterns of polarised light pollution (PLP) reflecting at the water's surface were quantified near the illuminated bridges, and its potential effects on aquatic insects were discussed.

The findings of the four studies highlight the need for (i) better communication frameworks between experts of ALAN research and the lighting practice, (ii) transdisciplinary interfaces and collaborations to efficiently translate ecological research into the lighting practice, as well as the need for (iii) quantified ALAN and PLP across inland waters to develop sustainable lighting solutions to preserve riverine nightscapes.

This thesis provides communication frameworks to bridge communication gaps, a knowledge infrastructure scheme to mitigate the transfer of knowledge between the domains, evidence on LP and PLP induced by surrounding and bridge illumination on a river transect, together with a conceptual model on ALAN as a potential barrier for migrating fish. Additionally, this thesis discusses transdisciplinary approaches, perspectives inclusive of natural environments, and a vision towards lighting approaches that require an urgent change and concludes with recommendations for the future of ALAN research and the lighting practice.

Graphical abstract

The environmental impact of artificial lighting in urban settings: gaps, challenges, and sustainable lighting design

1. Introduction

2. Proposal of transdisciplinary collaboration

Urban Lighting Research Transdisciplinary Framework—A Collaborative Process with Lighting Professionals

A transdisciplinary communication framework between actors of the research, practice, production inputs, and policy-making and planning of light was proposed with a four-step process to establish collaboration between experts.

3. Collaboration between experts, systematic review and translation of research into practice

A Systematic Review for Establishing Relevant Environmental Parameters for Urban Lighting: Translating Research into Practice

ALAN researchers and Lighting practitonners collaborated to:

- Translate of key terminologies and definitions related to natural and artificial light.
- Establish relevant radiometric and photometric parameters that ALAN researchers must consider in their research and lighting practitioners in their day-to-day lighting practice.

Via a systematic review, 216 studies reported behavioural and physiological responses on six categories of organism groups including plants, arthropods, insects and spiders, fish, amphibians, reptiles, birds, and non-human mammals incuding bas, primate, rodents, and marsupials.

A communication framework and a knowledge infrastructure diagram were created to set a better flow of information between the domains involved.

4. Pilot study on a riverine system: light at night measurements and proposal of a conceptual model

Light pollution from illuminated bridges as a potential barrier for migrating fish — linking measurements with a proposal for a conceptual model

Light at night was measured on a river transect considering stops at seven illuminated bridges from a boat. Light pollution was induced by surrounding and bridge illumination. A conceptual model was proposed to exhibit the potential unnatural light scenarios at illuminated bridges and their potential impact on the life history of two migrating fish species Atlantic salmon and European silver eels.

5. Polarised light pollution measurements and its potential impact on water seeking insects

Polarised light pollution on river water surfaces caused by artificial light at night from illuminated bridges and surroundings

The light field on a river transect where seven illuminated bridges (reported in the pilot study) cross was measured to quantify the potential patterns of polarised light pollution reflected at the water's surface. Surrounding and bridge illumination induced were reflected at the surface of the water inducing polarised light pollution at potential flying paths for water-seeking insects.

6. Discussion, conclusion and recommendations

Zusammenfassung

Künstliches Licht hat den Wert und die Wahrnehmung der Nacht bei denjenigen, die es anwenden, bei denjenigen, die an der Entwicklung von Technologien zu seiner Bereitstellung beteiligt sind, bei denjenigen, die seine Auswirkungen auf die Umwelt beurteilen, und bei denjenigen, die es nutzen, erheblich beeinflusst. Die unnatürliche Beleuchtung von Nachtlandschaften hat sich nahtlos in das gesellschaftliche Gefüge integriert und macht die Nacht zu einer hellen und übermäßig beleuchteten Landschaft, in der das natürliche Licht (z. B. des Mondes und der Sterne) durch künstliches Licht bei Nacht (Artificial Light At Night, ALAN) überdeckt wird. Auf diese Weise ist ALAN zu einem Schadstoff geworden, der als Lichtverschmutzung (Light Pollution, LP) bezeichnet wird und mit der exponentiellen Zunahme der unnatürlichen Helligkeit und der Veränderung der spektralen Zusammensetzung durch unsachgemäß gesteuerte Beleuchtungstechnologien entstanden ist.

ALAN verändert nachweislich die Lichtverhältnisse in nächtlichen terrestrischen und aquatischen Lebensräumen, was sich auf die physiologischen Prozesse, die Körperfunktionen und das Verhalten vieler Organismen auswirken kann und zahlreiche intra- und interspezifische Interaktionen und sogar Ökosystemprozesse beeinträchtigt. Die derzeitigen technologischen Fortschritte bei der Außenbeleuchtung haben das Potenzial, Strategien zur Verringerung der Lichtverschmutzung zu entwickeln, die einen Ausgleich zwischen den widersprüchlichen Bedürfnissen der Gesellschaft und den Umweltbelangen schaffen. Dieses Potenzial bleibt jedoch aufgrund der unzureichenden Kommunikation zwischen ALAN-Forschern und Beleuchtungspraktikern weitgehend ungenutzt. Das Problem der Verringerung der Lichtverschmutzung ist nach wie vor komplex, da es eine aktive Zusammenarbeit zwischen ALAN-Forschern und Beleuchtungspraktikern sowie eine gemeinsame Sprache zwischen den beteiligten Experten erfordert, um die Forschung in die Praxis zu übertragen und umzusetzen. Diese Arbeit befasst sich mit den Umweltauswirkungen der künstlichen Beleuchtung in städtischen Gebieten, einschließlich bestehender Wissenslücken, potenzieller Kommunikationsprobleme und zukünftiger Perspektiven für eine nachhaltige Beleuchtungsplanung.

Um die Kommunikationslücken zwischen ALAN-Forschern und Beleuchtungspraktikern zu schließen, schlage ich einen transdisziplinären Rahmen zwischen den Experten aus der Praxis, Forschung, Produktion, Politik und Planung von Licht und Beleuchtung vor. In Zusammenarbeit mit Experten aus der ALAN-Forschung und der Beleuchtungspraxis schlage ich einen vierstufigen Prozess vor, um die Zusammenarbeit zwischen den beteiligten Bereichen zu fördern.

Um ein gemeinsames Verständnis zwischen der ALAN-Forschung und der Beleuchtungspraxis zu schaffen, schlage ich eine gemeinsame systematische Überprüfung

vor, um die Übertragung der verschiedenen Reaktionen von Pflanzen, Arthropoden, Insekten, Spinnen, Fischen, Amphibien, Reptilien, Vögeln und nicht-menschlichen Säugetieren (einschließlich Fledermäusen, Nagetieren, Primaten und Huftieren) zu erleichtern, wenn sie ALAN ausgesetzt sind, sowie eine gemeinsame Vereinbarung von Vertretern beider Bereiche über Schlüsselbegriffe und Definitionen. Die systematische Überprüfung basiert auf 216 Studien, die über Verhaltens- und physiologische Reaktionen bei sechs relevanten Organismengruppen berichten. Um die Ergebnisse zwischen der Forschung und der Beleuchtungspraxis zu übertragen, wurde in gemeinsamen Diskussionen zwischen den Experten beider Bereiche eine ALAN-Lingua Franca zu den wichtigsten Begriffen und Definitionen im Zusammenhang mit natürlichem und künstlichem Licht als Wissen, das beide Bereiche kennen sollten, erstellt. Die gemeinsamen Diskussionen umfassten auch eine gemeinsame Sprache für relevante radiometrische und photometrische Parameter, die ALAN-Forscher in ihrer Forschung und Beleuchtungspraktiker in ihrer täglichen Beleuchtungspraxis berücksichtigen müssen. Die Diskussionen führten auch zum Vorschlag zweier Kommunikationsstrategien: ein Kommunikationsrahmen und ein Wissensinfrastrukturschema, um eine ökologische Obergrenze des Bewusstseins (zu vermeidende Reaktionen) und eine Beleuchtungsgrundlage (zu erwerbendes Grundwissen) für einen besseren Informationsfluss zwischen den beteiligten Bereichen festzulegen. Die Ergebnisse dieser Studie zeigen auch, dass aquatische Organismen und ihre Lebensräume noch zu wenig erforscht sind und dass weitere Studien über die Auswirkungen von ALAN auf aquatische Lebensräume und die darin lebende biologische Vielfalt erforderlich sind.

Darüber hinaus untersuchte ich die potenziellen Auswirkungen der Brückenbeleuchtung auf einem Flusstransekt, um die bestehende Wissenslücke über die potenziellen Auswirkungen von ALAN auf Flusssysteme mit beleuchteten Brücken zu schließen. Das Lichtfeld eines Flusses wurde von einem Forschungsschiff aus quantifiziert, wobei sieben beleuchtete Brücken berücksichtigt wurden. Die Ergebnisse zeigten, dass die LP durch die Umgebungsbeleuchtung und die Beleuchtung der Brücke hervorgerufen wird. Anhand eines konzeptionellen Modells wurden die unnatürlichen Lichtszenarien an beleuchteten Brücken und ihre potenziellen Auswirkungen auf die Lebensgeschichte von zwei wandernden Fischarten, dem Atlantischen Lachs und dem Europäischen Blankaal, untersucht.

Zusätzlich wurden am gleichen Flussabschnitt und an den beleuchteten Brücken die Muster der polarisierten Lichtverschmutzung (PLP), die an der Wasseroberfläche reflektiert wird, in der Nähe der beleuchteten Brücken quantifiziert und ihre möglichen Auswirkungen auf Wasserinsekten diskutiert.

Die Ergebnisse der vier Studien verdeutlichen die Notwendigkeit (i) eines besseren Kommunikationsrahmens zwischen Experten der ALAN-Forschung und der Beleuchtungspraxis, (ii) transdisziplinärer Schnittstellen und Kooperationen, um ökologische

Forschung effizient in die Beleuchtungspraxis zu übertragen, sowie die Notwendigkeit (iii) quantifizierter ALAN- und PLP-Werte für Binnengewässer, um nachhaltige Beleuchtungslösungen zur Erhaltung der nächtlichen Flusslandschaften zu entwickeln.

Diese Arbeit bietet einen Kommunikationsrahmen zur Überbrückung von Kommunikationslücken, ein Wissensinfrastrukturschema zur Abschwächung des Wissenstransfers zwischen den Bereichen, Beweise für LP und PLP, die durch die Umgebungs- und Brückenbeleuchtung an einem Flussquerschnitt induziert werden, zusammen mit einem konzeptionellen Modell für ALAN als potenzielles Hindernis für wandernde Fische. Darüber hinaus erörtert diese Arbeit transdisziplinäre Ansätze, Perspektiven, die natürliche Umgebungen einschließen, und eine Vision für Beleuchtungsansätze, die eine dringende Änderung erfordern, und schließt mit Empfehlungen für die Zukunft der ALAN-Forschung und die Beleuchtungspraxis.

List of publications with author contributions

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List of Figures

List of Appenndix Figures

List of Tables

List of Appendix Tables

List of Supplementary Tables

Chapter 1: Introduction

1.1. ALAN

ALAN has been considered an integral asset to human night-time experience [1-3]. It has introduced varied unnatural scenarios and illumination types to night-time environments. For instance, bright modes of passage have been implemented along pedestrian and vehicular roads; artificial illumination has been used to show the architectural structure of buildings, monuments, and landmarks; illuminated pathways through greeneries and illuminated bridges to cross waterways at night [1-4]. As shown in Figure 1, the application of ALAN constitutes unnaturally bright and colourful scenarios that make spaces visible at night using artificial illumination tailored to human daytime vision [4,5]. It is an optical change that disperses across nocturnal landscapes [6–8] and extends to natural environments, including inland waters and floodplains [9–12]. It has negatively altered terrestrial and aquatic habitats and organisms' exposure to natural cycles — light and dark [12–15], deteriorating the night skies, human well-being, and the behaviour and physiology of flora and fauna [15–19]. It creates a continuous and artificial light exposure cycle that can disrupt biological rhythms. It may also lead to the inhibition of melatonin — the night hormone that regulates the temporal organisation of physiological and behavioural functions, specifically concerning daily and seasonal environmental changes [18]. Research studies have shown various vertebrate species with altered melatonin levels even when exposed to low light levels of ALAN [18]. Alarmingly, the empirical evidence on the ecological consequences of ALAN sustains that LP threatens biodiversity [19–21] as negative behavioural and physiological changes have occurred across taxa [15,17–19]. Diverse groups, including micro-organisms, and terrestrial and aquatic species, are threatened by an artificial 24-hour exposure to light due to improperly managed ALAN. Nevertheless, the application of ALAN also highlights the two sides of a shared coin — it demonstrates the virtue of enduring lighting technologies that have allowed to extend the active hours of the day into the night [22] and the vice of over-illuminating or polluting with light, at the expense of losing the night [6,7,10].

The problem of LP not only stems from the inadequate management of ALAN but is also a consequence of the deficient communication between the domains of ALAN research and lighting practice. The lack of effective communication between fields has hindered a shared language that could aid in transferring ALAN evidence into applicable lighting solutions, especially for preventing LP near natural environments such as green spaces and water bodies. The effective mitigation of LP hinges on communication and awareness of the problem, shared values for the protection of the night, shared perspectives on the environmental impact of lighting technologies, and common knowledge on environmental conservation.

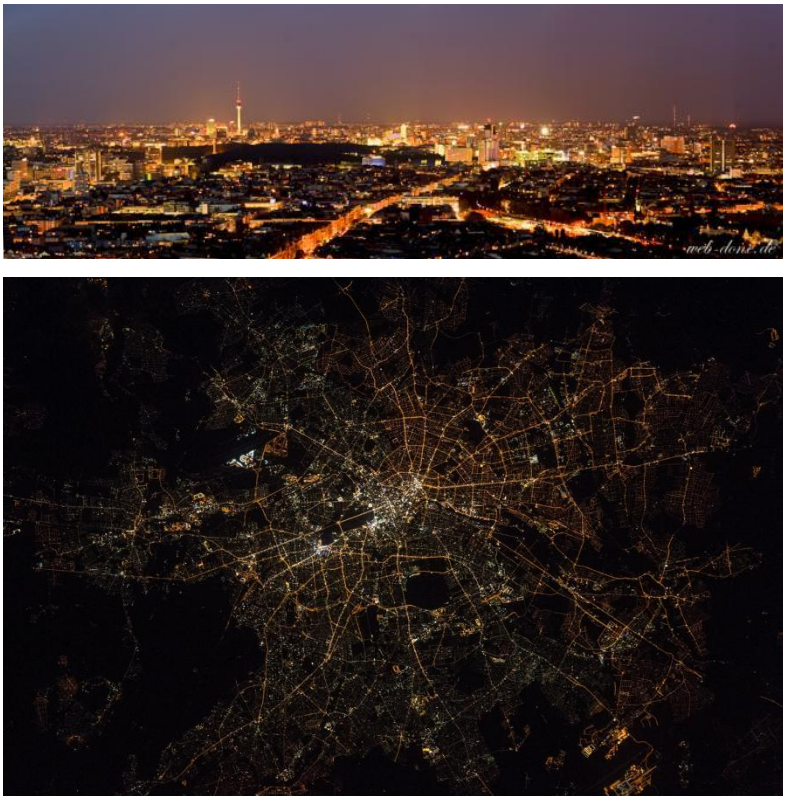

Figure 1. Panorama and view from above of Berlin's illuminated cityscape. (a) Alexander Steinhof, (b) Berlin at night (ISS047-E-29989), 2016. Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

1.2. ALAN as a pollutant — Attribution of meaning

The definition of LP can vary from one field to another, and the difference in terminologies can constitute the perspectives involved. ALAN researchers investigate what, when, where, and how ALAN is a pollutant. They gather research-based evidence and communicate the potential consequences of the pollutant. Firstly, the observed disturbance of the night sky during night-time was addressed as *photo pollution* [9,]. This phenomenon was later defined as LP when artificial brightness trespasses, glares, or clutters the night sky, producing energy waste and urban sky glow [24]. Secondly, when exposed to LP or artificial illumination at night, the impact of this pollutant was investigated in varied organisms. It revealed negative responses in the physiology and behaviour across taxa and coined the term *ecological light pollution* (ELP) to describe its impact [15,16]. Thirdly, the interdisciplinarity of fields researching the night — *nyctology* [25] and light as a pollutant of the night brought together the term *ALAN* [26], which defines any artificial light form used at night that induces a negative outcome [7,10,16,20]. It includes directly visible point light sources, or unshielded luminaires, that radiate light outside the edges of its intended region (e.g. towards the sky, in rivers, or greeneries). If the luminaire is not properly shielded, then its emission is likely to extend as indirect incident ALAN (skyglow) into dark [14,27], pristine environments [11,12], with illuminance (radiance) levels that often meet twilight standards [27,28] that operate during late hours of the night where no user is present or/and with spectral distributions rich in short-wavelengths or ultraviolet (UV) radiation [20,30]. The term of art for *ALAN* is well integrated across night studies, contributing to the knowledge that ALAN is a potential stressor [26,30].

At the same time, lighting practitioners and designers have traditionally studied the aesthetic and functional use of artificial illumination based on human-centric approaches and rendered designs with it. Recently, LP gained attention in the lighting practice [31–34]. However, the definition often considers LP a phenomenon that can occur solely in the night sky as the night sky brightens [35]. It involves a definition that unintentionally neglects the ecological consequences of ALAN and its negative impact on terrestrial and aquatic habitats. The prevailing understanding within the lighting practice characterises LP as a phenomenon caused by the excessive use of outdoor illumination that typically is associated with applied light based on misconceptions of increased light levels, or human daytime standards, as a beneficial solution to combat night-time crime, celebrate culture, economy and tourism [4,34]. Efforts to broaden the definition of LP and the value of emitting less light into the lighting practice have been attempted by researchers involved in the lighting practice [36–38]. Nevertheless, the current lighting design approaches for outdoor illumination continue to consider artificial light emissions in areas where it is not needed, during late hours of the night with no users present, and with unnatural brightness and colours. An example of such include the use of media architecture (e.g. self-luminous digital media such as screens and advertisements), light architecture (e.g. uplit building façades) [39,40] and illuminated structures passing through green spaces or waterways (e.g. illuminated trees and bridges) [14,34,41–43].

There seems to be a discrepancy in the interpretation of ALAN and a notable lack of common ground between ALAN research and the practice of lighting, which can alter the collective prescription of ALAN that can aid transfer approaches to reduce LP.

1.3. Existing gaps between ALAN research and the lighting practice

The difference in terminologies and perspectives on ALAN can be attributed to the need for communication, common language, and collaboration between the fields of ALAN research and the practice of lighting. A communication gap suggests existing knowledge lagoons regarding the applied tool and ALAN as a pollutant.

The field of ALAN research has sufficient literature that gathers the parameters of applied ALAN that need to change (e.g. the unnecessary emission of light in zones with no users at night, the direction of light into areas such as floodplains and waterbodies, the geometry of emitted light outside the intended area, the use of unnecessary illuminance levels, the upward emission of light, emission of light into pristine environments and environmental zones, unshielded luminaires, the lack of applied curfew hours to avoid illumination during late hours of the night, and the unnecessary emissions of ultraviolet wavelengths) and the measures that need to be acquainted by the professionals responsible of applying ALAN [30,44–46]. Nevertheless, LP has increased in recent years, regardless of the recommendations and guidelines available to lighting professionals.

In 2016, LP was reported to have increased worldwide by more than 2% yearly [6]. In 2023, European metropolitan cities reported an increase in LP where urban areas exhibited an increase of 1.7% per year, 1.8% in rural areas per year and 3.7% in intermediate areas per year [47]. Two recent studies demonstrated an increase in artificial sky brightness of 9.6% between 2011 and 2022 [48,49]. This increase suggests that the communication between ALAN researchers and lighting professionals is still an unfulfilled objective and that collaboration between experts may aid in bridging knowledge gaps on ALAN to transfer and translate insights on its ecological consequences [50-52].

As LP increases, lighting professionals must become aware of the consequences of the applied tools and the physical light parameters. If scientific results remain encrypted in scientific language commonly used only by ALAN researchers then it is likely for lighting practitioners to not grasp the problem, raise awareness, nor develop sustainable lighting outcomes to reduce LP. In addition, the lack of ecological foundation in the lighting practice hinders the proper understanding of the consequences and challenges involving the impact of lighting technologies.

The current habit of over-illuminating nightscapes reflects a lighting practice that prefers unnaturally bright nights that still need to integrate ecological conservation measures. This problem also implies the need to transfer the existing knowledge to preserve the night [50,51]. Lighting practices require evidence-based research to develop careful approaches to mitigate LP. Collaboration must become an objective to bridge communication and knowledge gaps between ALAN researchers and lighting practitioners, as it can aid in creating transferable knowledge from one field to another [52-54]. Such collaboration is crucial to introduce the interest in reducing LP and to develop sustainable lighting practices that preserve the night.

1.4. Mitigating collaboration to transfer ecological knowledge

It is crucial to foster inter- and transdisciplinary collaborations to initiate an ecologically inclusive design thinking process beyond conventional human-centric lighting concepts [52–55]. Exploring collaborations between experts of ALAN research and the lighting practice can only enrich the current body of knowledge. Mitigating communication between these two fields can set the foundation for transferring evidence-based knowledge from one field to the another [56]. For instance, the collaboration between domains can expand the current understanding of LP, a phenomenon typically considered by lighting practitioners to only occur above the urban built environment and over skylines. Collaboration between the fields can redefine the understanding of LP into any form of artificial illumination that induces a negative outcome. Also, collaboration can set a common language between the fields and expand the current limited scales of knowledge on ecology in the lighting practice. Unobstructed ecological knowledge transfer flow can provide a new meaning to preserve the night. It can raise awareness of the lighting approaches used, particularly in understudied systems, such as night-time aquatic environments [11,12,14,57], where varied forms of ALAN have been shown in recent studies to create unique and unnatural light scenarios [12,14], as shown in Figure 2.

The gathered knowledge on ecological conservation in the field of ALAN research can facilitate a more in-depth comprehension of the multiple levels of biodiversity that directly and indirectly respond to ALAN. The lighting practice, as a young and hybrid discipline linked to architecture, design, and arts and with an engineering-oriented industry [57], has yet to establish an ecological knowledge foundation to shift towards a sustainable lighting dialogue about applied light that addresses the ecological consequences beyond approaches centered only in humans.

Figure 2. Day-time and night-time views of Oberbaumbrücke, in Berlin, Germany. (a) Oberbaümbrücke after dusk, minutes before the lighting system of the bridge and its surroundings turns on. (b) Illuminated Oberbaumbrücke after dusk. Photos by: (a) Ahma; (b) Catherine Pérez Vega.

1.5. Examining the potential threat of night-time illuminated bridges for inland waters

Inland waters have become brighter by night as most human settlements are proximate to coastal waters, rivers, and lakes [59,60], and bridges that cross waterways are frequently illuminated at night. Artificially illuminated bridges typically promote traffic safety and comfort conditions, and their illumination shows bridges as iconic elements of the urban fabric [42,43,61]. As the presence of ALAN and LP has extended beyond its source of origin and reached aquatic habitats [6,62], examining the light scenarios induced by structures that cross freshwater systems and their potential consequences is imperative.

Bridge structures commonly have integrated lighting systems that apply artificial illumination beyond traffic safety [63] and into architectural elements of bridges such as girders, arcs, piers, beams, trusses, etc. These elements do not necessarily aid passage and are rather used to exhibit bridges as landmarks of the urban landscape or as public art installations to engage users at night [42,43,63].

Illuminated bridges have become representative landmarks of the night skyline of cities and towns [42,61,64], even when their illumination could imply a potential ecological threat to aquatic biodiversity in urban waterways (reviewed in [12,14,21]). The effects of illuminated bridges on aquatic environments and across aquatic taxa remain understudied. Nonetheless, certain studies suggest that bridge illumination can alter (i) the optics of aquatic landscapes by night once ALAN meets the water interface (ii) and behaviour across taxa, including the use of a landscape by both aquatic and terrestrial organisms [11,65–67].

In recent years, three field experiments have demonstrated altered behaviours when organisms are exposed to the night-time illumination of a bridge crossing a river. For instance, an increase in insect abundance that altered the food chain of the St. Lawrence River in Montréal, Canada, was reported induced by night-time illumination of the Jacques Cartier Bridge. Positive phototaxis, or the attraction of an organism to a source of light, was induced predominantly in Diptera when exposed to the bridge illumination of the Jacques Cartier Bridge, which increased the foraging activity of cliff swallows *Petrochelidon pyrrhonota*, and followed by the attraction of peregrine falcons *Falco peregrinus* [41,61]. Moreover, mayflies *Ephoron virgo* were reported to respond with strong positive phototaxis light emissions from unshielded luminaires located at the Columbia-Wrightsville Bridge, known as the Veterans Memorial Bridge, spanning the Susquehanna River in Pennsylvania, United States [68]. Furthermore, the positive phototaxis of Rainbow trout *Oncorhynchus mykiss* resulted in a density increase of Rainbow trout when exposed to the illumination of the Sundial Bridge, spanning the Sacramento River, in Redding, California, United States. The lighting system integrated into the Sundial Bridge emitted direct ALAN on the waterway section, known as the spawning habitat of the endangered winter-run Chinook salmon *Oncorhynchus tsawytscha* [69]. These three evidence-based examples (see Figure 3) highlight the importance of investigating the potential impact of illuminated bridges, the potential light scenarios induced by the illuminated bridges and the optical changes in the aquatic nightscape that can disrupt behaviours in an otherwise dark environment.

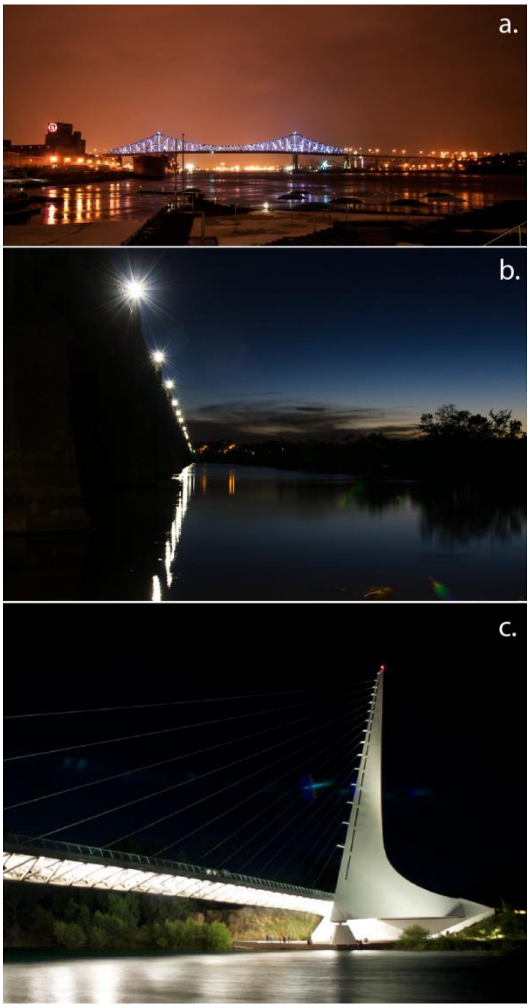

Figure 3. Overview of three illuminated bridges that reported an altered behaviour in species when exposed to bridge illumination. (a) Jacques Cartier Bridge spanning the St. Lawrence river in Montréal Quebéc. Image source: Axel Drainville, Flickr, CC BY-NC 2.0 DEED. (b) Columbia-Wrightsville Bridge, Veterans Memorial Bridge spanning the Susquehanna river in Pennsylvania, USA. Image source: Zac Evans, Flickr, CC BY-NC-ND. (c) Sundial Bridge spanning Sacramento river in Redding, California, United States. Image source: Greg Vierra, Flickr.

ALAN from illuminated bridges and reaching inland waters needs further investigation as little attention has been given to what occurs when ALAN reaches the water interface. ALAN is likely to become transmitted underwater into the water column, reflected at the water's surface through the horizontal polarisation of light, or create PLP [70,71]. The first scenario, ALAN transmitted underwater, will likely unfold unnatural changes underwater during periods typically in darkness and in areas that remain relatively less illuminated at night (e.g. deeper in the water column). Thus, ALAN underwater can potentially hinder the behaviour of individuals relying on natural day-night cycles (light and dark changes). Changes in the nocturnal visual environment have been shown to alter aquatic species' dispersal [66], migration [72], and movement behaviour [73,74]. The second scenario, ALAN at the water's surface, is likely to induce horizontally polarised ALAN by reflection, which might introduce PLP [71]. PLP is a phenomenon that can result from the reflection of natural or artificial illumination that can occur on artificial surfaces or waterbodies [75]. It has been shown to alter the upstream flights in mayflies *E. virgo*, inducing stop-overs at illuminated surfaces that artificially create polarised light, a characteristic particular of waterbodies used by species sensitive polarised signals to detect the surface of the water [67,76].

Furthermore, ALAN induced in such systems can interfere with the behaviours and biological processes of various species. For instance, interrupted movements and altered distribution, and avoidance of light in eels *Anguilla anguilla* [72,73], altered insect drift [57], the drift in gammarids [65], disrupted diel vertical migration of zooplankton [11], altered diel movement during migration in Atlantic salmon *Salmo Salar* [74,77], modified predator and prey interactions [78], interrupted flying path for bats above urban waters [66], positive phototaxis and polarotaxis (attraction to polarising surfaces) in mayflies during their upstream flights [76]. Thus, ALAN from illuminated bridges in riverine systems needs to be better researched as ALAN can induce a light barrier that can potentially disrupt the movement of aquatic species. Often, little attention is given to freshwater systems as ALAN is applied on land, and it is hardly perceived that illumination can threaten the natural light and dark cycles in these biodiversity hotspots. Bridge illumination near aquatic habitats can disrupt the energy expended in dispersal, movement, or altered migration patterns for underwater organisms and those above the water.

1.6. Thesis aims and approaches

Considering the existing lack of communication and exchange of knowledge between the research and practice of lighting, the need to transfer knowledge between domains that remain distant, the need to incite the lighting practitioner‘s interest in ecological conservation, the use of communication strategies using design approaches in ALAN research, and the understudied impact of ALAN on aquatic realms, this thesis investigates the environmental impact of artificial lighting in urban settings: gaps, challenges and sustainable lighting design. Four chapters explore the crossroads of ecology and lighting design, with a focus on transdisciplinary collaboration that integrates ecological knowledge applicable to the lighting practice (Chapter 2 and Chapter 3), including two pilot studies involving the impact of bridge illumination on the river Spree in Berlin, Germany (Chapter 4 and 5).

Chapter 2 aims to convey the contrasting perspectives of ALAN researchers and lighting practitioners, which often involves a communication process that typically requires more meaningful exchange to efficiently transfer the problem of LP in pursuit of sustainable lighting objectives. Here, it is hypothesized that transdisciplinary communication can aid in establishing and transferring ecological knowledge gathered in the field of ALAN research as an applicable solution to the lighting practice domain. The challenges, the regulatory frameworks, perspectives of the night, and the lingua franca of both fields are compared to propose a framework that can aid in reducing the knowledge gaps between the experts involved. The urban lighting research transdisciplinary framework (ULRTF) is proposed to facilitate the interaction between crucial pillars involving research, practice, production inputs, and policy-making and planning of lighting.

Chapter 3 aims to foster the collaboration between LP experts and lighting practitioners to collectively identify and report relevant environmental parameters and the impact of ALAN on various organism groups as transferable knowledge to the lighting practice. Here, it is hypothesized that organism groups, including plants, arthropods, insects, spiders, fish, amphibians, reptiles, birds, and non-human mammals (including bats, rodents, primates, and ungulates) present behavioural and physiological responses when organisms are exposed to ALAN. A systematic review following the PRISMA guidelines was used to review the impact of ALAN across different relevant taxa. Chapters 2 and 3 were carried out during the first two years. Chapters 3 and 4 highlighted, among other things, the need to address more research on night-time illuminated freshwater systems, as few studies have covered the impact of illuminated bridges on aquatic habitats. In Chapters 4 and 5, this research gap on the potential impact of ALAN on aquatic systems is addressed, and the aim is to obtain night-time measurements of a river system's impact by bridge illumination.

Chapter 4 aimed to obtain night-time measurements from a research vessel to determine the light levels along a transect of the river Spree in Berlin, Germany. Here, it is hypothesized that LP is induced at seven illuminated bridges that cross the selected Spree transect, which threatens the river's natural heterogeneity of the light environment at night and, thus, the responses of migratory fish. The light measurements should help describe the typical light scenarios occurring at illuminated bridges to propose concepts-based research for the behaviour of fish migrating species when exposed to light at night. Along a 10 km transect, ALAN was quantified with sky radiance and camera measurements at seven illuminated bridges. At these bridges, different types of possible light barriers were identified and the potential effect of two light barrier types on migratory fish were estimated to propose a conceptual framework focusing on two distinct aquatic species — Atlantic salmon smolts (*S. salar*) and European silver eel (*A. anguilla*). The measurements of this pilot study were carried out over one night, while the analysis of the measurements was carried out over two years.

Chapter 5 aimed to obtain ground-based and night-time measurements on the same transect of a river Spree, described in Chapter 4, to exhibit illuminated bridges as potential PLP hubs that could mask moonlight polarisation. Here, it is hypothesized that ALAN from seven illuminated bridges and surroundings is horizontally polarised by reflection at the water's surface. It is an optical change that can interfere with the natural moonlight polarisation signals reflected off the water's surface and the behaviour of organisms sensitive to the polarisation of light at night. The reflection of ALAN-induced polarisation patterns was quantified at the water's surface to determine ALAN's degree of linear polarisation. The measurements of this pilot study were carried out over one night, while the measurements' analysis was carried out for one year. These chapters provide insights into communication strategies, ALAN's potential impact on riverine systems, and their inhabiting fauna's movement and dispersal.

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Chapter 2:

Urban Lighting Research Transdisciplinary Framework—A Collaborative Process with Lighting Professionals

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2.1. Abstract

Over the past decades, lighting professionals have influenced the experience of the night by brightly illuminating streets, buildings, skylines, and landscapes 24/7. When this became the accepted norm, a dual perspective on night-time was shaped and the visual enjoyment of visitors after dusk was prioritized over natural nightscapes (nocturnal landscapes). During this time, researchers of ALAN observed and reported a gradual increase in unnatural brightness and a shift in colour of the night-time environment. As a consequence, ALAN has been identified as a relevant pollutant of aquatic and terrestrial habitats, and an environmental stressor, which may adversely affect a wide range of organisms, from micro-organisms to humans. Unfortunately, lighting professionals and ALAN researchers usually attempt to solve today's sustainable urban lighting problems distinctive to their fields of study, without a dialogue between research and practice. Therefore, in order to translate research knowledge as an applicable solution for the lighting practice and to minimize the impact on the environment, a collaborative framework involving a transdisciplinary process with lighting professionals is crucial to potentially bring the practice, research, production, decision-making, and planning closer to each other. This paper presents a framework to help reduce the existing gap of knowledge, because appropriate lighting applications depend upon it. Access to less light polluted nightscapes in urban environments is just as important as access to unpolluted water, food, and air. This call for action towards sustainable urban lighting should be included in future lighting policies to solve the urgent environmental and health challenges facing our world.

2.2. Introduction

Today, most cities and towns have a prolific network of artificial light at night (ALAN) that illuminates traffic and pedestrian routes, as well as buildings and landscapes, not only for visibility but also to provide visitors and residents with visual enjoyment and entertainment after dusk [1,2].

Over time, as the network of ALAN expanded from urban to peri-urban environments towards rural landscapes [3], the globe has endured the spread of unnatural brightness and vivid colors of light at night, which is today encroaching into new territories that were previously unlit [4].

Over the past two decades, night-time studies have reported evidence on the presence of ALAN as an unintended form of anthropogenic pollution, known as LP [5,6] and ELP [7] which has significantly increased over the years [4,8,9]. It has been described as the inappropriate application and management of artificial light sources and luminaires cohered to the rapid development of urbanization, which leads to the unnecessary and undesired emissions of ALAN across landscapes [10,11]. The latest research on the environmental impact of ALAN indicates that night-time environments in aquatic and terrestrial ecosystems are increasingly impacted by light pollution [12,13,14,15]. ALAN has become a stressor of natural cycles and biological processes that potentially threatens biodiversity [16,17,18,19], and biological rhythms in humans and nature [20,21,22,23,24]. Moreover, an induced suppression of melatonin, the night hormone, has been reported in various vertebrate species [25] even when exposed to comparative low skyglow light levels. Although the lighting practice has gained awareness of the concept of light pollution, [26,27] as the result of incorrectly managed properties of artificial lighting, the challenge remains to translate research notions beyond the known concept of light as a pollutant to the actual planning and design of lighting schemes that provide appropriate illuminance levels for visibility, whilst also protecting the natural night-time environment [11,28,29,30,31].

2.3. Challenges for the Practice

Practical solutions to address the rapid rise of ALAN and minimize its adverse effects have become challenging and complicated to implement due to various reasons.

2.3.1. Reasons to Consider

Firstly, the prompt development of urbanization encouraged the planning, designing, and application of technical lighting parameters that centered on users [32]. These solutions corresponded to photopic vision during the day [33], which is the visual sensitivity and ability to see when exposed to bright environments [34]. Eventually, the simulation of daylight conditions for night-time environments was implemented as a means to translate a sense of visual understanding across night-time landscapes. The lighting practice recognized the application of artificial lighting as a way to provide safe passage for pedestrians and to allow vehicles to circulate at night [35,36], but environmental concerns were usually ignored. This use of artificial lighting soon became an environmental concern because luminaires were continuously operated from dusk to dawn, which impaired circadian rhythms (set by location-specific natural day and night cycles). It also created a continuous period of brightness with unnatural colors of light at night, emitted from artificial lighting across landscapes.

Secondly, potential environmental problems related to, for example, biodiversity and the protection of natural nightscapes have rarely been discussed in the lighting practice [37,38,39]. This is mostly owing to the fact that to understand the impact of artificial lighting technologies on biodiversity, at least a basic disciplinary knowledge of ecology is required.

Thirdly, in recent years, the lighting industry and its practice continues to promote the replacement of conventional lighting technologies (e.g., high- and low-pressure sodium—LPS and HPS) to solid-state lighting applications (with the focus on light-emitting diodes—LEDs). LEDs are considered a “sustainable lighting solution” that delivers higher efficacy at a lower cost. However, saving energy costs does not solve the problem of increased emissions of light at night (rebound effects, e.g., [4,40]) or luminaires that direct undesired and unnecessary light upwards, without considering the impact of downward emissions towards aquatic and terrestrial environments, whilst also operating luminaires continuously from dusk to dawn.

Lastly, in regards to the temporal and spatial emission patterns of ALAN, the current discussion about light pollution and available lighting standards and guidelines, both focus solely on the protection of the night sky [41,42,43,44]. However, the evaluation of obtrusive light and the approval of lighting installations as an enforced practice rarely occurs [26]. Although in some countries there are existing regulatory frameworks such as guidelines, procedures, standards and codes, or legal acts relevant for urban lighting and light pollution (Table 1), unfortunately there are no globally established design and technical parameters available for lighting projects that aim to be respectful to ecology and the natural environment. Most often, the lighting design process lacks an Ecological Impact Assessment in Feasibility Study, which may vary from one country to the next [45,46]. Additionally, lighting professionals and ALAN researchers usually attempt to overcome problems particular to their field of expertise, with insufficient dialogue across research and practice disciplines. The vocabulary and know-how of both domains differ, as they address issues that are specific and relevant to their field of study.

Table 1. Examples of regulatory frameworks for urban lighting and light pollution based on [40,47,48] and references therein.

Category	Year	Name	Country of Origin
Guidelines	1997	CIE 126-1997. Guidelines for minimizing sky glow by the International Commission on Illumination (CIE)	International
	2009	Artificial Light in the Environment Report by the Royal Commission on Environmental Pollution	UK
	2017	CIE 150:2017. Guide on the Limitation of the Effects of Obtrusive Light from Outdoor installations, 2nd Edition by the International Commission on Illumination (CIE)	International
	2018	IDA – International Dark Sky Community Program Guideline	International
	2019	The Austrian Guidelines for Outdoor Lighting, by the Department of Environmental Protection	Australia
	2020	GN01-20. Guidance Note 1 for the reduction of obtrusive light 2020 by the Institution of Lighting Engineers (ILE)	UK
Procedures	2002	A handbook of practical guidelines for managing street lighting to minimise impacts on sea turtles by the Florida Power Company, Coastal Roadway Lighting Manual	USA
	2011	Model Lighting Ordinance (MLO) – User's Guide by the International Dark Sky Association (IDA) and Engineering Society of North America	USA/ International
	2018	Dark Sky Manual For Homeowners by the Utah State Parks	USA

Table 1. Examples of regulatory frameworks for urban lighting and light pollution based on [40,47,48].

Category	Year	Name	Country of Origin
Standards and Codes	1989/ 2011	Flagstaff Outdoor Lighting Code	USA
	2003/ 2015	EN 13201-2: Road lighting - Part 2: Performance requirements	EU
	2014	EN 12464-2 Light and Lighting - Lighting of Work Places, Part 2: Outdoor Work Places by the European Committee for Standardization (CEN)	EU
	2020	ANSI/IES LP-11-20 Environmental Considerations for Outdoor Lighting by the American National Standards Institute and Illuminating Engineering Society	USA/ International
Legal Acts	1958	Flagstaff Lighting Ordinance	USA
	2006	Section 102 of the Clean Neighbourhoods and Environment Act (2005)	UK
	2007	Light Pollution Law concerning street lighting, facade illumination	Slovenia
	2011	Public Lighting decree in Berlin	Germany
	2011	Decree No. 2011-831 of 12 July 2011 on the prevention and limiting of light pollution	France

Table 1. Examples of regulatory frameworks for urban lighting and light pollution based on [40,47,48].

Category	Year	Name	Country of Origin
Legal Acts	2013	Light pollution Law	France
	2012	Decree No. 2012-118 of 30 January 2012 on the outdoor advertising, signs and signposting	France
	2013	Order of 25 January 2013 on the night-time lighting of non-residential buildings in order to limit light pollution and energy consumption	France
	2018	Decree of 27 December 2018 on the prevention, reduction and limitation of light pollution	France

Consequently, the adoption of collaborative practices via the exchange of vocabulary, expertise, and knowledge rarely occurs, even if both lighting practitioners and ALAN researchers have an increasing interest in collaboration [2,49,50,51].

2.3.2. Towards Inclusive, Collaborative, and Transdisciplinary Lighting Research and Practice

In 2010, ALAN researchers had already emphasized that a transdisciplinary research agenda can potentially favour the development of regulations and guidelines that meet environmental needs and the demands of modern societies [8]. Interestingly, lighting professionals were often not considered back then as part of the actors involved. However, today, lighting professionals are judged to be crucial team members who can introduce new ways of thinking about research problems. They can also provide essential research inputs based on their practical knowledge of artificial lighting.

As the dialogue between lighting professionals and ALAN researchers remains insufficient to translate the acquired data as knowledge into the practice domain, it is of great significance to improve the application of artificial light to minimize the impact of light pollution on the environment via a more efficient and effective collaboration between researchers, lighting practitioners, policy-makers, and society in the context of urban lighting. With this paper, we aim to provide a brief insight into the perspectives of the lighting practice and research on night-time studies, we explain the actors involved in each domain, while also offering potential platforms to exchange and transfer knowledge, and we make a call for action on an improved transdisciplinary approach. The proposed collaboration framework has the purpose of bringing those involved in practice, research, production inputs, planning, and policy-making domains all closer in order to conduct and coordinate the organizational structure in which information flows. This transdisciplinary teamwork may serve to translate and convey research knowledge between lighting professionals and ALAN researchers, to better provide healthier and more sustainable urban settings, which are inclusive and protective of the night.

2.4. Development of the Dual Perspective of the Night

In medieval times, most cities and towns were in darkness after dusk so additional illumination via lit candles and torches was used for wayfinding along routes [52]. Since then, the practice of lighting incorporated varied approaches to deliver illuminated night-time scenarios in built and natural environments (see Figure 1).

Figure 1. The evolution of urban illumination over time, illustrating the varied approaches of artificial lighting practice used to deliver illuminated night-time scenarios in built and natural landscapes. In the beginning, there were (a) relatively dark pedestrian pathways with dappled pools of light at street intersections and soupçons of light washing the first-floor façade of important buildings mainly used by citizens at night. Later, (b) robust iron poles with lanterns were applied to luster streets, roads, and paths. Then, (c) skyscrapers and tall buildings acquired illuminated elements for advertisement with vertically illuminated façades that reveal the structure of buildings. In the following years, (d) functional and decorative lighting co-existed in the same urban realm to make cities and towns functional and aesthetically pleasing at night. In recent years, (e) functional lighting for pedestrian and vehicular circulation and decorative lighting for skyscrapers, buildings, monuments, and landmarks have presented a changing luminosity and colour condition with shifting shapes, patterns of shadow and light, along with videos projected onto buildings so they become illuminated canvases at night. Source: authors' own work.

Dark pathways were dappled with pools of artificial light in core key locations (e.g., pedestrian street intersections or the façades of important buildings). Areas were illuminated with light rich in long wavelengths with warmer correlated colour temperatures (CCT) at approximately 1800–2200 K [52]. The light distribution of these light sources was also closer to the ground and restricted to areas of common passage. Night-time illumination had not yet infiltrated terrestrial and aquatic landscapes as portrayed in the 1879 impressionist oil painting *Walk with lanterns* by Ilya Repin [53]. Skyglow was also not considered a problem, as cities still remained relatively dark at night (Fig. 1a).

Later, gas lighting technology and the emergence of electric lighting provided the means to establish urban lighting systems with multiple fixed lanterns in poles to increase illuminance parameters and to deliver horizontal homogeneous illumination that did not occur in medieval times. An increased number of lanterns per fixed pole were applied in streets, roads, and paths to enable pedestrian and vehicular circulation. The spectral power distribution (SPD) of these point sources was considered rich in long wavelengths with a correlated colour temperature that increased from approximately 2000 up to 2700 K. The introduction of these forms of urban artificial lighting producing low light levels were expected to attract, for example, insects in the vicinity of the applied sources, "*Wie Motten um das Licht*"—*like moths around a flame*, as mentioned in the song *Falling in love again* by Marlene Dietrich [54]. Urban areas began to show the first traces of skyglow in cities and towns (Figure 1b).

Then, in addition to the horizontal illuminance parameters, artificial light was used as a medium on the vertical surface of tall buildings and skyscrapers to sculpt volumes for three-dimensional spaces. During the 20th century, multiple techniques emerged that included the uplighting of building façades as well as the use of searchlights, which are high-intensity electric sources of light used for finding objects in the distance at night. Searchlights were positioned to direct emissions of light towards the sky [55]. Furthermore, decorative advertising lighting systems were used to illuminate the top of buildings with marquee signs and letterings. Unfortunately, the position and direction of point sources used to illuminate the vertical plane directed light towards the sky. They also delivered higher illuminance parameters when compared with lighting systems used in previous years. Such light sources were present in illuminated parks, exposing the leaves of trees and plants to the emissions of light; as observed and reported in 1975, ALAN was considered to affect the flowering state in varied flowering plants [56].

Additionally, the beams of floodlights on the roofs of theatres and cinemas became iconic urban illuminated elements that were observed to attract migrating birds at night, as shown at the Eddystone lighthouse illustrated in 1912 [57]. In comparison to previous years, artificial lighting began to feature broad ranges of SPD from approximately 400 to 700 nm, with richness in short wavelengths of light and less red wavelengths. This was coupled with an increase in the range of CCT from approximately 2000 K up to 5000 K [58,59]. The combination of techniques and applied light sources resulted in an unintended diffused luminous dome, visible over densely populated areas at night. This man-made effect is called skyglow. The use of light sources with a broad SPD rich in short wavelengths has allowed illuminated landscapes at night to appear as they would during the day. Artificial light at night became an artificial accoutrement of nightscapes and a convincing cultural and social excuse to construct and promote over-illuminated cities that unintentionally neglect the loss of the night [60]. Population growth, the exponential increase in illumination per capita, and the increased number of point sources and numerous applied techniques across landscapes have all presented unforeseen consequences, reported at the end of 1980s with the first research articles on light as an anthropogenic, artificial, and detrimental component. The aim of this research was to raise awareness about the problem in the form of skyglow and to also help reduce light pollution from urban and rural environments [5,6] (Figure 1c).

It soon became strategic to use new lighting techniques for the scene setting of local historical landmarks to change the overall perception of urban built environments. At the end of the 20th century, applied lighting techniques mainly focused on engaging the user with the encountered space at night with higher illuminance parameters, varied correlated colour temperatures, and spectral power distributions that ranged across the visible spectrum, shadows, and the duality of brightness and darkness [61,62,63,64,65]. The upward emission of artificial lighting coupled with higher levels of brightness has resulted in significant light pollution across ecosystems (e.g., night-time illuminated bridges, which emit artificial light towards aquatic ecosystems and are known to negatively affect migrating salmon fish [66], and uplit trees and green areas in parks and public gardens, which may adversely alter other organisms, such as insects [16,67]). Night-time illumination soon reached areas that were once unlit (Figure 1d). These approaches typically defined lighting practices that focused on the role of night-time illumination in an urban context to engage the user with the various spaces they used at night [68], and the detrimental impact of artificial lighting on humans and nature was not yet considered by lighting experts. Meanwhile, ALAN researchers focused on gathering evidence of artificial light as a long-term phenomenon and pollutant of night-time environments [69]. This includes the founding notions and observations of the sky by night. Since the 1900s, the earliest measurements of photon emissions produced per capital demonstrated that cities were under an artificially bright night sky [70].

Astronomers and astrophysicists reported a noticeable reduction in the visibility of the naturally dark sky due to an increase in illuminance and the use of unnaturally vivid colors of light at night in densely populated areas [71,72]. Over the years, the application of artificial lighting with upward emissions of light and higher levels of brightness resulted in significant light pollution across landscapes.

Unfortunately, opportunities to acquire this new knowledge to understand the consequences of the inappropriate use of ALAN was scarce, as the notion that ALAN is a pollutant was still being explored by ALAN researchers.

Moreover, at the beginning of the 21st century, there was a distinct lack of knowledge about the numerous properties of artificial lighting, which are now known to be pollutants. There was also a lack of communication, which was needed in order to translate research into the practice of lighting.

New technological developments enabled multiple techniques to emerge. This included dynamic artificial lighting with changes in brightness, colour temperatures, colored light, and shadow patterns, as well as the projection of videos onto buildings so they became illuminated canvases [61,62,63,64,65]. The increased application of artificial lighting came at the expense of the natural night-time environment. ALAN researchers estimated that there was a higher variability of artificial lighting conditions across landscapes, such as significantly increased levels of brightness [4,19] as well as the widespread use of unnatural colors, which is considered to affect varied organisms [14]. Upward illumination towards the sky, such as the 9/11 Memorial—*Tribute in Light* [73], has been reported to affect migrating birds [74]; anotreher example is the bat colonies in various illuminated churches across Sweden, where bats have been observed to change their flight trajectories to avoid illuminated areas, which can potentially affect the choice of corridors during flight and may fragment the selection of foraging areas for bats [75] (Fig. 1e).

Previously unlit areas at night were now being illuminated, (e.g., illuminated bridges that disturb the ecology of rivers and bodies of water, as well as skyscrapers and tall building that emit light towards the sky, which harms bird life and insects). During recent years, light pollution and ecological light pollution have been diligently investigated via scientific research to broaden the understanding of the impact of night-time lighting applications on humans and nature [7,20,21,22,24,25,76]. Table 2 provides a description of the evolution of outdoor lighting chronologically over time.

Table 2. The evolution of outdoor lighting in Fig. 1. Source: authors' own work.

	Description
(a)	During medieval times, most cities and towns were illuminated by night with point source illumination (e.g., candles placed adjacent to windows, lanterns positioned at a determined height in façades, and hand-held lanterns. Fire (e.g., present in candles and hand-held lanterns) was used as a beacon of light to help shape a sense of understanding of the urban realm after dusk.
(b)	Later, electrical engineers (EE) and illuminating engineers (IE) used gas and electrical light sources that included incandescent, low-pressure sodium (LPS), and high-pressure sodium (HPS) as point light sources for streets, roads, and paths to facilitate pedestrian and vehicular circulation [77]. Gas and electrical point sources of illumination were considered static as they lacked movement compared to previously applied light sources such as carried hand-held lanterns and gas-fueled fixtures that were frequently moved to the locations to provide visibility at night. Mounted lanterns on poles were introduced, and in the years following, the number of lanterns per fixed pole increased.
(c)	During the 20th century, IE and architectural lighting designers (ALD) favoured an ensemble of lighting systems that vertically illuminated skyscrapers and tall buildings. Decorative advertising lighting systems also became popular. The economic growth of the post-war years instigated the application of emerging static point light sources that included fluorescent lamps (FL), ceramic metal-halides (CMH), and neon lamps to built environments that had formerly only been illuminated by incandescent, LPS, and HPS. Neon lamps were used for the lettering placed on the top of buildings to advertise brands, products, and locations, whereas incandescents were used to illuminate marquee signs and letters [78, 79].
(d)	The end of the 20th century saw the introduction of urban lighting masterplans (ULM) by IE, EE, and ALD, and urban lighting planners (ULP) introduced ULM to revitalize the function of cityscapes and also to create a decorative appearance of cities at night as a symbol of economic growth and to boost tourism [65]. A wide range of approaches included functional point sources (e.g., for pedestrian and vehicular circulation), as well as decorative point sources (e.g., for the vertical illumination of historical buildings and landmarks for advertisement).
(e)	During the early years of the 21st century, a new emerging lighting technology called light emitting diodes (LEDs) became the preferred choice of technology by the IE, EE, ALD, ULP, and entertainment designers (EA) to illuminate built and natural landscapes (Fig. 1e). LEDs offered low cost, easy application, and miniaturization for functional lighting for pedestrian and vehicular areas, decorative lighting for the enhancement of historical and modern

buildings (e.g., skyscrapers, buildings, monuments, and landmarks), and static and dynamic lighting characteristics (rich in movement with changing colors and illuminance parameters) to the modern cityscape.

In the first decades of the 21st century, ALAN researchers have provided evidence on night-time illumination as a pollutant that disrupts biological rhythms in humans and nature [9,80,81] and have estimated an increase in LP of 2–6% per year [4,19]. Additionally, environmental researchers have reported that LP and ELP inhibit crucial day and night-time cycles across taxa, since 30% of all vertebrates and more than 60% of all invertebrates have visual sensitivities attuned to natural low light levels, which involves the ambient illuminance of lunar cycles and starlight in the night-time environment [19]. An extensive body of empirical evidence has identified potential behavioural and physiological changes in responses induced by properties of ALAN across taxa; this includes terrestrial organisms such as bats [82], birds [83], and insects [16,84], micro-organisms, and aquatic species exposed to artificial lighting near waterfronts, bridges, rivers, and lakes [13,85,86].

Eventually, a dual perspective of the night was formed as both lighting professionals and ALAN researchers developed individual outlooks focused on ALAN. This caused a no-win/Gordian Knot situation [87,88,89] that challenged the research and lighting practice due to different approaches and limitations. For the majority of the lighting practice, the method for lighting technologies involved expertise that mainly focused on delivering the user visual accessibility for visited areas at night, and beyond that, a sense of connection to urban night-time environments. Meanwhile, ALAN researchers presented expertise focused on the study of an unnatural component, such as artificial light and its properties and the resulting adverse effects across night-time environments, and this included the widespread use of ALAN causing skyglow: a global phenomenon responsible for the loss of the night (e.g., [90,91]).

The actions against light pollution and the improper management of lighting applications are not necessarily a confrontation between ALAN researchers and lighting professionals [39,92], but rather an attempt to start a transdisciplinary collaboration between experts, which includes best practice and sustainable lighting applications that serve society's interests while respecting ecology [93]. An example of a transdisciplinary collaboration between environmental and lighting experts occurred in the city of Berlin, Germany, in 2011. This involved a Lighting Advisory Board, which included lighting and environmental experts in collaboration with the Senate Department for Urban Development of the city of Berlin, to conceptualize the urban lighting masterplan for the city of Berlin (Stadtbild Berlin–Lichtkonzept) (Senatsverwaltung für Stadtentwicklung und Umwelt, 2011). The lighting masterplan concept portrays the city as an economic center and provides citizens with a sense of safety and security whilst enhancing the allure of the city with lighting technologies that minimize the impact of light upon ecology at night.

The conceptualization of a transdisciplinary masterplan for the city of Berlin demonstrated one of the first attempts towards openness for an environmental lighting perspective during a time when the scientific evidence on the impact of ALAN across urban and natural environments was still unclear. Ten years later, scientific research on the topic has substantially increased.

2.5. Bridging Domains in the Collaborative Process

It is essential to understand that any successful collaborative process involves a philosophy of empathic interactions that acknowledge the diverse languages, perspectives, skillsets, backgrounds, and expertise of each domain [94].

The collaborative nature can potentially occur only as a dynamic interaction driven by a shared interest as an emboldened modality [95], aimed at reducing the impact of artificial lighting on the environment with solutions that address different night-time conditions (e.g., cloudy nights or clear sky conditions) and different nightscape contexts.

In order to communicate crucial knowledge about ALAN (as a potential pollutant, while also recognizing that ALAN is a tool to implement visual accessibility for users at night), the lingua franca becomes a strategic asset and a frame of reference to communicate the knowledge acquired by experts, the contrasting perspectives, and the platforms for the transmission of evidence into practical solutions [96].

The language used to transfer information may serve to bridge the existing gaps between practice, research, production, planning, and policy-making domains and may enrich a shared empathic comprehension of the research questions and problems that each domain is focused upon. Over the past century, the field of lighting design/technology and the field of biology/environmental sciences have both developed key terms independently of each other, in regards to the study of the night-time environment. However, the interpretation of these definitions varies.

Lighting professionals define properties of artificial lighting for the built environment that consider human vision focused on the perception of brightness, contrasts, and colors in objects under lighting conditions. Whereas, light pollution researchers and environmental experts in biology, ecology, chronobiology, and light pollution developed a vocabulary that identifies and describes the effect of natural and artificial light on biological processes, living organisms, and ecosystems, as well as how environments and organisms affect each other. The International Commission on Illumination (CIE)—the international authority on light and lighting—recently created an online international lighting vocabulary [97], but terms such as "ALAN" and "ecological light pollution" have not been defined [98]. The CIE Technical Committee TC 4-61 has yet to produce a report and propose additions to the missing definitions to reduce this communication gap between ALAN researchers and lighting professionals.

Furthermore, the application of light can also greatly vary among scholars, experts, and professionals in these fields. Lighting professionals see it positively for the visual perception of built and natural landscapes at night and the added value it gives cities and towns, which supports their visual appearance and so forth, however, this is often without consideration of the possible consequences of added light. Whereas, environmental experts consider artificial light as a component of society in need of careful management to reduce the current negative burden on biodiversity and the natural environment.

It is important to stress that accessibility to knowledge in both domains requires on-going interactions between the participants involved in order to build responsiveness and potentially address current and emerging issues [99]. If guided incorrectly, it may amplify the existing gap between lighting professionals and ALAN researchers, stoking existing tension that may lead to uncertainties that disrupt the dynamic and co-learning circumstances for each domain.

For instance, it is crucial to start with a dialogue about the problems that each field of study addresses. Lighting professionals can attempt to answer the following questions: How to design lighting schemes in urban environments that are based on research? What lighting technology to implement? How to apply it for a specific project application?

Meanwhile, ALAN researchers can consider the following questions in their day-to-day work: Based on the requirements of the lighting practice, what needs to be researched? What properties in artificial lighting technologies are considered a light stressor? When is it considered a stressor? [8,65].

The background and know-how of lighting professionals and ALAN researchers may create new approaches and enrich techniques to achieve goals beyond the individual narrative of each domain. The dialogue between experts may serve as a negotiating process to address existing differences while creating a new vision to answer the question of how to translate research knowledge to be applicable for the lighting practice.

Educational awareness on LP has also taken place by means of nonprofit organizations, networks, and conferences.

The International Dark-Sky Association (IDA) [100], the Australasian Dark Sky Alliance [101], and other nonprofit organizations [48] educate communities and government officials on the protection of night skies and biologically/ecologically responsible outdoor lighting.

Additionally, the interdisciplinary and transdisciplinary network EU-COST Action “Loss of the Night Network” (LoNNe, ES1204) presents projects, raises awareness pertinent to ALAN, and stimulates an exchange of ideas and concepts [102,103].

Another form of knowledge exchange is via professional lighting and light pollution conferences. Professionals and academics across disciplines gather at these events to exchange content related to the latest developments within their profession. These events have become the locus of networking for likeminded and opposed individuals to discuss root problems and information related to their field of study. Today, the international conferences, as presented in Table 3 (in pp. 79-80], exchange an array of subjects with content strongly focused on topics relevant to the expertise of its audience’s disciplines (e.g., lighting professional conferences for lighting professionals, the lighting industry and manufacturers; light pollution conferences for academics, scientists, and experts on ALAN as a pollutant). These conferences adhere to their statement of purpose (e.g., lighting professional conferences present content relevant to the design practice, whereas light pollution conferences present content relevant to light pollution and ecological light pollution, and technical conferences present content relevant to technology and design focused on light as the primary technical solution).

Interdisciplinary participation rarely occurs due to the narrow and specific requirements and protocols of these conferences. An exception is the ALAN conference series, which is dedicated to examining all aspects of artificial light at night, including technology and design, biology and ecology, and health. In recent years, an initiative has begun to expand beyond the usual content and purpose statement in conferences and across disciplines (e.g., the presentation of empirical data on light pollution for lighting professional conferences or the presentation of a project or urban lighting application for light pollution conferences).

However, equitable transdisciplinary content is still required in order to evolve conferences into an interchangeable platform to exhibit the utility of the lighting practice and present evidence of artificial light as a pollutant. This commitment may provide more perspective and offer appropriate tactics that broaden the interpretation of lighting applications, as well as raise awareness about technological tools for urban environments.

Another step towards collaborative interactions between the practice and research of lighting is defining platforms and networks to make knowledge transferable. Due to globalization, the rise of networking has increased interactions via international conferences [104] and digital platforms [105], which render an opportunity to contextualize the exchange of ideas. These tools serve as knowledge transfer mediums to facilitate transdisciplinary and inclusive peer community praxis. They should be considered as a modus operandi to develop potential alliances that reduce cultural and societal ambiguities experienced by experts from different domains [106]. Again, the participation of the actors via knowledge transfer platforms may empower dialogue and blur the existing boundaries between the lighting practice, environmental research, and the policy-making of lighting, as well as the lighting industry.

Table 3. Overview of lighting design and light pollution international conferences. Source: authors' own work.

Conference	Main Topics	Focus
Light Pollution: Theory, Modelling and Measurements (LPTMM)	Astronomical observations, theoretical concepts and solutions, numerical modelling, and field campaigns on various topics that include the effects of atmospheric aerosols, clouds, terrain, and obstacles on light pollution, the impact of spectral and angular characteristics of light sources and reflecting surfaces, observational techniques instrumentation, data and products, and the design and evaluation of dark-sky-friendly lighting technologies, regulations, and outreach.	Scientific
European Symposium for the Protection of the Night Sky	Societal and cultural perspectives on light pollution, light pollution policy, citizen science resources, biodiversity and ecology, sustainable development, and outreach and initiatives.	Scientific
Artificial Light at Night (ALAN) Conference organized by the steering committee of the ALAN Conference	Technology and design, e.g., artificial lighting technology, architectural lighting, energy efficiency, outdoor lighting and street lighting; measurements and modelling, e.g., citizen science, human exposure, modelling, remote sensing, urban and pristine areas; society, e.g., economics, legislation, lighting governance, lighting conflicts, outdoor lighting applications, perceptions of the night and the preservation of natural areas, science and technological advancements, spatial security, and the history of lighting; biology and ecology, e.g., biodiversity, chronobiology, evolutionary adaptation, behaviour, and food webs; health, e.g., circadian rhythm disruption, exposure to outdoor and indoor light, illness related to ALAN, and melatonin.	Scientific Practice-oriented

Table 3. Overview of lighting design and light pollution international conferences. Source: authors' own work.

Conference	Main Topics	Focus
Professional Lighting Design Convention (PLDC) organized by VIA Verlag	Lighting application case studies, professional practice issues, philosophy and debate, office and retail lighting applications, plus workshops that include excursions to view illumination projects.	Design Practice-oriented
Enlighten Americas, Europe, Asia Conferences organized by International Association of Lighting Designers (IALD)	Art, e.g., communicating design and the artistic/creative side of lighting design (e.g., architectural lighting design (ALD) as an artistic medium), the artistic process in projects, the poetics of lighting design, artistic conceptions, future artistic trends, experimental design, and holistic approaches for lighting applications; science, e.g., lighting technology (sources, controls, fixtures, and software), development and trends, alternative energy sources (e.g., solar power), the internet of things (IoT), project management strategies, control integration, project case studies, cross-discipline topics and theory-based ideas, as well as the latest research; professional tools, e.g., factors and challenges of the practice, technology and creativity, business and social media, business and economy, trends and business, management tools, client management skills, contract negotiations, budgeting, marketing tools, as well as hiring and employee benefits.	Design Practice-oriented
International Commission on Illumination (CIE) Conferences	The physiology of human vision, vision and quality of light and colored light, optical characteristics; light measurement methodologies, physical measurements of light, photometry and the spectrum of light sources; interior lighting and lighting design, quality of lighting, transportation and exterior applications; photobiology, photochemistry; energy efficiency, LED lighting, renewable energy sources; photobiological risk of artificial lighting.	Technology and Science

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2.6. Urban Lighting Research Transdisciplinary Framework—Actors, Framework, and the Four-Step Process

A theoretical principle of an organization towards sustainable lighting applications should encourage the interaction of four main domains: research, practice, production inputs, and policy-making and planning. The collaborative process between these four pillars can potentially facilitate the understanding of data as knowledge, the application of the acquired knowledge as standards to follow that may serve as guidance for the development of lighting equipment, and the development of methodologies to design lighting schemes protective of the night.

To gain knowledge, in the context of ALAN as a pollutant from applied lighting technology, the Urban Lighting Research Transdisciplinary Framework (ULRTF) (Figure 2) proposes the participation of four domains and various actors to distinguish the practices and approaches of each field. It is of great importance to note that the lighting practice is not a uniform domain as it is characterized by different strategies and techniques. For instance, the main distinguishing difference between electrical illuminating engineers (e.g., street lighting engineers) and lighting designers (e.g., architectural lighting designers (ALD) and urban lighting design ULD) is their approach to lighting applications. Street lighting engineering is mainly focused on the application of visible luminaires to create homogeneous horizontal illuminance for pedestrian paths and vehicular circulation based on strict technical lighting standards (e.g., by the European technical standard EN 13201, CEN). In contrast, the approach of lighting design aims to create lighting for three-dimensional spaces that focus on light as a medium on a surface and not the luminaire. Additionally, the application of light by lighting designers integrates knowledge from different fields (e.g., architecture, urban planning, industrial and product design, landscape design, and perception psychology) to apply a modest presence of light on surfaces to sculpt volumes, enhance materials, create gradients, and reveal shadows in a determined space and context, as well make night-time spaces welcoming and user friendly.

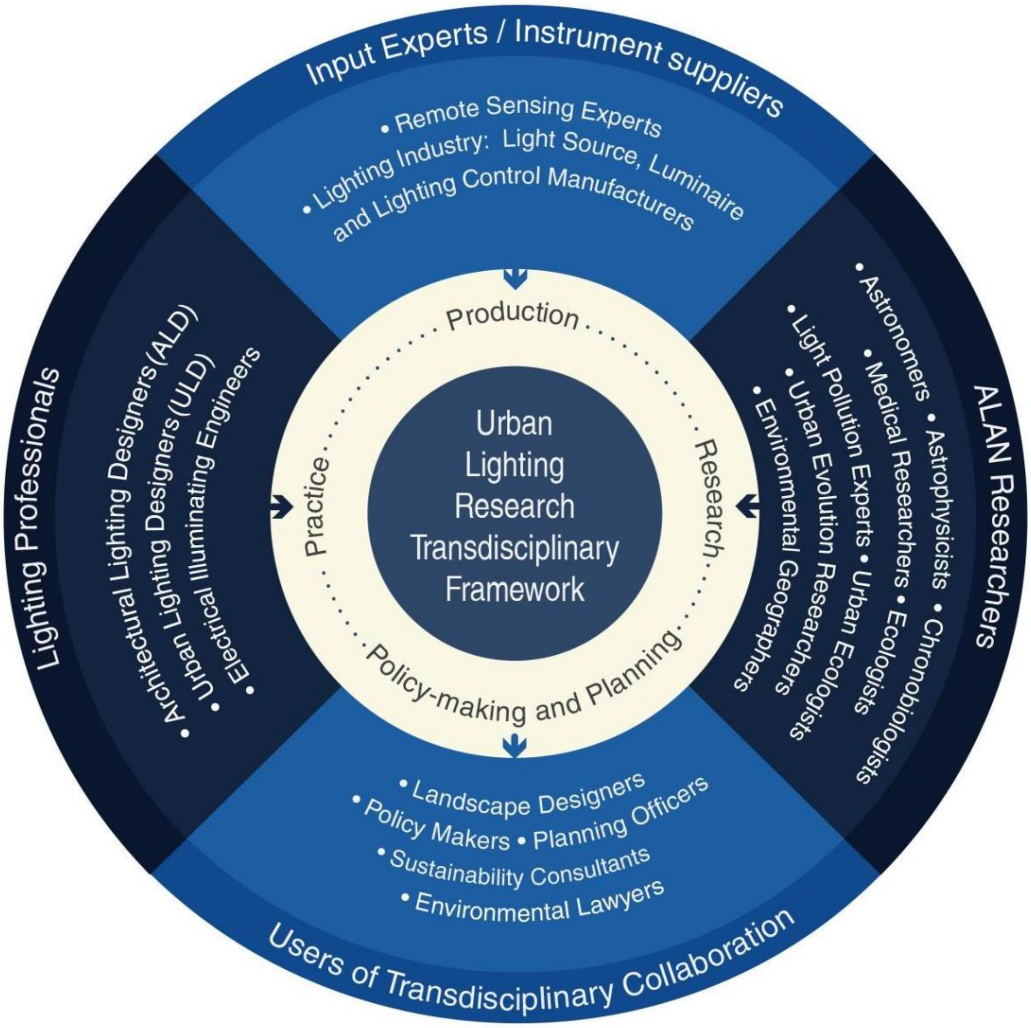

Figure 2. Proposal for an urban lighting research transdisciplinary framework. Source: authors' own work.

ALAN experts (e.g., astronomers, astrophysicists, chronobiologists, medical researchers, ecologists, light pollution and ecophysiology experts, urban ecologists, urban evolution researchers, and environmental researchers) focus on lighting applications with scientific findings that assess the practice of lighting to consider light-sensitive species and ecosystems and to preserve night-time environments, and experts from the remote sensing field and instrument suppliers from the lighting industry (e.g., light source, luminaire and lighting control manufacturers) provide the necessary assistance on research, including light pollution data and the development of new lighting technologies, and testing tools to assess the application of lighting (e.g., [4,71,72,107]). However, one cannot forget about the users of this transdisciplinary collaboration, including urban planners, landscape designers, policy-makers, planning officers, sustainability consultants, and environmental lawyers, and their role in regulating fundamental aspects involving urban lighting masterplans and assessing the application of ALAN that balances the safety and security of users while considering nocturnality across nightscapes (e.g., [31,108,109,110]).

Table 3 presents a list of conferences as venues to exchange theoretic lenses on particular subjects of interest. These venues may offer an initial contact to a particular field of expertise considered foreign, to expand the scope of knowledge and jargon, to implement a preliminary social contact at an accepting level, to acquaint potential actors to establish ULRTFs, and to potentially generate new platforms (e.g., conferences and technical committees). These new platforms may serve as settings to implement ULRTF with effective communication and a periodic engagement of the actors in a collaborative fashion towards lateral thinking strategies and problem-solving mechanics rather than dwelling on monologues with essentially linear and vertical thinking [111]. ULRTF is a process to mindfully consider when attending these conferences as these may provide venues to meet potential actors to establish an opening to a collaboration framework [110].

Beyond the collaborative framework, it is also essential to establish a process with a series of key steps to align, structure, and develop sustainable short- and long-term goals. The collaborative development of steps and crucial processes can potentially favor the dissemination of diverse knowledge and the expertise of each domain to create crossover linkages of emerging approaches and procedures based on scientific practice curricula, and to provide a platform for emerging transdisciplinary professionals that attempt to involve scientific knowledge in their lighting practice. Table 4 presents an overview of a proposed four-stage collaborative process that aims to involve lighting professionals in urban lighting research.

Table 4. Overview of a proposed four-step process for lighting professionals in urban lighting research. Source: authors' own work.

Steps	Category	Description
Step 1	Problem Definition	• State the problem by clearly defining questions, identifying the topics involved, and defining the existing solutions or case studies; • Develop background research on the defined problems by searching scientific and lighting practice literature for comparison; • Translate problem-driven topics into research questions and hypotheses.
Step 2	Research Design Development	• Define the most appropriate properties of artificial lighting to be investigated during the research study; • Determine the research procedure connected to artificial lighting; • Define and evaluate the parameters of lighting samples used in the future study; • Exchange and disseminate knowledge across disciplines related to the research; • Identify of the limitations of the study.
Step 3	Conducting Research (Collecting and Analyzing Data)	• Partner across organizational boundaries to assess and exchange on current (local and global) standards, regulations, and guidelines; to collect, exchange, and interpret data; and for the use of measuring equipment, light sources, luminaires, and lighting control types.
Step 4	Take Actions (Reporting Research Findings)	• Translate and share research outcomes with the lighting practice in specific lighting publications; • Co-write scientific research papers with other team members; • Speak at lighting conferences and seminars; • Develop guidelines and recommendations for the improvement of existing lighting approaches based on teams' research study outcomes.

2.7. Conclusions

The challenges of presenting collaborative perspective approaches for urban lighting research rely on decoding various opportunities and practices that include the social exchange of the actors, their professional motivation and purpose, and the collaborative nature to structure processes that encompass the diversity of ideas.

This insight article presents a brief overview of the rapid development and application of lighting technologies, which have unintentionally resulted in the widespread increase in unnatural brightness, and the application of colors of light across landscapes in cities and towns. Unfortunately, due to the problems distinctive to each separate field, the deeply rooted and different perspectives present in the principles of each profession, along with a lack of dialogue between them, this has resulted in a no-win/Gordian Knot situation. Therefore, this work proposes the application of the urban lighting research collaborative process as a community framework in order to identify the challenges that need to be addressed, the similarities that should be shared, the steps and procedures that must be followed, and the motivations and purposes that will help towards creating collective ecological awareness. Furthermore, this paper presents a new and potentially useful model for bringing different professionals together, where for the first time, lighting professionals as key players are introduced into the collaborative process.

In conclusion, the proposed ULRTF relies on various opportunities and practices to encourage the diversity of ideas in order to consider lighting parameters that operate ecologically and deliver safe and secure measures for users at night.

Moreover, this article also highlights the need for correctly designed urban lighting research, and it proposes the collaboration of knowledge between environmental experts, lighting professionals, and experts from other fields. Such a concept is envisaged as a continuous work in progress with periodic adjustments, with the understanding that the lighting practice is often ahead of the research field due to its knowledge of new technological developments in urban lighting. Research studies on ALAN continue to exponentially increase, which can provide an optimistic overview of the impending outcomes of the practice. The reasonable and logical next phase will be to translate the acquired knowledge of the research into practice to develop sustainable lighting concepts and techniques for future nightscapes [8] and to build an ecologically conscious and responsive society [48].

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Chapter 3:

A Systematic Review for Establishing Relevant Environmental Parameters for Urban Lighting: Translating Research into Practice

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3.1. Abstract

The application of lighting technologies developed in the 20th century has increased the brightness and changed the spectral composition of nocturnal night-time habitats and night skies across urban, peri-urban, rural, and pristine landscapes, and subsequently, researchers have observed the disturbance of biological rhythms of flora and fauna. To reduce these impacts, it is essential to translate relevant knowledge about the potential adverse effects of artificial light at night (ALAN) from research into applicable urban lighting practice. Therefore, the aim of this paper is to identify and report, via a systematic review, the effects of exposure to different physical properties of artificial light sources on various organism groups, including plants, arthropods, insects, spiders, fish, amphibians, reptiles, birds, and non-human mammals (including bats, rodents, and primates). PRISMA 2020 guidelines were used to identify a total of 1417 studies from Web of Science and PubMed. In 216 studies, diverse behavioural and physiological responses were observed across taxa when organisms were exposed to ALAN. The studies showed that the responses were dependent on high illuminance levels, duration of light exposure, and unnatural colour spectra at night and also highlighted where research gaps remain in the domains of ALAN research and urban lighting practice. To avoid misinterpretation, and to define a common language, key terminologies and definitions connected to natural and artificial light have been provided. Furthermore, the adverse impacts of ALAN urgently need to be better researched, understood, and managed for the development of future lighting guidelines and standards to optimize sustainable design applications that preserve night-time environment(s) and their inhabiting flora and fauna.

3.2. Introduction

From the 20th century onward, cities and towns around the globe have applied artificial lighting technologies at night. This human-centric widespread illumination of the nightscapes has been implemented to provide a sense of safety and security [1,2], to showcase the historical and architectural significance of past and present times [3], to enable a 24/7 lifestyle, and to boost the economy [4,5] and tourism [6]. Traffic and pedestrian routes, as well as buildings and landscape elements, have often been brightly and colourfully illuminated by artificial light at night (ALAN) not only for visibility but also to provide lit networks and infrastructures so individual users and society can function efficiently at night (Fig. 1).

Figure 1. A schematic diagram that illustrates the extent of artificial lighting in four different scenarios: urban, peri-urban, rural, and natural landscapes. (a) Architectural lighting in urban areas illuminates buildings, façades, architectural structures, and monuments. In some scenarios, it is accompanied by commercial and retail advertisements in the form of backlit panels, self-illuminated sources, and decorative lighting for non-permanent events. (b) Pole-mounted luminaires and bollards provide visibility for pedestrian and cycling paths at night for public amenity areas and neighbouring urban zones, such as parks. (c) Street lighting is used for the safe passage of pedestrians and cyclists and to also assist in visibility for vehicular circulation at night. (d) In natural environments, lighting on roads and motorways aids vehicular travel. In addition, stopover locations, such as gas and train stations, as well as villages with rural houses, become illuminated spots at night. Source: Authors' figure.

In recent decades, ALAN has extended in scale and form [7], causing the unintentional anthropogenic stressor known as light pollution (LP), which can occur both as astronomical light pollution [8] and ecological light pollution [9]. Unshielded luminaires and improperly managed lighting can radiate light toward the sky, where it scatters within the atmosphere, creating a diffuse glow called skyglow [10]. Skyglow is detrimental to the night sky, and it often extends into dark habitats that have natural day–night light cycles [8]. Typically, artificial skyglow is relatively dim (0.001–0.1 lx) [10] but peak skyglow levels can be brighter than the full moon [10,11]. A recent skyglow model suggests that about 80% of the world's population now lives under light-polluted skies [12] and there is an increase in LP of more than 2% per year [13,14], which poses a serious threat to biodiversity and human health [15,16,17,18,19,20]. ALAN can also suppress melatonin, known as the night hormone, in various vertebrate species even at skyglow-like low light levels (0.01–0.03 lx) [11,21]. This may inhibit crucial day- and night-time cycles because 30% of all vertebrates, and more than 60% of all invertebrates, have visual systems adapted to (low) natural nocturnal light levels (i.e., moonlight maximum at ca. 0.3 lx and starlight at ca. 0.001 lx) [11,15].

The concept of LP and ALAN as an anthropogenic pollutant that unintentionally causes the “loss of night” (Fig. 2) is relatively new to urban lighting practice (ULP). For most lighting professionals, which includes architectural lighting designers (ALDs), urban lighting designers (ULDs), and electrical illuminating engineers, ALAN is considered a technological tool that drives their field of study rather than an element that can have adverse effects upon the surrounding environment (i.e., the night sky, flora, and fauna), resulting in negative effects that have a local and global impact [22]. Improperly managed ALAN may extend to areas where it is not intended and needed. With this in mind, the current urban lighting practice lacks a foundation on ecology, astronomy, and environmental science to address matters related to minimizing this issue.

Figure 2. Overview of the unintended consequences of improperly managed lighting in the form of LP. (a) Images of the Earth at night from the International Space Station (ISS). (b) The density of light emissions from cities causes skyglow, which prevents the visibility of stars. (c–h) The source of LP and obstructive light from artificial light is commonly located in urban areas with (c–d) the illumination of landmarks, buildings, and monuments, (i–m) the illumination of gateways and bridges, and (h) self-luminous advertisement screens. (h,j) Some applications can potentially over-illuminate an area and cause light trespass/spill light beyond the intended function. (f,h,k,l) The improper management and application of artificial lighting technologies may even extend toward natural environments, spilling light into (r–v) land, (i–m,p,q) waterbodies, and (e–h,n–p,r,s) the sky and, in consequence, adversely affect (n,o,q,s,t,v) ecosystem services and living organisms. (f,h,k,l) For instance, the improper

application of artificial lighting may over-illuminate the sky when luminaires emit light toward the sky. (i–m,p) Other artificial lighting applications, such as illuminated river bridges, may over-illuminate the nearest waterbody and potentially shift its optical composition at night. Image sources: (a) NASA/Unsplash, (b) Johams Leguisamo, (c) Suhyeon Choi/Unsplash, (d) Lynn Friedman/Flickr (CC BY-NC-ND 2.0), (e) Daniel Jolivet/Flickr (CC BY 2.0), (f) Mihaly Koles/Unsplash, (g) Dylan LaPierre/Unsplash, (h) Andrea Leopardi/Unsplash, (i) Jamie McGlinchey/Unsplash, (j) Charles Koh/Unsplash, (k) Bill Xi/Unsplash, (l) Cees Van Wageningen/Unsplash, (m) Jason Polychronopulos/Unsplash, (n) Potyo Imre/Flickr (CC BY 2.0), (o) Potyo Imre/Flickr (CC BY 2.0), (p) Hans Permana (CC BY-NC 2.0), (q) Paul Vecsei, (r) Luca Fontanarosa/Unsplash, (s) Tine Ivanic/Unsplash, (t) Zdenek Machacek/Unsplash, (u) Bradleypjohnson (CC BY 2.0), and (v) Valeria Moschella.

ALAN researchers have built an extensive body of empirical evidence across taxa that identifies potential negative behavioural and physiological responses induced by ALAN [23,24,25]. For instance, studies on terrestrial organisms, such as bats [23], birds [24], and insects [25,26,27], as well as micro-organisms and aquatic species [28,29,30], have revealed changes in their behaviour and physiology when their habitat (aerial, aquatic, or terrestrial) is exposed to ALAN. Various studies have investigated ALAN to question the current habit of over-illuminating nightscapes and encourage the re-evaluation of night-time illumination. This is based on research-informed design in order to introduce knowledge on ecology and to implement environmental values in the practice of urban lighting [31,32,33].

However, while ALAN researchers report the ecological consequences of ALAN to their peers, with some efforts to propose the need for environmental conservation measures, less focus has been given to efficiently translate ecological knowledge toward lighting practitioners and the industry. Consequently, the insights obtained by ALAN researchers seldom reach the lighting professionals who are involved in the application of lighting technologies. This is a problem because for the lighting community it is difficult to evaluate the relevance of biological studies. It is also challenging to interpret the results in the context of ULP without clear guidance, all of which can hinder the planning and designing of lighting schemes to provide visibility, safety, and security while also minimizing the adverse impact on the natural environment.

To reduce these impacts, it is essential to translate relevant knowledge on the adverse effects of ALAN into applicable ULP. Therefore, the aim of this paper is to identify and report, via a systematic review, the effects of exposure to different physical properties of ALAN on various organism groups, targeting mainly lighting professionals and research gaps.

This work should also motivate research-informed ULP by raising awareness about the impact of ALAN on the night-time environment. It is not only lighting professionals who will gain from this research review; those involved in the design, planning, and approval process will also benefit. This includes architects, urban planners, landscape designers, sustainability consultants, and planning officers (representatives of local planning authorities) [22].

This article is organized into the following sections: Section 3.3 provides an overview of concepts and terminologies and the physical parameters of ALAN considered by ULP and ALAN research as tools required to properly translate the existing knowledge and ensure better communication between ULP and ALAN research. Section 3.4 defines the scientific questions. Section 3.5 demonstrates the procedure performed for the systematic review based on PRISMA 2020 guidelines. Section 3.6 provides the results of the systematic review. Section 3.7 includes the limitations of the study. Section 3.8 discusses the research findings and their implications. Section 3.9 presents the conclusions of the review; it also provides a synthesis of the key points and recommends new areas for future urban lighting research. Appendix A includes terminologies and definitions related to artificial lighting applications. The supplement includes additional detailed content relevant to the results of Section 5.

3.3. ALAN Lingua Franca

3.3.1. Concepts and Terminologies

The key terms on the urban night-time environment and the presence of light were developed by the field of lighting/technology (ULP) and the field of astronomy/ecology/environmental sciences (ALAN research). Each domain shares an interest in light and darkness; however, each field independently develops terminologies [22,31,34,35,36]. The domain of ULP combines the knowledge of human vision (during the day) with applied lighting technologies in the built environment, which forms a practice focused on the application of brightness, contrast, and colors that mimic typical day-time conditions. However, too often, these solutions unintentionally neglect the negative consequences of added artificial light on natural nocturnal environments and ecosystems. The ULP still relies on terms for the application of ALAN based on human vision that mimics typical day-time conditions for cities and towns at night. In contrast, the domain of ALAN research already involves scientists from varied fields [22,34], which results in a heterogeneous vocabulary and the use of non-SI units (units that are not defined as part of the International System of Units) for nocturnal light, making it sometimes difficult for members outside of these domains to follow.

ALAN research acknowledges lunar cycles and starlight, the interaction of ALAN and natural nocturnal light with environmental conditions (e.g., cloud cover or snow [37,38]) as important, and it recognizes ALAN as a potential anthropogenic pollutant. This means that in order to consider sustainable objectives [39], a collaborative framework between ULP and

ALAN research is needed to potentially establish a common ground. A mutual understanding between domains can clarify terminologies to carefully communicate and efficiently transfer scientific research on the night-time environment and the lighting approaches used in the practice to assess solution-oriented systematic learning [40,41,42].

For further reading on the terminologies and definitions addressed by both domains, see Table 1 and Appendixes A1–A5.

Table 1. Summary of tables on terminologies and definitions related to ALAN research and ULP (see Appendix A).

Table Nº.	Description
A1	Overview of terminologies and definitions of natural and artificial light sources relevant for ALAN research and ULP
A2	Overview of terminologies and definitions of responses to light in living organisms and ecosystems
A3	Overview of various types of electric light sources commonly used in urban settings in the past and the present
A4	Overview of radiometric and photometric quantities of light and units
A5	Overview of terminologies and definitions of ALAN as a pollutant

3.3.2 Physical Properties of Artificial Lighting Considered by ULP and ALAN Research Domains

ULP domains usually rely upon a commonly developed technical language of lighting to deliver illuminated settings based on the spectral sensitivity of human day-time vision [43,44,45]. For many years, the practice of lighting has treated the night as a blank canvas to showcase historic, architectural, cultural, economic, technological, and societal legacies of cities that needed to be not only visible during the day but also illuminated at night as a reminder of society's achievements, without performing environmental impact assessment studies. Some practitioners are advocating for a change in this approach [31]. The current lighting practice often disregards lighting approaches focused on reducing the amount of implemented light as it lacks foundations on how the applied light might become an anthropogenic pollutant and how light is perceived by other organisms (e.g., low light intensities from natural light sources and environmental conditions [37,46,47].

In contrast, ALAN research provides a broad understanding of light as a potential artificial pollutant in need of careful management [7,10,48]. The presented detailed results of studies address physical parameters of light (e.g., ultraviolet and infrared radiation) that are typically considered as parameters hardly detected by humans [49] and have been shown to be used as a source of information by many other organisms [50,51,52].

To ease the communication between these two domains and to understand the difference in commonly used units and symbols of different physical quantities of artificial light, Table 2 is elaborated based on discussions of representatives from these two domains. In short, one can distinguish mainly between radiometric and photometric quantities (the photometric spectral band that matches human day-time responsivity) and units as well as measurement geometries. Irradiance is the radiometric quantity for light incident on a surface per unit time and has illuminance as the photometric counterpart. Biologists sometimes report radiometric quantities [50,51,52,53,54] in a spectral band relevant for photosynthesis called photosynthetically active radiation (PAR) [20,54]. Radiance is the light emitted from or incident on a surface per unit time within a specific solid angle and has luminance as the photometric counterpart, sometimes casually called “brightness”. The night sky radiance (also often called “night sky brightness”) is often reported in astronomical units of magnitudes that are confusing for non-astronomers as they are a negative logarithmic scale, recently used also in ALAN research due to the common use of small sky radiometers called “sky quality meters” (see Hänel et al. [21] for an introduction on night sky brightness). Radiant flux is the light per unit time with the photopic counterpart of luminous flux, often given with luminaires. Spectral properties are becoming more and more important recently, and there is a shift from correlated colour temperature (CCT) to spectral power distribution (SPD), given a wavelength-resolved physical quantity of light (e.g., spectral irradiance), which would enable the use of new methods, such as the spectral G-index or similar indices (please note that the G-index is not yet evaluated or adopted by a standards development organization but recommended in some regulations already) [53]. Other properties of light that are not widely characterized yet but are becoming more and more important are, for example, flicker in ULP and the degree of polarization in ALAN research.

Table 2. Overview of usage of physical quantities of artificial light by each domain. "*" The photosynthetically active radiation (PAR) originates from horticulture but is also used widely in biology (e.g., for primary production of phytoplankton). Irradiance is then substituted with photosynthetically active photon flux density (PPFD) and radiant flux with photosynthetically active photon flux (PPF); "**" sky radiance is reported in astronomical magnitudes from star brightness, used in ALAN research with small night sky radiometers, like the sky quality meter (SQM).

Physical Quantity	**Domains**	
	ULP	**ALAN Research**
Irradiance, Ee (W/m2)	rare	common
Illuminance, Ev (lx)	common	rare
PAR * photon flux density (PPFD) EPAR (μmol photons/m2)	not used	rare
Radiance, Le (W/m2·sr)	not used	rare
Luminance, Lv (cd/m2)	common	not used
Sky radiance (astronomy) ** Lsky,SQM (mags/arcsec^2)	not used	rare
Radiant flux, Φe (W)	not used	rare
Luminous flux, Φv (lm)	common	rare
PAR* photon flux (PPF) ΦPAR (μmol photons/s)	not used	rare
Spectral power distribution (SPD; e.g., spectral irradiance in W/m2·nm)	rare (increasing)	rare (increasing)
Correlated colour temperature (CCT; K)	common	rare
Color rendering index (CRI; Ra)	common	not used
Flicker frequency (Hz)	rare (increasing)	not used
Flicker %	rare (increasing)	not used
(Degree of) Polarization	not used	just emerging

3.4. Scientific Question

To accomplish the research goal of establishing relevant environmental parameters for urban lighting and to identify the properties of artificial light, which are considered to be profoundly detrimental to natural day- and night-time cycles of flora and fauna, the following questions have been posed:

Question 1. *What are the most relevant parameters of artificial lighting for evaluating impacts on different organism groups that should be used by ALAN researchers in their research studies and by lighting professionals in their day-to-day practice in order to minimize the negative effects without having to turn off lighting?*

Question 2. *How do we translate ALAN research for lighting practice to address environmental concerns?*

3.5. Materials and Methods

This section presents the scoped literature procedure via a systematic review and synthesis criteria, which involved the findings of research studies that demonstrated ALAN as a potential stressor to the behaviour, physiology, or survival of selected organism groups. The review follows PRISMA 2020 guidelines (Figure 3) [55,56,57,58]. First, categories of organism groups were arranged to develop keyword combinations for literature search. Only English keywords were chosen. The summary of keywords is presented in Table 3.

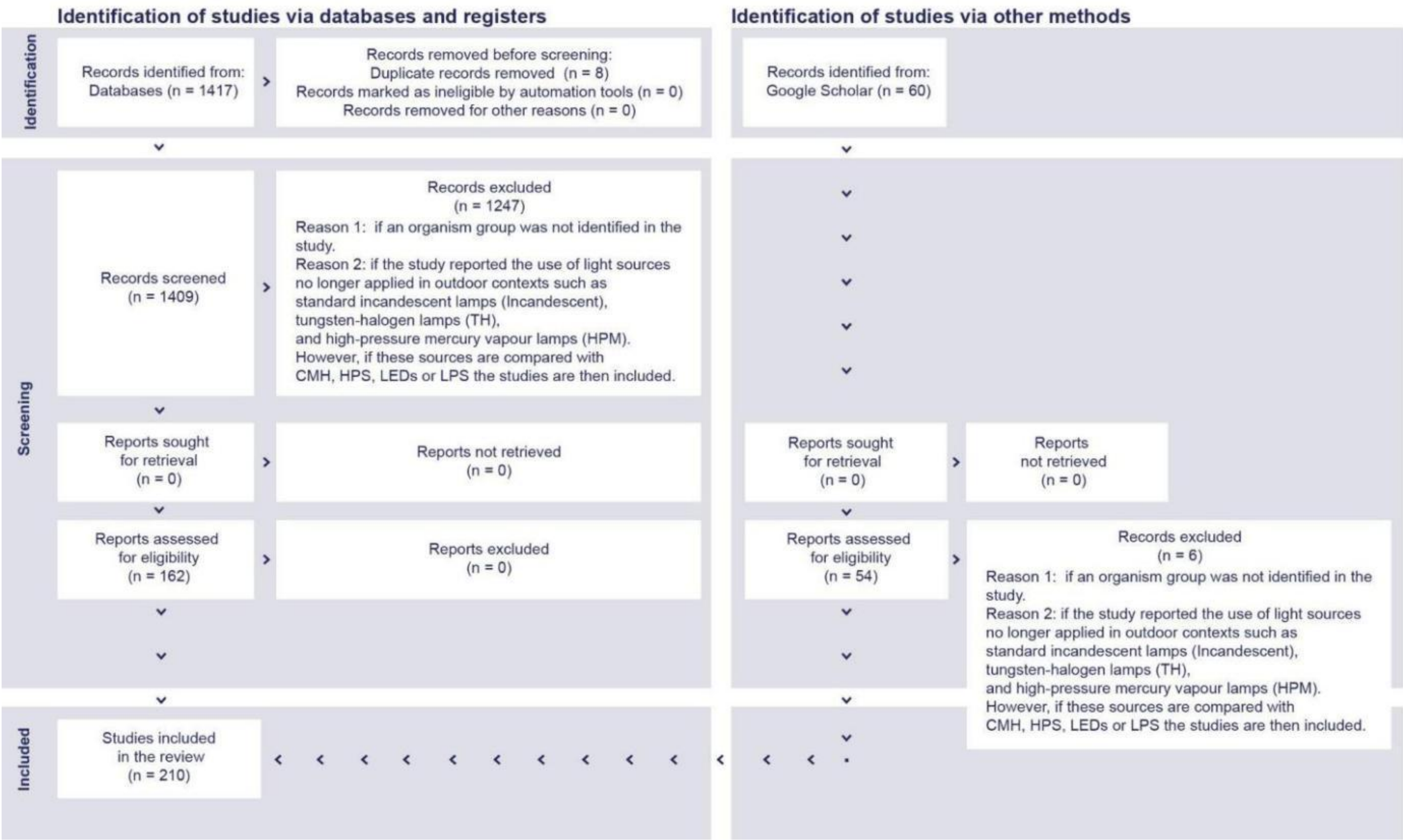


Figure 3. Flow chart depicting the selected studies according to the preferred reporting items for systematic reviews (PRISMA 2020). Declaration and the exclusion criteria presented in Section 3.

Table 3. Search strategy: Summary of keywords used for selected organism groups.

Category of organism group	Keyword #1		Keyword #2		Keyword #3		Keyword #4		Keywo rd #5
Plants	"artificial + light"	AND	plant *	-	-	-	-	-	-
Arthropods	"artificial + light"	AND	arthropod *	OR	insect *	OR	spider *	-	-
Fish	"artificial + light"	AND	fish *	-	-	-	-	-	-
Amphibians	"artificial + light"	AND	amphibian *	-	-	-	-	-	-
Reptiles	"artificial + light"	AND	reptile *	-	-	-	-	-	-
Birds	"artificial + light"	AND	bird *	-	-	-	-	-	-
Non-human mammals	"artificial + light"	AND	mammal *	OR	ungulate *	OR	primate *	OR	rodent *

In the group of arthropods, three separate searches were performed: one for arthropods, one for insects, and one for spiders. In the group of non-human mammals, four separate searches were performed: one for mammals, one for ungulates, one for primates, and one for rodents. The keywords were searched for in titles, abstracts, and the keyword section. "AND" is used to bind keywords (e.g., artificial light with an organism group) and "*" to broaden the search finding by including word stems or plural forms of the keywords.

All review article types were excluded. The searches were aimed to identify only peer-reviewed articles in the English language. The literature searches were performed in January 2020, and the abstracts were subsequently reviewed (from March to June 2020). The literature searches were performed via an electronic database search in Web of Science and PubMed. The content in titles and abstracts was scanned to identify physical properties of artificial light linked to a change or no response in the determined selected organism groups.

To minimize bias, the data from the studies included in the systematic review were extracted in two categories: (a) one that identified key indicators of artificial light properties (see Table 2 and Fig. 3) and (b) one that identified key findings in the study reports in an organism group when exposed to artificial lighting properties. Table 2 shows the physical properties of artificial lighting with the corresponding symbol and unit used for the systematic review. Figure 3 shows an overview of artificial light sources included in the systematic review. Exclusion criteria were applied to the records in the case any of the following elements were present: organism group was not identified; there was day-time exposure to artificial light; horticultural studies were performed to enhance plant growth; phased-out light sources were still often used for outdoor illumination, including incandescent lamps (Incandescent), tungsten-halogen lamps (THs), and high-pressure mercury vapour lamps (HPMs); illuminance > 200 lx, as a maximal threshold to represent typical light-polluted scenarios in outdoor environments; and studies were conducted addressing the impact of ALAN on humans.

These criteria were designed to present a review on the properties of artificial lighting that shape typical applied artificial light by lighting professionals creating light-polluted scenarios. In addition, the intent was to reconcile an understanding of ecology with a commitment to sustainable demands relevant to the application of lighting technologies at night and for those in charge of managing lighting scenarios.

The titled and abstracts of records were screened, and then the full texts of studies were reviewed to identify, order, and aggregate the results as follows: (a) an organism group defined as the main study subject, (b) the reported light source used, (c) the reported physical properties of artificial lighting, and (d) a response, multiple responses, or no response to ALAN. Six researchers participated in the screening assessment of Table 2 and Figures 4–9. One researcher performed a double screening of the studies to properly identify the results and to assess the content in Figure 4-9 and the Supplementary Materials. Two researchers performed an additional screening of the studies to properly translate the results taken into account for

Figures 4–9 and for the Supplementary Materials. Three researchers screened and assessed the appropriateness of the summarized content for Figure 4-9. A final screen was performed by all researchers for Figures 4–9.

Category of organism groups		Research Databases: Web of Science	Research Databases: PubMed	Additional articles	Total of studies per category
Plants		13	1	5	19
Arthropods, Insects, and Spiders	Uncat.	6	4	9	43
	Insects	21	1		
	Spiders	2	0		
	Total	29	5		
Fish		20	0	8	28
Amphibians		8	0	4	12
Reptiles		4	0	4	8
Birds		62	2	12	76
Mammals (non humans)	Uncat.	7	0	12	30
	Primates	2	1		
	Ungulates	0	0		
	Rodents	7	1		
	Total	16	2		
Total of included studies					**216**

Plants | Arthropods, Insects, and Spiders | Fish | Amphibians | Reptiles | Birds | Mammals (non humans)

Figure 4. Summary of reported studies that investigated the impact of ALAN in organism groups. A total of 216 studies were included in the systematic review. The subcategory of "Uncat." indicates all studies that were searched using the main category of the group as a keyword.

Once the studies were arranged by organism groups, the reported studies were screened to identify the light source type that was investigated in each study. Some studies did not report the type of artificial light source and instead, described the physical properties of artificial light. For this reason, if a non-identified artificial light source was presented in the included studies, the non-identified artificial light source was addressed as ALAN. ALAN was then categorized as direct ALAN (e.g., if described as a point source) or indirect ALAN (e.g., if described as skyglow).

Figure 4 presents an overview of the total number of studies included per electronic database search; the number of studies in additional articles that were included; the total number of studies included, which are categorized by organism groups; and the total amount of studies reported for the systematic review. A double screening of the studies was assessed by one researcher.

3.6. Results

3.6.1. Impact of Artificial Lighting on Organism Groups

A total of 216 studies were identified. These studies included behavioural and physiological responses in:

- Plants [59,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75,76,77];
- Arthropods, including insects and spiders [71,78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119];
- Fish [120,121,122,123,124,125,126,127,128,129,130,131,132,133,134,135,136,137,138,139,140,141,142,143,144,145,146,147];
- Amphibians [148,149,150,151,152,153,154,155,156,157,158,159];
- Reptiles [160,161,162,163,164,165,166,167];
- Birds [168,169,170,171,172,173,174,175,176,177,178,179,180,181,182,183,184,185,186,187,188,189,190,191,192,193,194,195,196,197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212,213,214,215,216,217,218,219,220,221,222,223,224,225,226,227,228,229,230,231,232,233,234,235,236,237,238,239,240,241,242,243];
- Non-human mammals, including bats, primates, rodents, and marsupials [24,160,161,174,244,245,246,247,248,249,250,251,252,253,254,255,256,257,258,259,260,261,262,263,264,265,266,267,268,269], when their habitats, aquatic or terrestrial, were artificially illuminated with direct or indirect emissions of ALAN (i.e., all light sources of artificial light).

The results of our systematic review show that the most studied organism groups exposed to night-time illumination were birds (76 studies); arthropods, insects and spiders (43 studies); non-human mammals, including bats, primates, rodents, and marsupials (30 studies); fish (28 studies); plants (19 studies); amphibians (12 studies); and reptiles (8 studies). A total of 4 studies are doubled marked as these present results for more than one group (e.g., results for birds and mammals) [71,160,161,164].

3.6.1.1. Plants

In general, it appears from the 19 plant studies that growth is stimulated to increase foliage [59], stems [60], density, and cover [61,62] when the oscillations of natural day and night cycles are less clear and nights are lighter due to ALAN. In addition, ALAN was shown as a disruptor of processes that can even affect interactions between plants and other organisms. For instance, plants exposed to ALAN demonstrated an earlier initiation of budburst [63], an early and increased flowering process [60,64,65], a delayed flowering state [66], altered plant–herbivore interactions [67,68], altered leaf litter decomposition [69,70], and disrupted pollen transport [68].

3.6.1.2. Arthropods: Insects and Spiders

The 43 arthropod studies showed clear ALAN-mediated behavioural responses (mainly attraction or avoidance) and physiological responses (e.g., gene expression, growth, and fecundity). Light is considered an essential cue for this organism group at night. Therefore, if ALAN is present at the wrong time and place, it can disturb orientation, navigation, finding resources, foraging, courtship, reproductive behaviour, interaction between species, and predator avoidance, which can lead to changes in population dynamics and community structure.

The majority of studies reported a positive phototactic response, i.e., the attraction of organisms toward a stimulus of light, for example, when exposed to the emission of light or when proximate to illuminated locations, varied types of light sources, or polarized light pollution at night.

For instance, spiders [78,79], female and large-sized non-biting midges, which include *Chironomus plumosus* and *Procladius* sp.; the small-sized midges *Tanypus punctipennis* [80]; moths [81,82,83,84]; and camel spiders, were observed moving toward illuminated locations that presented higher densities of prey at night. A total of four studies reported aquatic and terrestrial arthropods, insects, and spiders that commonly move between aquatic and terrestrial landscapes as attracted to illuminated settings located nearby [78,85,86,87]. A total of seven studies compared varied types of light sources that may trigger attraction in arthropods [88,89,90,91,92,93,94,95]. Three of the five studies compared the attraction of arthropods and insects when they were exposed to two different types of light sources. These studies showed altered insect flight activity in various arthropods [88], an altered flight activity in flying insects that leads to attraction toward urban and peri-urban night-time illuminated environments [82], and the attraction of flying terrestrial insects toward light sources with varied CCTs [83]. Two of the five studies defined a level of attraction in arthropods, insects, and spiders when comparing the amount of attracted organisms detected at the light sources [84,86]. Two studies reported that the degree of horizontally polarized light can potentially interact with illuminated man-made structures, which can induce attraction to ALAN in arthropods, insects, and spiders [94,95].

A total of four studies demonstrated a negative phototactic behavioural response (the opposite to positive phototactic, which refers to the avoidance by organisms of or their repulsive response toward a stimulus of light) in arthropods, insects, or spiders. The studies reported avoidance behaviour in female arthropods (*Operophtera brumata*) [96], a lower propensity to fly toward light in urban moths when compared to moths from darker habitats [97], avoidance of ALAN as an anti-predator behaviour in the tree weta (*Hemideina thoracica*) and cave weta (*Rhaphidophoridae*) [98], and a reduced light avoidance behaviour in urban spiderlings that exhibited a choice of location for web building near illuminated areas [99].

Exposure to ALAN resulted in altered predator–prey interactions [100,101,102,103,104] in aphids and bean plants [100]; altered locomotor activity in male parasitoid wasp (Aphidius ervi) and its main host, the pea aphid (*Acyrthosiphon pisum*) [104]; and altered web selection for foraging and for prey capture in Australian garden orb-web spiders (*Eriophora biapicata*) [101]. Exposure to ALAN was shown to affect the abundance, community structure, density, and coverage of arthropods, insects, and spiders in a determined location. ALAN was observed to increase the abundance and diversity of insects compared to terrestrial predators as it alters the nutritional flux of aquatic webs to terrestrial food webs when habitats are artificially lit at night [105].

Furthermore, the biomass of attracted insects was affected by the moon illumination fraction (sometimes given as a percentage) [103]. Four studies reported an altered mating and courting behaviour in arthropods when they were exposed to ALAN [96,106,107,108].

A higher number of mated female arthropods (*Operophtera brumata*) were observed in non-illuminated trunks, as a negative phototactic response to ALAN, which was observed to disrupt the reproductive behaviour in female arthropods [96]. Female fireflies were observed not to flash when they were exposed to ALAN. No flashing light is an atypical behaviour in fireflies compared to fireflies that were observed in darker locations, where female fireflies tethered at least once [106].

One study reported an altered courtship and an increase in mating behaviour in Australian black field crickets (*Teleogryllus commodus*) when they were under ALAN [107]. However, another study under ALAN exposure observed a longer time initiating movement on exposure to ALAN, which appeared to potentially alter aspects of mate finding and exploratory behaviour [108].

Four studies demonstrated an altered physiology and development in arthropods when exposed to ALAN [109,110,111]. When black-bellied fruit flies (*Drosophila melanogaster*) were exposed to a gradual increase in illuminance, oviposition (the process of laying eggs) was less likely to occur and even decreased. This was considered to affect the fecundity and survival rate of fruit flies [109]. Orb-web spiders (*Eriophora biapicata*) exposed to ALAN were observed to mature significantly earlier, and their growth was stunted. There was also an increased mortality rate and a reduced number of eggs produced by females, which was considered to decrease reproductive success and survival [110]. For *Apamea sordens*, exposure to ALAN was linked to a decrease in body mass gain and altered development during the larval stage [71]. Meanwhile, a prolonged egg period, a decreased hatch rate, a shortened larval development period, an increase in the larval survival rate, a decrease in fecundity per female, a decreased oviposition quantity per day, and a prolonged pre-oviposition and oviposition period were reported in *Mythimna separata* when they were exposed to ALAN [111].

3.6.1.3. Fish

A total of 28 studies demonstrated behavioural and physiological responses in fish when they were exposed to ALAN. The attraction to [120] or avoidance [121,122,123,124,125] of illuminated waters was observed to cause a behavioural response to ALAN. For instance, the attraction of fish toward illuminated water areas has been shown to be a response exhibited by various fish species, such as lance (*Ammodyteshexapterus* sp.), three-spined stickleback (*Gasterosteus aculeatus*), Pacific herring (*Clupea pallasi*), great sculpin (*Myoxocephalus polyacanthoscephalus*), and soft sculpin (*Psychrolutes sigalutes*) [120]. In contrast, lit water sections were avoided by European eel (*Anguilla anguilla*) [121,122], American eel (*A. rostrata*) [123], vendace (*Coregonus albula*) [124], and *B. boops* [125]. In this context, altered dispersal, movement, or migration patterns in fish have also been observed. For example, Atlantic salmon (*Salmo salar*) smolts showed a change in migration behaviour when leaving their natal waters [126].

A delayed fry dispersal was shown in Atlantic salmon (*S. salar*) when they were exposed to ALAN [127]. Similarly, delayed dispersal timing and a disturbed diurnal pattern were found for Atlantic salmon (*S. salar*) under ALAN [128]. One study even suggested using artificial light to guide eels into safe waters [123].

Other changes in behavioural responses in fish that were exposed to ALAN were altered foraging behaviour, habitat use, and invertebrate prey assembled at a determined location [129]. An altered predator–prey interaction was observed in zooplanktivorous juvenile rudd (*Scardinius erythropthalmis*) and their prey (*Daphnia pulex* × *pulicaria*) [130].

^Changed physiological responses in fish that were exposed to ALAN include a suppression of melatonin production in Eurasian perch (*Perca fluviatilis*) [117,118,119], roach (*Rutilus rutilus*) [134] golden rabbitfish (*Siganus guttatus*) [135], and zebrafish (*Danio rerio*) [136]. In addition, when Atlantic salmon (*S. salar*) were exposed to ALAN, low cortisol rates were observed, which indicates altered stress perception [137], and juvenile, bonefish (*Albula vulpes*) exhibited elevated blood glucose and blood glucose concentrations [138]. When roach (*R. rutilus*) and Eurasian perch (*P. fluviatilis*) were exposed to ALAN, their blood concentrations of sex steroids (17β-estradiol; 11-ketotestosterone) as well as their mRNA expression of gonadotropins (luteinizing hormone and follicle stimulating hormone) were reduced. Larvae surgeonfish (*Acanthurus triostegus*) were observed to have a reduced thyroid hormone levels [139].

A total of two studies reported altered growth rhythms. For instance, larval fish Nile tilapia (*Oreochromis niloticus*) demonstrated low larval growth and feed conversion efficiency [140] and Atlantic salmon (*S. salar*) showed an increase in their growth and body weight, which may reduce the incidence of sexual maturation [141]. One study reported that ALAN had no significant effect on the growth rate of Atlantic salmon (*S. salar*). However, accelerated oocyte reabsorption was demonstrated, which might alter their basic pattern of growth.

3.6.1.4. Amphibians

A total of 12 articles described ALAN as an invasive component of night-time environments near aquatic and terrestrial habitats and a stressor of behavioural and physiological responses in amphibians. Amphibians are a highly vulnerable taxon group. The impact of ALAN is not always population threatening, but it can reduce resilience and, thus, increase vulnerability against other anthropogenic stressors. Disturbances of these species have to be avoided, and technological solutions that have less negative impact should be a priority.

ALAN was reported to alter amphibian behavioural responses, including the preference for shelter [148]; attraction toward urban edges, which might lead to an altered passage choice of habitats typically visited [149,150]; altered vocalization calls [151,152]; altered detection and consumption of prey [153]; altered attempts to capture prey [154]; increased activity [155]; and mate selection and reproductive success [156].

Physiological responses in amphibians when they were exposed to ALAN included reduced growth [157] and high production levels of neutrophil proportions and altered ratios of neutrophils to lymphocytes [158].

3.6.1.5. Reptiles

A total of eight articles reported ALAN as an invasive artificial condition that may have a detrimental impact on the natural habitat of reptiles and as a consequence, it may drive reptiles away from dark areas and distract them from their common behaviors at night. Two studies looked into the emergence of reptiles at night in illuminated locations. The attracted reptiles derived visual range sensitivities that were significantly stimulated by the wavelength composition of light sources with a broad SPD [160,161]. Artificially illuminated habitats appeared to trigger opportunistic foraging behaviour in Moorish wall geckos (*Tarentola mauritanica*) for easily finding prey, which increased their foraging activity [162]. In addition, in the reptile organism group, four studies documented that different turtle species are adversely affected by the presence of ALAN when their aquatic habitats on coastlines and shores, specifically turtle nesting sites, are artificially illuminated by night [163,164,165,166].

Marine sea turtles, including loggerhead sea turtles (*Caretta mauritania* L.), green sea turtles (*Chelonia mydas*), hawksbill sea turtles (*Eretmochelys imbricate*), olive ridley sea turtles (*Lepidochelys olivacea*), flatback sea turtles (*Natator depressus*), and leatherback sea turtles (*Dermochelys coriacea*), were attracted to illuminated locations away from their nesting sites [163], which also deviated marine turtles from their nocturnal trajectories [164]. In addition, as their nocturnal behaviour was affected by the presence of ALAN, it could incite the aggregation of marine turtles inland, away from the water [165]. In addition to an altered movement and trajectory pattern inland, ALAN may disturb the hatching behaviour of marine turtles that arrive inland [166].

Eight studies demonstrated that exposure to ALAN in terrestrial and aquatic reptiles results in different behavioural responses that draws them, for example, away from their typical nocturnal habits and to illuminated areas [160,161,162,163,164,165,166,167].

3.6.1.6. Birds

A total of 76 articles revealed evidence of individual impacts of ALAN on birds. Among these studies, ALAN was considered an invasive stressor that reaches bird nests at night, particularly nests in proximity to urbanization [168]. ALAN was shown to alter behavioural responses during flight, migration, rest, and active periods during both night and day, as well during breeding periods and the egg-laying process [169,170,171]. Furthermore, ALAN was reported to impact physiological responses that involved altered reproduction [172], development [173,174], body mass [175], and hormonal levels [176,177,178,179].

Studies related to the attraction and disorientation of birds during flights or migration at night described ALAN as a subjective visual barrier that can potentially affect the ability of birds to locate stopover sites during flights [180]. ALAN also impedes the perception of migrating routes during seasonal avian migration [181,182], which can lead to looped migrations [183], grounded flying birds [184], collisions against tall buildings [185], and the injury or death of nocturnally migrating birds [186].

A total of 6 studies reported altered behaviour during flights at night or during migration [180,181,187,188,189,190]. Flying Leach's storm-petrels (*Oceanodroma leucorhoa*), European storm-petrels (*Hydrobates pelagicus*), and Manx shearwaters (*Puffinus puffinus*) were reportedly grounded when they were exposed to ALAN during nights with moon visibility (with less than 20% of the moon's face illuminated) [187]. Nights with a visible new moon at approximately 0.1–0.3% coincided with grounded Hutton's shearwater fledglings (*Puffinus huttoni*) [191]. A consistent pattern of grounded Newell's shearwaters (*Puffins newelli*) was shown near coastlines [192]. During migration, when basra reed warbler (*Acrocephalus griseldis*) and the sakhalin leaf warbler (*Phylloscopus borealoides*) are exposed to ALAN [189,190], their orientation and navigation cues can be altered, which can potentially lead to destination shifts and changes in flying routes [181].

Fifteen studies showed altered activity or efficacy in birds when they were exposed to ALAN [179,193,194,195,196,197,198,199,200,201,202,203,204,205,206]. A total of three studies demonstrated altered foraging behaviour in birds when they were exposed to ALAN [207,208,209]. For instance, longer foraging periods were observed in urban blackbirds (*T. merula*) [210]. Mockingbirds (*Mimus polyglottos*) were reported to feed their nestlings later in the night [207]. Redshanks (*Tringa totanus*) spent less time foraging during the new moon and on clear nights [208]. Nighthawks were observed foraging at higher locations in illuminated areas [209].

A total of nine studies reported altered timing for singing in birds when they were exposed to ALAN [211,212,213,214,215,216,217,218,219]. An altered timing for singing was reported in European robins (*Erithacus rubecula*), blackbirds (*T. merula*), great tits (*P. major*), and blue tits (*C. caenleun*) [211]. Chaffinches (*Fringilla coelebs*), blue tits (*C. caenleun*), great tits (*P. major*), blackbirds (*T. merula*), and robins (*E. rubecula*) showed altered communication and singing patterns, which affected reproductive behaviour when they were exposed to ALAN [212]. Four studies showed an onset of dawn singing in birds [213,214,215,216]. One study demonstrated no impact of ALAN on the dawn singing behaviour of birds [217]. One study reported that ALAN and noise pollution did not affect dawn singing. However, social factors were acknowledged to induce earlier singing behaviour in male house wrens (*T. aedon*) [218]. For wood pigeons (*Columba palumbus*), ALAN did not affect their calling activity [219].

A total of nine studies reported altered sleep in birds when they were exposed to ALAN [195,196,197,220,221,222,223,224,225]. One study reported no altered night-time sleep behaviour in great tits (*P. major*) when they were exposed to ALAN [226].

Studies that investigated physiological responses to the exposure of ALAN observed advanced reproductive maturity in urban blackbirds (*T. merula*) [172], a preference for illuminated nest selection in urban blackbirds (*T. merula*) [227], an early onset of gonadal development, an early onset of hormonal secretion in urban blackbirds (*T. merula*) [173], lower levels of testosterone in female blackbirds (*T. merula*), no increase in body mass for nestling great tits (*P. major*) compared to great tits in dark locations, altered sexual selection process [175], altered gonadal growth in male great tits (*P. major*) [174], elevated corticosterone hormone in great tits (*P. major*), accelerated reproductive endocrine activation of the hypothalamic–pituitary–gonadal axis in tree sparrows (*Passer montanus*), low levels of estradiol in female and male scrub-jays (*Aphelocoma coerulescens*) [176], an earlier increase of luteinizing hormone, a lower peak in the secretion of luteinizing hormone, lowered levels of testosterone and estradiol in urban tree sparrows exposed to ALAN, and lowered or suppressed melatonin levels [177,178,179].

Lastly, five studies reported ALAN and noise pollution as environmental factors that can affect the density [222] and activity of birds [228,229] at night in an illuminated location.

3.6.1.7. Non-Human Mammals: Bats, Primates, Rodents, and Marsupials

Non-human mammals are considered a threatened organism group due to the expansion of ALAN [160,245]. A total of 11 studies reported an altered behaviour in bats when they were exposed to ALAN. *Pipistrellus nathusii* and *Pipistrellus pygmaeus* exhibited attraction toward illuminated locations [246]. One study showed that *Pipistellus* spp. were one of the most abundant and active species at night [247]. Noctules (*Nyctalus noctula*) displayed attraction toward ALAN, which led them to forage near ALAN [213]. One study reported bat activity at night and calls made by lesser noctules (*Nyctalus leisleri*) as a behavioural response to the density of luminaires and the type of light source [248]. In contrast to this behaviour, two studies presented a repulsive behaviour toward ALAN in lesser horseshoes (*Rhinolophus hipposideros*), *Myotis* spp., and Sowell's short-tailed bats (*Carollia sowelli*) [249,250]. One study reported an increase in activity at night when bats were exposed to ALAN [194]. For instance, Pond bats (*Myotis dasycneme*) demonstrated an altered flight path [251] and Lesser horseshoe bats (*Rhinolophus hipposideros*) [23,252], Kuhl's pipistrelles (*Pipistrellus kuhlii*), and Botta's serotine bats (*Eptesicus bottae*) [251] showed altered flying behaviour and trajectories.

A total of three studies demonstrated altered behavioural and physiological responses in primates when they were exposed to ALAN. For instance, female Japanese monkeys (*Macaca fuscata fuscata*) had suppressed melatonin [254]. Gray mouse lemurs (*Microcebus murinus*) showed delayed nocturnal emergence [255], a high core temperature, and short locomotor activity [256] when they were exposed to ALAN.

A total of nine studies investigated behavioural and physiological responses in rodents when they were exposed to ALAN. Three studies on rodents demonstrated suppressed or decreased activity when they were exposed to ALAN [257,258,259]. In contrast, two studies reported increased activity in rodents when they were exposed to ALAN [260,261]. Rodent bank voles (*Myodes glareolus*) showed increased activity and altered use of space during the quarter moon and the new moon. In this same study, males showed greater body mass compared to females [260]. One study reported delayed sleep, increased glucocorticoid (an indicator of induced stress), and behavioural arousal in Male *C57BL/6* when they were exposed to ALAN [261]. Three studies reported physiological responses in rodents when they were exposed to ALAN, involving an increase in testes size [174], an altered core temperature [262], a remodeled retina, a noticeable reduction of the outer nuclear layer of the retina [263], and an impaired and healing process [264].

A total of four studies reported behavioural and physiological responses in marsupials when they were exposed to ALAN. One study showed increased foraging activity and a decrease in time spent avoiding predators in Tammar wallabies (*Macropus eugenii*) [265]. Two studies reported reduced or suppressed melatonin in Tammar wallabies (*Macropus eugenii*) when they were exposed to ALAN [167,266]. One study reported no effect on the activity and behaviour of wombats (*Vombatus ursinus*) when they were exposed to ALAN [161].

3.6.2. Translating ALAN Research into Applicable Lighting Practice

3.6.2.1. Application Value for Environmental Conservation

Figure 5A–G presents the application value that each study offers for environmental conservation and the required level of ecological knowledge. Two researchers identified and assessed the appropriateness of the application value each study offered and assigned a ranking system that allows the identification of the application value offered by each study following its reference number. The application value for environmental conservation is assigned as follows: "+" if the study presents relevant findings on the effects of ALAN on organisms, "++" if the study presents a significant impact of ALAN with an indication of adverse stress on organisms, and "+++" if the study presents adverse effects of ALAN with ecological relevance. The application value for ULP assigns three different ranks to classify studies based on the required level of ecological knowledge: "+" if the content of the study is considered easy to understand by a lighting professional to raise awareness on the impact of ALAN on an organism group, "++" if the content is considered academic and a basic knowledge of ecological concepts is required, and "+++" if the content of the study requires proficient knowledge in ecology for a better understanding of the study's results.

(5A) Overview of studies for the organism group of plants

	Application value for environmental conservation	Application value for ULP
+	[60,64]	[59,64,72]
++	[59,61,62,66,67,71,73–76]	[60,64,65,66,68,73–76]
+++	[63,65,68–70,72,77]	[61–63,67,69,70,71,72,77]

(5B) Overview of studies for the organism groups of arthropods: insects and spiders

	Application value for environmental conservation	Application value for ULP
+	[78,79–83,88,90–93,97–103,107,109,111–116]	[78,81,83,85,88,89,96,98,112,113]
++	[71,79,85,86,89,94–96,105,106,110,117–119]	[82,86,87,90–93,97,99,101,103,104,106, 107,109–111,114–117,119]
+++	[81,84,87,108]	[71,79,80,84,94,95,100,102,105,108,118]

(5C) Overview of studies for the organism group of fish

	Application value for environmental conservation	Application value for ULP
+	[120,123–125,130–135,137,140,141,142–144]	[124,129]
++	[121,122,126–129,136,138,139,145,146]	[120–123,125,128,146,147]
+++	[147]	[126,127,130–141,142–145]

Figure 5. (a,b,c) Overview of all studies with assigned application values for environmental conservation and ULP. See the text for details.

(5D) Overview of studies for the organism group of amphibians

	Application value for environmental conservation	Application value for ULP
+	[148–155,158]	[149,150,154]
++	[157,159]	[148,150,152,153–157,159]
+++	[156]	[158]

(5E) Overview of studies for the organism group of reptiles

	Application value for environmental conservation	Application value for ULP
+	[160,161,162,167]	[160,161,163–167]
++	[161,163]	[162]
+++	[164–167]	-

(5F) Overview of studies for the organism group of birds

	Application value for environmental conservation	Application value for ULP
+	[169,170,171,173–178,180,182, 185,187,189–192, 194,197–207,209–213,214–224,226,227–229,230, 233,236,239]	[172,181,182,183,184–186,189,190,200–203,205, 209,226,227,239]
++	[168,172,179,181,183,184,193,195,196,212, 225,231,232,234,237,238,240,241–242]	[168,170,171,175,180,187,188,191–193, 195–199,204,206,207,210–217,219,220, 222–224,230,231,233,238]
+++	[186,188,208,235,243]	[169,173,174,176–179,194,208,218,221,225, 228,229,232,234–237,240–243]

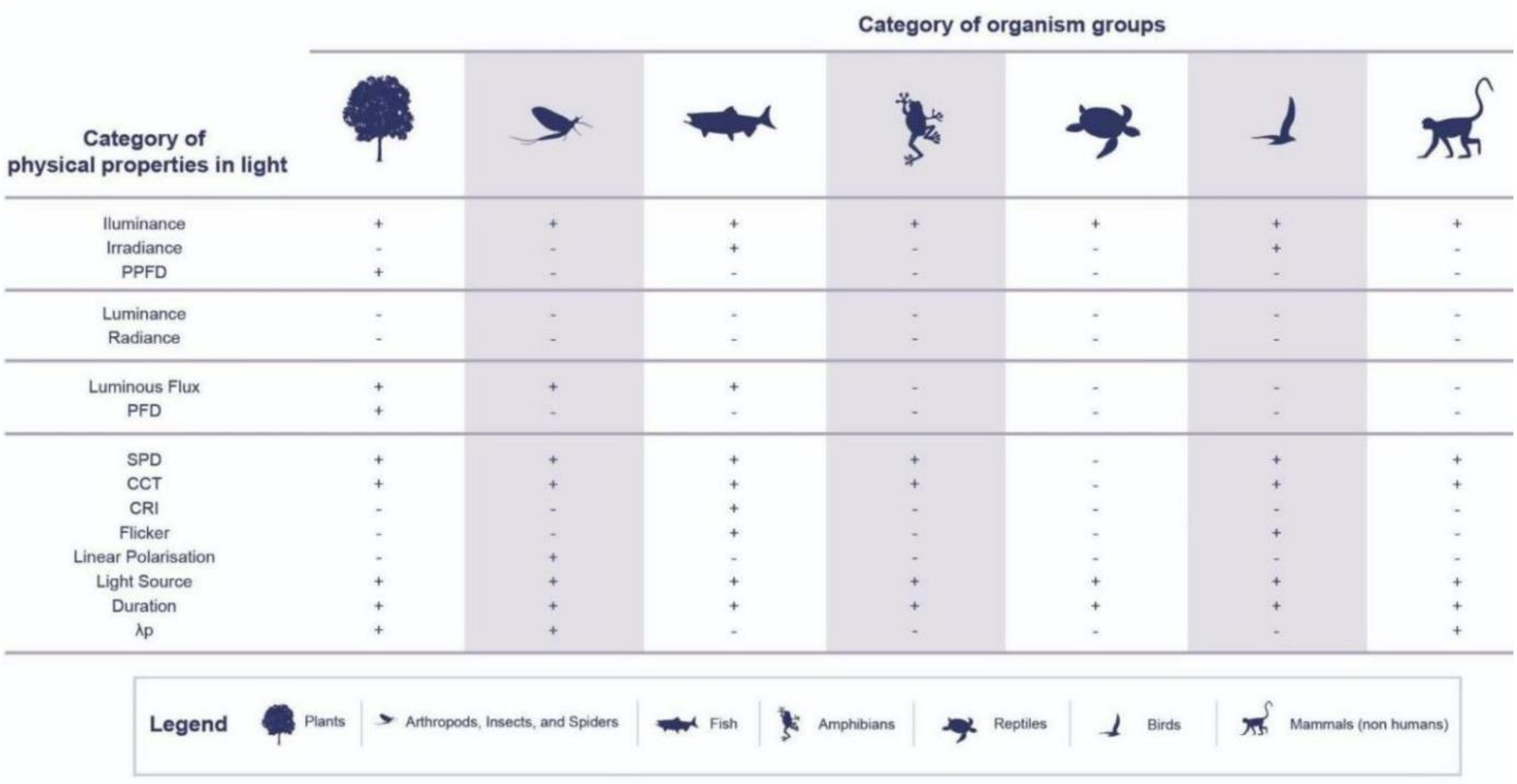
(5G) Overview of studies for the organism group of non-human mammals: bats, primates, rodents, marsupials

	Application value for environmental conservation	Application value for ULP
+	[161,261,267]	[160,161,246,247,248–250,252,258,265]
++	[194,254–258,262–266,268,269]	[23,194,244,245,251,253,255,257,259–261]
+++	[23,160,244–253,259,260]	[254,256,262–264,266–268,269]

Figure 5. (d,e,f,g) Overview of all studies with assigned application values for environmental conservation and ULP. See the text for details.

3.6.2.2. Physical Properties of Artificial Lighting Based on the Responses of Various Organism Groups

Figure 6 shows the physical properties of artificial lighting that are identified or if no results were identified in varied organism groups. Varied usage of physical quantities was identified when describing ALAN. Illuminance was reported across all taxa, and irradiance for fish, birds, and plants (in the PAR band as PPFD) was used as a parameter to describe light intensity. Luminance and radiance were rather uncommon. SPD and CCT were reported for almost all taxa and lamp type for all taxa. A significant number of studies reported the continuous exposure of ALAN to address ALAN operating from dusk to dawn. Only two studies reported a periodic exposure to ALAN, with a determined interval of time. For the organism group of birds, flicker was commonly reported in various articles as a component to consider in light that can potentially alter avian responses.



Category of physical properties in light	Plants	Arthropods, Insects, and Spiders	Fish	Amphibians	Reptiles	Birds	Mammals (non humans)
Iluminance	+	+	+	+	+	+	+
Irradiance	-	-	+	-	-	+	-
PPFD	+	-	-	-	-	-	-
Luminance	-	-	-	-	-	-	-
Radiance	-	-	-	-	-	-	-
Luminous Flux	+	+	+	-	-	-	-
PFD	+	-	-	-	-	-	-
SPD	+	+	+	+	-	+	+
CCT	+	+	+	+	-	+	+
CRI	-	-	+	-	-	-	-
Flicker	-	-	+	-	-	+	-
Linear Polarisation	-	+	-	-	-	-	-
Light Source	+	+	+	+	+	+	+
Duration	+	+	+	+	+	+	+
λp	+	+	-	-	-	-	+

Figure 6. Physical properties of light as reported per organism groups. "+" indicates it was reported. "-" indicates it was not reported

3.6.2.3. The Identified Light Sources

A significant number of studies identified terrestrial organisms, such as birds, that were exposed to direct ALAN and LEDs. There are five categories of organism groups that were reported as being exposed to direct ALAN and LEDs. Fewer studies presented a comparison of an organism group when it was exposed to natural light conditions at night, for example, moonlight, and an artificial light source. The majority of studies focused on reporting behavioural or physiological responses when an organism group was exposed to one type of light source. Table 4 shows the identified types of light sources for each category of organism group.

Table 4. Overview of the number of studies based on the identified light sources and the organism group each study investigated. The category of light sources presents two variations of ALAN, which are defined as follows: "ALAN (dir.)" refers to a point light source and "ALAN (indir.)" refers to indirect skyglow. "-" indicates that no studies were identified for that category.

Category of Artificial Light and Light Sources	Category of Organism Groups						
	Plants	Arthropods: Insects and Spiders	Fish	Amphibians	Reptiles	Birds	Non-Human Mammals: Bats, Primates, Rodents, and Marsupials
ALAN (dir.)	10	6	4	2	4	16	8
ALAN (ind.)	-	3	5	4	2	28	4
CMH	-	-	5	-	-	2	-
FL	1	5	2	1	-	4	2
HPS	-	5	2	1	-	1	3
LED	7	15	6	4	1	23	8
LPS	-	-	-	-	-	-	-
CMH and LED	-	-	2	-	-	-	-

Table 4. Overview of the number of studies based on the identified light sources and the organism group each study investigated. The category of light sources presents two variations of ALAN, which are defined as follows: “ALAN (dir.)” refers to a point light source and “ALAN (indir.)” refers to indirect skyglow. “-” indicates that no studies were identified for that category.

	Category of Organism Groups						
Category of Artificial Light and Light Sources	**Plants**	**Arthropods: Insects and Spiders**	**Fish**	**Amphibians**	**Reptiles**	**Birds**	**Non-Human Mammals: Bats, Primates, Rodents, and Marsupials**
CMH, HPS, and LED	-	2	-	-	-	1	-
CMH, HPS, and TH	-	-	1	-	-	-	-
CMH, HPM, LED, and LPS	-	1	-	-	-	-	-
FL and LED	-	2	1	-	-	-	1
HPS and HPM	-	1	-	-	-	-	-
HPS and LED	1	1	-	-		-	-
HPS, LED, and induction lamp	-	-	-	-	-	-	1
HPS, MH, LPS, and LED	-	-	-	-	1	-	-
LED and HPM	-	2	-	-	-	-	-
ALAN and moonlight	-	-	-	-	-	1	2
LED and moonlight	-	-	-	-	-	-	1

A total of 18 studies, compared two different light sources (2 studies on the impact of CMHs and LEDs on fish; 2 studies on the impact of CMHs, HPSs, and LEDs on the arthropods insects and spiders; 1 study on the impact of CMHs, HPSs, and THs on fish; 1 study on the impact of CMHs, HPMs, LEDs, and LPSs on the arthropods insects and spiders; 2 studies on the impact of FLs and LEDs on the arthropods insects and spiders; 1 study on the impact of FLs and LEDs on fish; 1 study on the impact of FLs and LEDs on non-human mammals, such as bats, primates, rodents, and marsupials; 1 study on the impact of HPSs and HPMs son the arthropods insects and spiders; 1 study on the impact of HPSs and LEDs on plants; 1 study on the impact of HPSs and LEDs on the arthropods insects and spiders; 1 study on the impact of HPSs, LEDs, and induction lamps on non-human mammals, such as bats, primates, rodents, and marsupials; 1 study on the impact of HPSs, MHs, LPSs, and LEDs on reptiles; and 2 studies on the impact of LEDs and HPMs on the arthropods insects and spiders).

Figure 7, Figure 8 and Figure 9 show an overview of the varied organism groups, the type of ALAN, and the three identified physical parameters (illuminance, SPD, and CCT). The types of ALAN are categorized as direct ALAN (dir.), which refers to a point source, and indirect ALAN (ind.), which refers to artificial skyglow. Illuminance was categorized as dim for illuminance below 10 lx, low for illuminance between 10 and 50 lx, mid for illuminance between 50–100 lx, and hi for illuminance between 100 and 200 lx. The SPD was categorized as UV for ultraviolet wavelengths (<400 nm), SW for short wavelengths below 500 nm, MW for mid-wavelengths of 500–550 nm, and LW for long wavelengths of 550–780 nm. CCT was categorized as warm for a CCT < 3300 K, neutral for a CCT of 3300–5300 K, and cold for a CCT > 5300 K.

Figure 7 summarizes studies where ALAN is described unspecifically (i.e., no detailed information of lamp type, etc., is given).

Figure 8 summarizes studies with a specific lamp type given and single sources being investigated (e.g., CMHs or LEDs).

Figure 9 summarizes studies with specific lamp types given and where multiple light sources were compared (e.g., CMHs and LEDs).

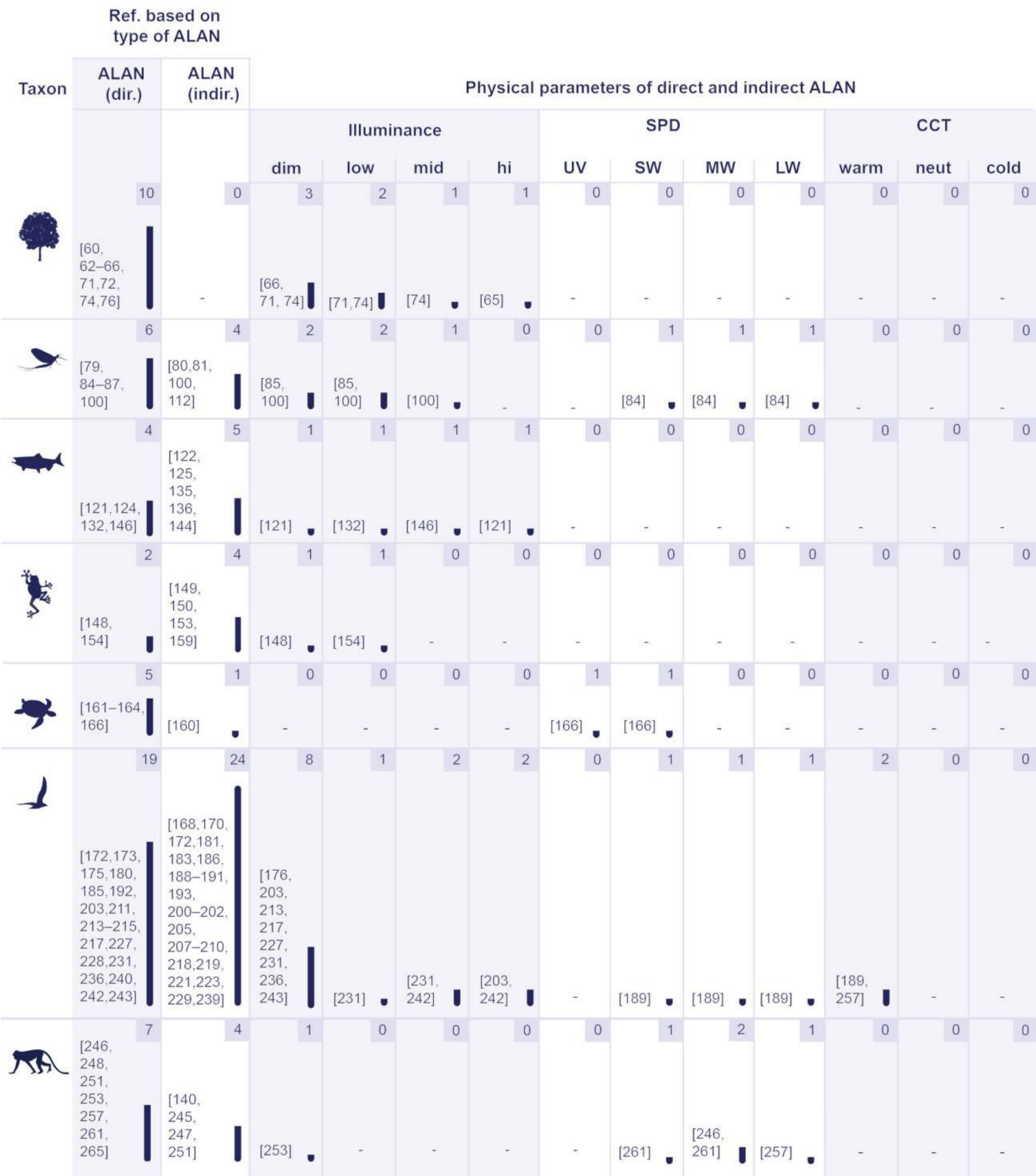


Figure 7. Reported physical parameters per organism group. See the main text for details on categories.

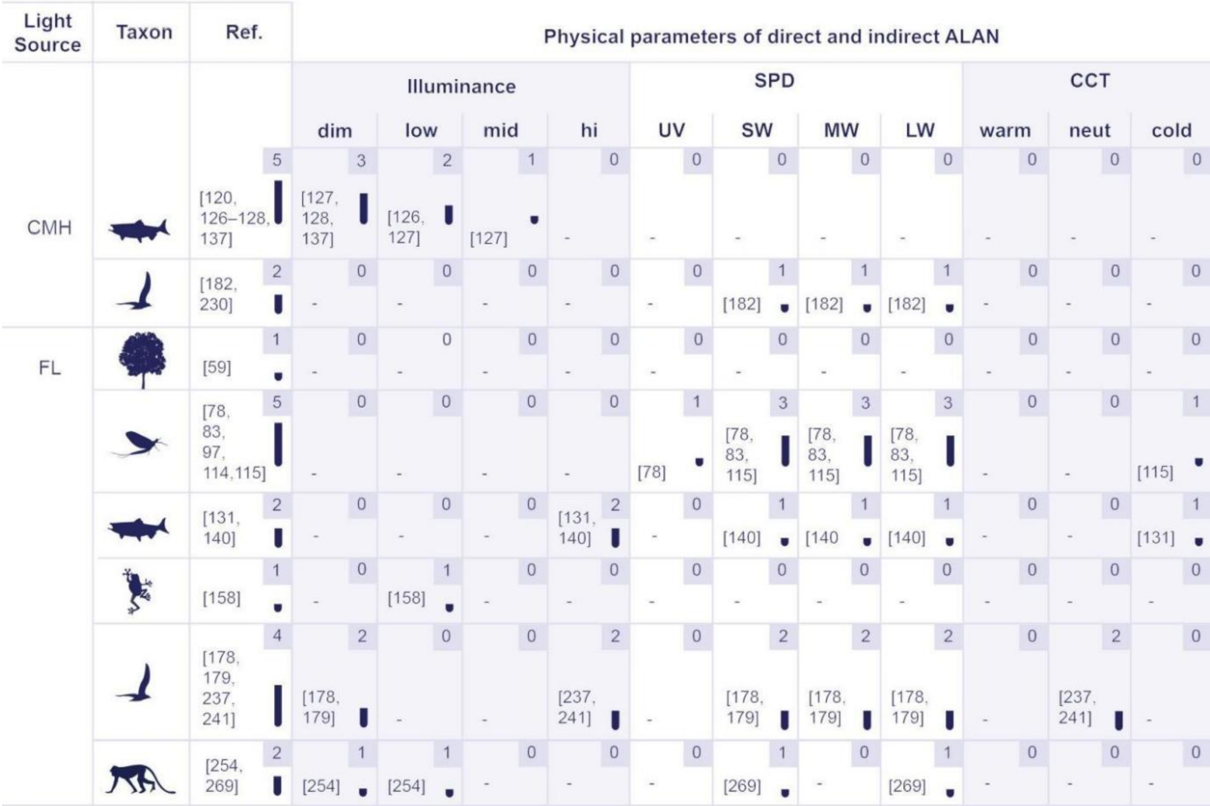


Figure 8. (a) Reported physical parameters per organism group for different (single) CMHs and FLs. See the main text for details on categories.

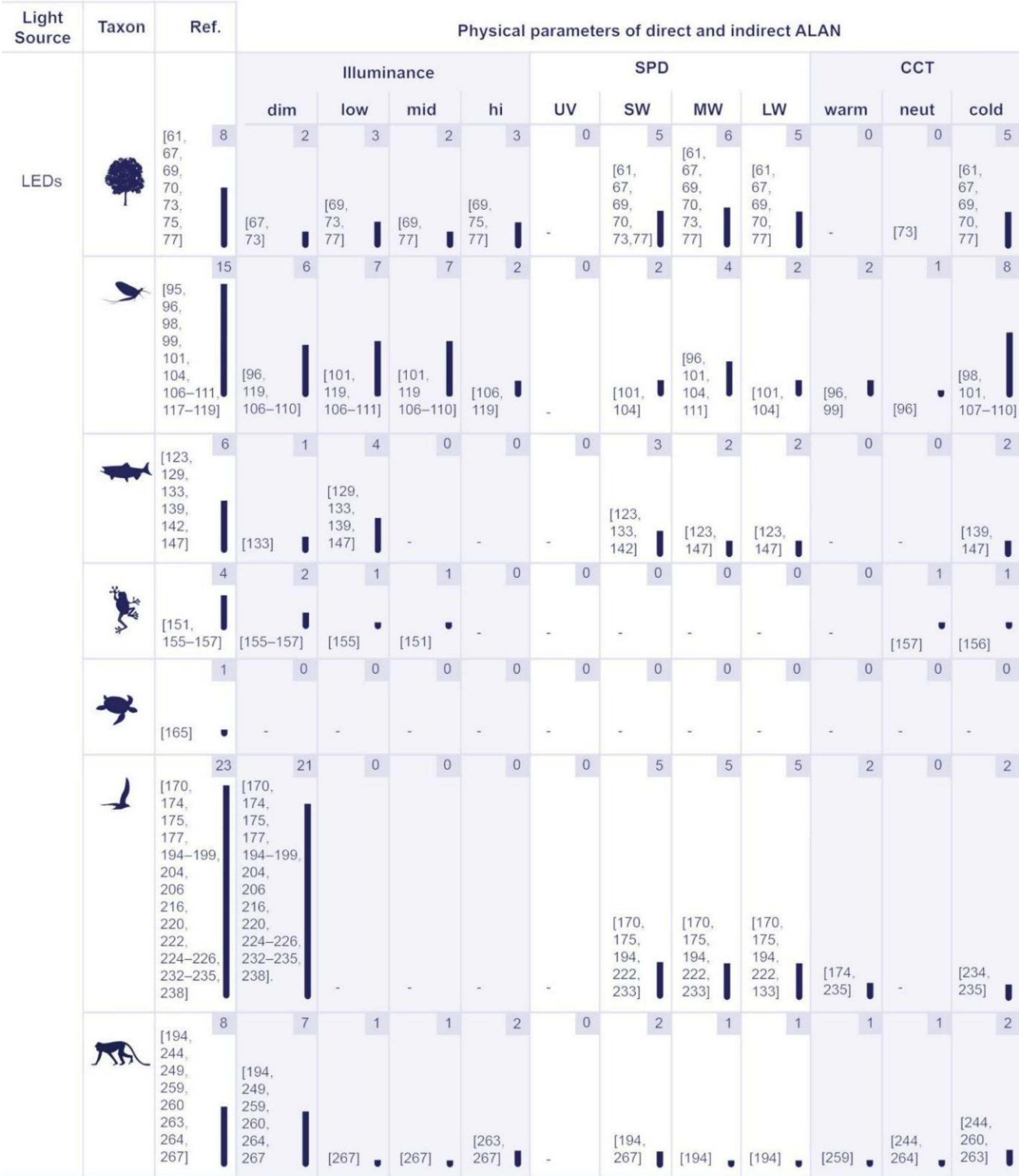
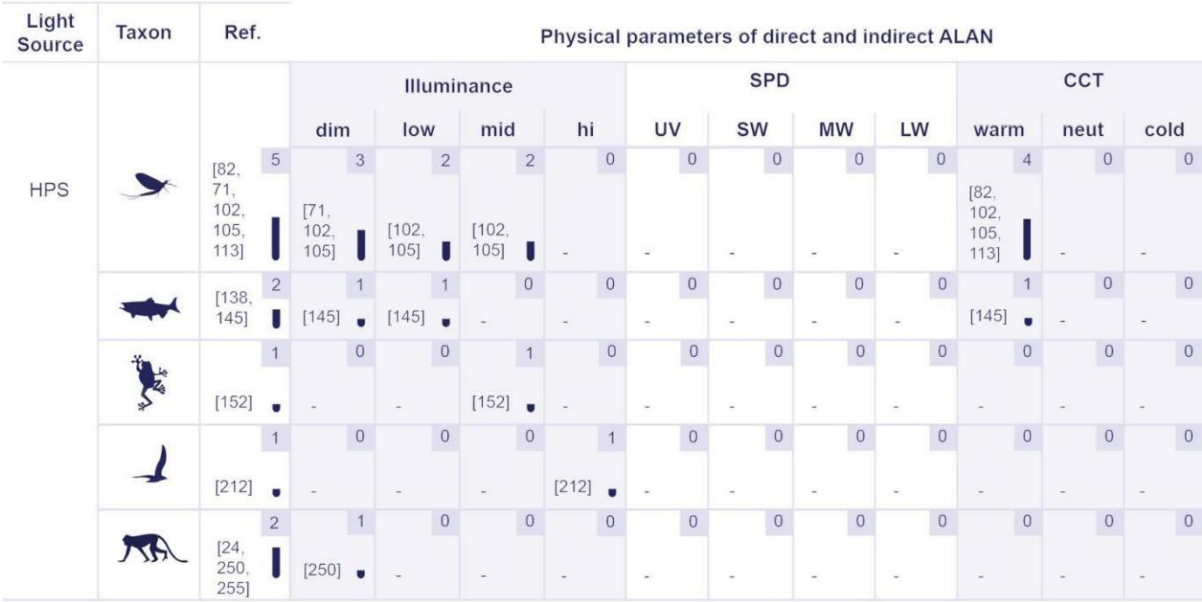


Figure 8. (b) Reported physical parameters per organism group for different (single) LEDs. See the main text for details on categories.



Light Source	Taxon	Ref.	Illuminance: dim	Illuminance: low	Illuminance: mid	Illuminance: hi	SPD: UV	SPD: SW	SPD: MW	SPD: LW	CCT: warm	CCT: neut	CCT: cold
HPS		5 [82, 71, 102, 105, 113]	3 [71, 102, 105]	2 [102, 105]	2 [102, 105]	0 -	0 -	0 -	0 -	0 -	4 [82, 102, 105, 113]	0 -	0 -
		2 [138, 145]	1 [145]	1 [145]	0 -	0 -	0 -	0 -	0 -	0 -	1 [145]	0 -	0 -
		1 [152]	0 -	0 -	1 [152]	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
		1 [212]	0 -	0 -	0 -	1 [212]	0 -	0 -	0 -	0 -	0 -	0 -	0 -
		2 [24, 250, 255]	1 [250]	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -

Physical parameters of direct and indirect ALAN

Figure 8. (c) Reported physical parameters per organism group for HPS. See the main text for details on categories

Muliple light sources	Taxon	Ref.		Physical parameters of direct and indirect ALAN										
				Illuminance				SPD				CCT		
				dim	low	mid	hi	UV	SW	MW	LW	warm	neut	cold
CMH and LEDs		[141, 143]	2	0 -	0 -	0 -	0 -	0 -	1 [143]	1 [143]	1 [143]	0 -	0 -	0 -
HPS and LEDs		[68]	1	0 -	1 [68]	0 -	0 -	0 -	1 [68]	1 [68]	1 [68]	0 -	0 -	1 [68]
		[91]	1	0 -	0 -	0 -	0 -	1 [91]	1 [91]	1 [91]	1 [91]	1 [91]	1 [91]	1 [91]
FL and LEDs		[90, 116]	2	0 -	0 -	0 -	0 -	1 [116]	1 [116]	1 [116]	1 [116]	1 [90]	1 [90]	0 -
		[134]	1	0 -	0 -	0 -	0 -	0 -	1 [134]	1 [134]	1 [134]	0 -	0 -	0 -
		[258]	1	0 -	0 -	0 -	0 -	0 -	1 [258]	1 [258]	1 [258]	0 -	0 -	0 -
HPS and HPM		[88]	1	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
HPS, LEDs and induction lamps		[252]	1	1 [252]	1 [252]	0 -	0 -	0 -	0 -	1 [252]	1 [252]	0 -	1 [252]	0 -
HPS, CMH, LPS, and LEDs		[167]	1	0 -	0 -	0 -	0 -	0 -	1 [167]	1 [167]	1 [167]	0 -	0 -	0 -
CMH, HPS, and TH		[130]	1	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
CMH, HPS, and LEDs		[93, 94]	2	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
		[184]	1	0 -	0 -	0 -	0 -	0 -	1 [184]	0 -	0 -	0 -	0 -	0 -
CMH, HPS, LPS, and LEDs		[92]	1	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
LEDs and HPM		[89, 103]	2	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
ALAN and moonlight		[187]	1	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -
		[256, 262, 265]	3	0 -	0 -	0 -	0 -	1 [265]	1 [265]	1 [265]	1 [265]	0 -	0 -	0 -
LEDs and moonlight		[266]	1	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -	0 -

Figure 9. Reported physical parameters per organism group for different (multiple) light sources. See the main text for details on categories.

3.7. Limitations of the Study

Despite the contributions mentioned in Section 5, this systematic review study has its limitations, which are identified below:

3.7.1. Experimental Setting (Laboratory and Field Studies) versus Applied Outdoor Lighting

To examine the impact of ALAN on the behavioural and physiological responses in flora and fauna, the review was based on published data. However, results from experiments performed in a laboratory environment might be different from the results from similar experiments undertaken in a more complex, real-world environment and, in the end, may cause different interpretations.

3.7.2. Research Methodology

There is a lack of proper research methodology to conduct environmental research in relation to the impact of urban lighting on flora and fauna. This includes establishing specific, commonly approved lighting parameters to allow for the reproducibility of research, as they form the knowledge foundation on which future studies are built.

3.7.3. Language of the Reviewed Studies

Although significant research has been performed all over the world by non-native English researchers in various languages, in our review, we only focused on studies written in English because this is the dominating scientific language. We are aware that when language is a barrier for the work being reviewed, widely shared, and understood by others, that this selection process may have omitted some important data.

3.7.4. Sample Size (Number of Reviewed Research Studies and Publication Bias)

The number of studies considered for a systematic review depends on the keywords, the electronic database, and the defined inclusion criteria used [55,56,57,58]. Furthermore, there are almost no published examples in which no effect was documented, which suggests either that biological effects are fairly widespread or that there is a potential for strong publication bias. Whereas some problem with publication bias would not be surprising, the reality most likely lies somewhere in between [270].

3.8. Discussion

The varied negative effects of ALAN on organism groups are partly investigated and understood by ALAN researchers. However, lighting professionals often struggle to understand these complex findings and on how to apply them into solutions for day-to-day ULP. Therefore, in this paper, we present relevant parameters of artificial lighting that can be applied to minimize its negative effects on the natural environment and to aid in the assessment of ecological conservation.

Existing research on ALAN as an environmental stressor [17,18,20,271,272] indicates strong behavioural and physiological responses of individual organisms, with potential impacts on population communities and entire ecosystems. For instance, the book by Rich and Longcore is the first collection of scientific chapters on potential impacts on mammals, birds, reptiles and amphibians, fish, invertebrates, and plants when they are subject to ALAN. This unique research provides essential information on how ALAN can affect the behaviour and physiology across taxonomic groups. However, little attention is being paid yet to the description of the artificial lighting conditions, which includes the light sources and the physical parameters of artificial light known to affect the mentioned taxonomic groups, in order to better understand the components in the applied light, which raises concern [271]. Gaston et al. [17] developed a framework to put forward space (the location at which ALAN is applied), time (the duration of operating ALAN), and wavelength composition (the spectral signature of ALAN) as three crucial components to consider in ALAN that can potentially affect biological systems (i.e., visual system in animals, photosynthetic system in plants, or non-visual pigments in plants and animals) and how light is distinguished as a resource (i.e., for the photosynthetic process in plants to occur, for the distinction of night and day) or as an information source (i.e., photoperiodism, visual perception, and spatial orientation). Their framework addresses ALAN principles applicable for a better understanding of the impact of ALAN on species and ecosystems [17]. Schroer and Hölker reviewed the perception of light and photoreceptors, and they detail that the time and duration for which luminaires operate, the colour spectra of the emitting sources, and the intensity, as well as the position of luminaires and the direction of light at night, can impact various organism groups, including plants, arthropods, fish, amphibians, birds, reptiles, and mammals. The review concludes with recommendations for three parameters of artificial light. This includes the lowest illuminance level required for its use; the avoidance of spectral distribution rich in short wavelengths as it can alter circadian signals for higher vertebrates, including humans; and the restriction of the direction of light to areas where it is needed. The authors emphasized the importance of avoiding illuminating areas where endangered species live (e.g., natural habitats of aquatic species) and, in general, natural blue and green spaces in urban areas (as long as security and safety requirements are not compromised), as well as natural darkness reserves and corridors for the movement of nocturnal species, such as fish and bats. Despite this, light sources considered for urban lighting applications were not addressed in the review to better comprehend the components applied across nightscapes and their impact on varied organism groups [18]. Furthermore, Grubisic et al., via a systematic review of impacts of ALAN on melatonin production in vertebrates (fish, amphibians, reptiles, birds, and mammals, including humans), concluded that melatonin is suppressed, for some fish species even at an illuminance as low as 0.01–0.03 lx. They also found that melatonin is suppressed at 6 lx for sensitive humans and at much lower illuminances for monochromatic light in the melanopic band. The study provides insights into the disruption of natural photic environments, circadian rhythms, and photoreceptor systems. However, including the type of light source and other physical parameters (i.e., spectral distribution) of the exposed light could aid in understanding the artificial light factors that prevent the production and synthesis of melatonin [20]. Sanders et al. reported via a meta-analysis that when taxa were exposed to ALAN, responses were dominated by changes in physiology, the life history trait of organism groups, the population, and community-based measures. The study briefly mentions that the timing, intensity, and spectrum of artificial light should be restricted to when it is genuinely required by users, humans, to therefore, minimize its ecological impact. Yet, the light sources and physical parameters of the artificial light that induces changes in responses were not addressed to better comprehend the light-polluted scenarios that varied organism groups are exposed to [272]. Recently, Hölker et al. addressed fundamental knowledge gaps, ranging from basic challenges on how to standardize light measurements, through the multi-level impacts on biodiversity, to opportunities and challenges for more sustainable use [273]. All these reviews gather crucial evidence on the night-time environment as a temporal niche in an ALAN context. They address in depth the adverse impact of artificial light at night at the wrong time and place, with unnatural brightness and colors, on biodiversity. In addition, the reviews provide statements about appropriate solutions to the problem as a crucial and straightforward task. The evidence gathered by ALAN researchers indicates that a paradigm shift must happen in the lighting approaches currently used in ULP. However, the lack of detailed information about the applied artificial light across studies, particularly the light sources and the physical parameters that were used, does not adequately inform ULP as there is insufficient information about the parameters to avoid and the ones that can be applied. This lack of information manifests a disconnection between ALAN research, the ULP (i.e., architectural and urban lighting designers and electrical illuminating engineers), and the experts involved in the lighting sector.

Our review shows that varied organism groups experience a wide range of alterations under ALAN (as a single source, as multiple sources, and as an indirect component in a nocturnal landscape). It also shows that wavelength-dependent responses of affected behaviours and physiological processes vary among species. The widespread use of ALAN with continuous emitted light from dusk to dawn, with illuminance levels that mask natural low-light conditions, such as moonlight and starlight; emissions directed toward the sky or downward, toward water bodies, or other natural environments; and emissions rich in short wavelengths and with high CCTs (or a better measured SPD) should be important factors that are taken into account in ULP. The majority of the literature gathered by ALAN researchers confirms that the operating time, illuminance, direction, and spectral appearance of light sources can alter night and day cycles and the actual physical nightscape, which needs protection.

Most studies explored the behavioural and physiological responses of an organism group when it was exposed to direct ALAN (50 studies), while fewer studies explored the potential impact of indirect ALAN across all organism groups (46 studies). However, these studies lacked detailed descriptions that might clarify the stressor parameters observed to alter changes in organism groups.

A large number of studies across all organism groups were focused on LEDs (64 studies). The second-most-studied impact of a light source across all organism groups, except for plants and reptiles, involved HPSs (21 studies). The third-most-studied impacts of a light source across all organism groups (except for reptiles) involved FLs (15 studies). This suggests that the research field recognizes the global shift from conventional lighting toward solid-state lighting in recent years [13]. However, several studies were excluded from this systematic review, as they focused on light sources that are hardly used anymore in urban lighting practice (e.g., incandescent lamps, tungsten halogen lamps, and high-pressure mercury vapour). Instead, our review gathers studies that report the impact of light sources typically considered for urban lighting, including HPSs, LPSs, LEDs, and FLs.

Most of these studies concerning single light sources showed the impact of three different light parameters: (1) broad spectral distributions, including short, mid, and long wavelengths; (2) illuminance levels below 10 lx, and (3) CCTs of 3300–5300 K. Meanwhile, when multiple light sources were compared, only their spectral power distribution was considered. This supports the need for a consensus on measuring and reporting physical parameters of artificial light sources, as it is necessary to properly address the components of artificial light known to be stressors [273].

Fewer studies addressed and compared artificial light with natural light conditions, such as moonlight (two studies on ALAN and moonlight and one study on LEDs and moonlight). This suggests that our knowledge about the extent that artificial light at night can potentially mask natural light conditions still needs to be explored.

3.8.1. Recommendations for Future ALAN Research and Urban Lighting

Future ALAN research should define the type of light source that is used, as well as the physical parameters of the artificial light that is emitted, for a better comprehension of the lighting conditions considered to cause a disruption and to better communicate and translate the potential implications across taxa. Moreover, it is recommended to use ALAN as a term to address studies related to artificial lighting conditions.

It is obvious that ALAN researchers tend to provide different quantities and use different units than lighting professionals. It is crucial for mutual understanding that both groups, ALAN researchers and ULP, try to provide both photometric and radiometric quantities and units (i.e., illuminance in lx and irradiance in W/m2) and ideally an SPD (in W/m2 nm).

Often, studies focus on the continuous exposure of ALAN (from dusk to dawn). Future studies should also consider addressing the periodic exposure to ALAN (for a determined time at night) across taxa.

Furthermore, the exposure to weather and varied atmospheric conditions is rarely considered in research studies that provide evidence on a changed behaviour or physiological change. Future ALAN research should include weather and varied atmospheric conditions (i.e., cloudy days and clear sky) and varied natural light conditions (i.e., lunar phases) when measuring the varied parameters of illuminated nightscapes, which can provide a better understanding of the exposed environment [54,273].

Visual ecology has become a subject of increasing interest among ALAN researchers. Future studies should also explore commonly used light sources for outdoor night-time illumination at varied illuminances in relation to how artificial light at night might impact visual ecology among organism groups [274].

In the past, only a handful of studies addressed two recently explored physical parameters of ALAN, flicker and polarization [94,95,275], and our review does not cover these two parameters in detail as only three studies focused on arthropods reporting polarization as an important parameter for mayflies. Flicker was reported as an important parameter of light in two studies for migrating birds. However, as our current knowledge on the impact of these two parameters remains limited, future ALAN research should acknowledge the degree of polarization and flicker as parameters that can induce a negative response in flora and fauna.

This systematic review tailors ecological knowledge for lighting professionals so they can better understand that artificial lighting can potentially affect individual organisms differently and that the physical parameters of artificial lighting must be carefully managed to minimize the negative impact of ALAN when applying light at night in cities and towns so no organism, ecosystem, or habitat is injured when outdoor lighting is applied. Translating research findings about ALAN implies that ULP must consider the night as a natural resource that needs protecting, with its inhabiting organisms, rather than only addressing tailored solutions for endangered species [34,273,276].

3.9. Conclusions

While the use of artificial illumination has exponentially increased in recent years, and applied lighting technologies have become present across urban and natural environments, ALAN as an anthropogenic pollutant can still be reduced and better controlled by wisely addressing three challenges. These challenges involve (1) rethinking the human-centric approach in ULP, (2) improving communication between ULP and ALAN research, and lastly (3) developing transferable knowledge between these two domains and establishing relevant environmental parameters for urban lighting.

Firstly, these days, urban lighting focuses on mainly presenting the visual experience of nightscapes [33] as well as providing lighting for the safe passage of pedestrians or vehicles, often neglecting natural environments and biodiversity [15,273] and unintentionally polluting naturally dark skies [277]. Therefore, we postulate that lighting professionals involved in ULP should rethink their user-centered approach and become aware of ALAN research. They should also embrace a broad understanding of the detrimental effects of ALAN on natural environments by acquiring ecological knowledge to realize sustainable lighting design that maximizes environmental conservation while also providing safety and security.

Secondly, a shift in the current forms of communication is necessary to bridge between ALAN research and ULP in order to adopt solutions and to instigate an open and collaborative communication between the domains. This approach can help to interpret the challenges, identify boundary concepts, and translate the results developed by each domain [22,273]. The introduced conceptual communication framework (CCF) might serve as a strategy to encourage a collaborative mode of knowledge construction (Figure 10). CCF combines the interests and values of each domain and the knowledge infrastructure offered. It assigns (a) a lighting foundation, as a starting point to define the essential knowledge required by both domains to comprehend the robust nature involved in the ULP and ALAN research, and (b) identifies an environmental ceiling as the boundary necessary for environmental conservation.

Lastly, the difficulty of efficiently translating scientific results between domains hampers developing ecologically friendly and sustainable lighting solutions that consider flora and fauna [279].

For future studies, it is therefore recommended that ALAN researchers consider for their experiments, and for lighting professionals, to consider in their projects, both radiometric and photometric characterization of the artificial light sources used, based on the International System (SI) of units.

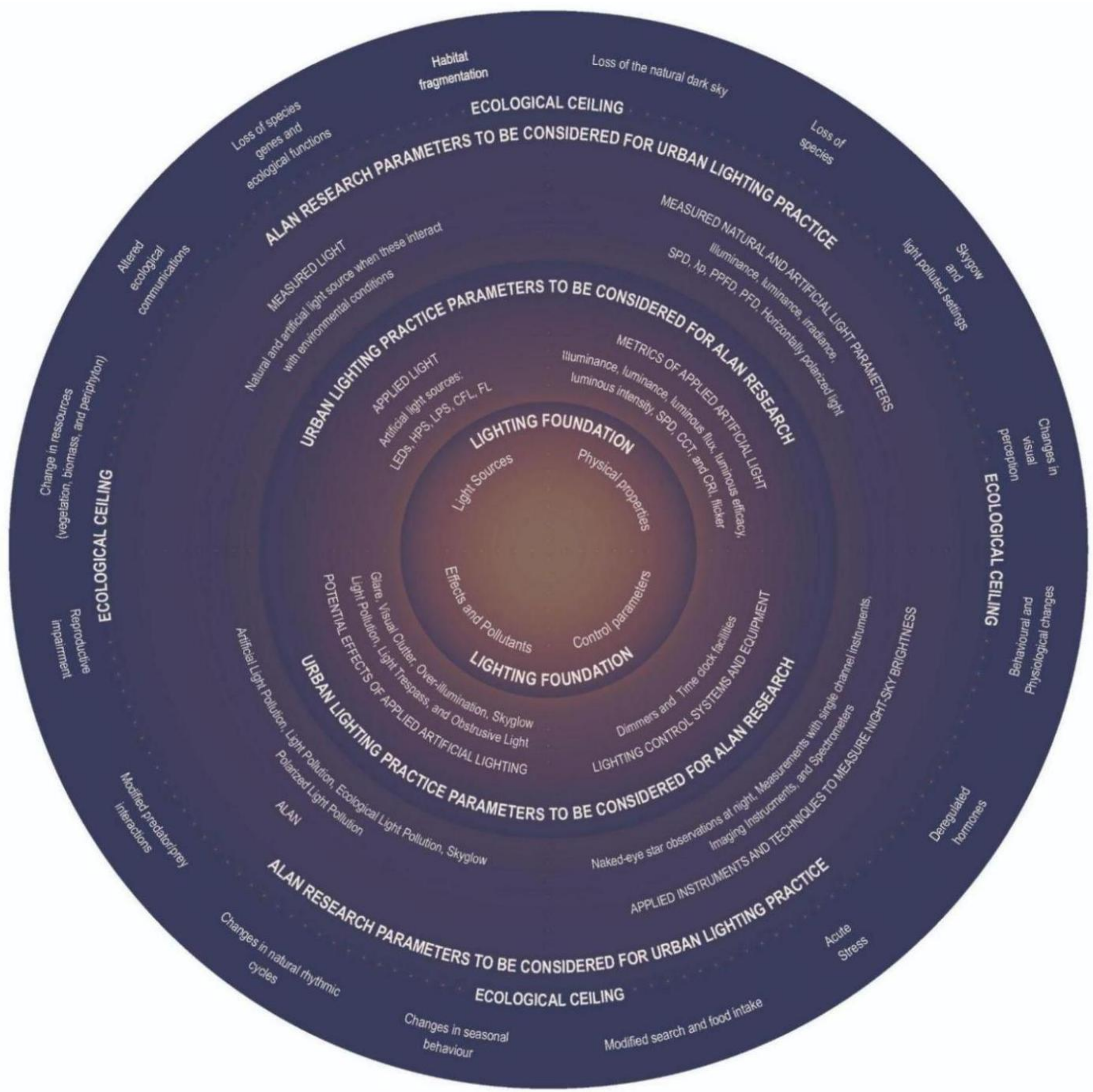


Figure 10. The communication framework and knowledge infrastructure diagram presents four cluster rings, which include the following key components: (a) lighting foundation, (b) ULP parameters to consider for ALAN research, (c) ALAN research parameters to consider for ULP, and (d) an ecological ceiling, inspired from Doughnut Economics [278]. Authors' elaboration.

Additionally, we recommend the development of a common measurement and reporting strategy for physical quantities and units to mitigate potential misunderstandings [20,54] (see, e.g., Kalinkat et al. [54] or Appendix of Grubisic et al. [20]). This collaborative work in the form of systematic review between ULP and ALAN research marks a new chapter in better communication between the two domains and supports more sustainable lighting approaches across nightscapes that involve the protection of the naturally dark skies, flora, and fauna.

3.10. Appendix A for Chapter 3

3.10.1. Terminologies and Definitions Connected to Natural and Artificial Light

While performing interdisciplinary research, many lighting professionals may be unfamiliar with the meaning of biologically related terms, which can result in misunderstanding. Therefore, to enhance comprehension, communication, and collaboration, a list of explanations and descriptions of specific terminologies and definitions has been created (Table A1, Table A2 and Table A3).

Figure A1. (a–l) Various natural day-time and night-time conditions, including light generated by living organisms. Sources: (a) John Westrock/Unsplash, (b) Harry Knight/Unsplash, (c) George Hiles/Unsplash, (d) Nelson Santos Jr/Unsplash, (e) Paul Esch Laurent/Unsplash, (f) Clint Mackoy/Unsplash, (g) Lester Salmins/Unsplash, (h) Nathan Anderson L./Unsplash, (i) Claudio Schwarz Purzlbaum/Unsplash, (j) Leon Mengoli/Unsplash, (k) Andrew Wallace/Unsplash, and (l) Jessica Lucia/Flickr (CC BY-NC-ND 2.0).

Table A1. Overview of terminologies and definitions of natural and artificial light sources relevant for ALAN research and ULP [13,21,47,280,281,282,283,284,285,286,287,288,289,290].

Natural Energy Source	Terminology	Definitions
Sunlight	Sunrise/Sunset	The period when the Sun is at the horizon (at 0°); typical illuminance ca. 800 lx [280].
	Daylight	Solar radiation that reaches the Earth. This includes direct illumination and diffuse illumination from light scattered by air molecules, aerosol particles, cloud particles, or other particles in the atmosphere [281].
	Twilight	The illumination of the lower atmosphere when the Sun is below the horizon [281,282].
Night	Civil twilight	The period when the Sun is between 0° and −6°; the lowest illuminance ca. 3.4 lx [21].
	Nautical twilight	The period when the Sun is between −6° and −12°; the lowest illuminance ca. 0.008 lx [21].
	Astronomical twilight	The period when the Sun is between −12° and −18°; the lowest illuminance ca. 0.001 lx [21].
Lunar cycle	Moonlight	Sunlight reflected on the surface of the moon, which due to changing phases and altitude during orbit, results in varied illuminance on the Earth; the maximum possible illuminance is ca. 0.3 lx for a full moon near zenith; typical peak full moon illuminances in mid latitudes are 0.1–0.2 lx [13,47].
Stars, constellations and the Milky Way	Starlight and the Milky Way	The light emitted by stars of the Milky Way, as observed from the Earth during night time [283,284,285].
Night sky brightness	Radiance/luminance of the night sky	The luminance of a typical clear night sky without light pollution and without airglow is around 200–250 mcd/m^2.

Table A1. Overview of terminologies and definitions of natural and artificial light sources relevant for ALAN research and ULP.

Natural Energy Source	Terminology	Definitions
Airglow	Nightglow	A natural dim light caused by the interaction of solar radiation and gases in the upper atmosphere of the Earth, which creates the natural glow of the night. The resulting glow means the night sky is never completely dark [285].
Aurora (Borealis, Australis)	Polar lights	A natural source of light in the sky caused by the collision of charged particles from the Sun (the solar wind) with atmospheric constituents [286]. As shown in Figure A1j.
Living Organisms	Bioluminescence	The light emitted by a living organism caused by a chemical reaction [287]. As shown in Figure A1k–l.
Artificial Energy Source	**Terminology**	**Definitions**
Gas	Gas lighting	A structured system of underground pipes installed in cities to supply gaseous fuel combustion to produce artificial light for the night-time environment. Gas lighting has mainly been replaced with electric lighting, but a few remain as examples of industrial heritage in the urban landscape of cities such as Berlin and London [288,289,290].
Electric	Electric lighting	A structured system powered by electrical current to produce artificial light at night [290].

Table A2. Overview of terminologies and definitions of responses to light in living organisms and ecosystems.

Responses	Terminology	Definition
Behavioural response	Diurnality	A behaviour occurring during daylight or an organism active during the day and dormant during the night [291,292].
	Nocturnality (crepuscular)	A behaviour occurring during the night or an organism active around sunset, sunrise, or at night, when light conditions are lower compared to daylight [293].
	Migration	The active movement of an organism or group of organisms from one location to a different one. The principle of migration could be periodic (seasonal, with a relative distance, due to changes in climate, temperature, or the availability of resources) or general (the active movement of an organism or group of organisms that may affect the distribution or range of a group of organisms across a landscape [291].
	Navigation	The orientation of a living organism toward a destination (e.g., reaching a breeding area) regardless of its direction, by means other than the recognition of landmarks (e.g., the use of compass orientation) [291].
	Orientation	The ability of an organism to head toward a particular direction without the reference of a landmark [291].
	Phototaxis	The movement or direction of a living organism toward a light source as a behavioural response to changes in illuminance and colour in light. This behaviour is called positive phototaxis when the living organism is attracted or directed toward the light source, while avoidance or repulsion is called negative phototaxis [294].
Physiological response	Melatonin	A hormone secreted during the dark phase of the day responsible for regulating the sleep/active schedule and the modulation of circadian rhythms that varies between organisms [295].

Table A2. Overview of terminologies and definitions of responses to light in living organisms and ecosystems.

Responses	Terminology	Definition
Physiological response	Metabolism	Chemical reactions that occur within the cells of an organism that provide energy for biological processes to occur, (e.g., breathing, repairing cells, growth, or digesting food) [291].
Characteristics and processes in plants	Short-day plants	Plants that require short periods of exposure to daylight and long periods of exposure to darkness to initiate the generative phase (less than 8 h/16 h light/dark rhythm) [291].
	Long-day plants	Plants that require long periods of exposure to daylight, with short periods of exposure to darkness, to initiate the generative phase (more than 16 h/8 h light/dark rhythm [296].
	Photosynthesis	The complex process by which plants transform absorbed light (artificial or natural), carbon dioxide, water, certain inorganic salts, and chlorophyll into energy for growth and survival. An important by-product of this process is O2 and carbohydrates generated by the conversion of CO2 and water [297].
Visual response to light	Mesopic vision	The visual sensitivity of a vertebrate to see when exposed to conditions such as twilight at luminances between 0.01 and 3 cd/m2. Mesopic vision involves both photoreceptors (rods and cones) for scotopic and photopic vision [53,298].
	Photopic vision	The visual sensitivity of a vertebrate to see under lit conditions, such as daylight, which relies on the function of cones (a photoreceptors in the eye's retina) and facilitates perception of colours [298,299].
	Scotopic vision	The visual sensitivity of a vertebrate to perceive its surrounding environment under dim light conditions or during night time, which relies on the function of rods (a photoreceptors in the eye's retina) and facilitates the perception of contrasts without colours [53].

Lighting professionals and ALAN researchers should be able to identify the correct light source by its physical appearance, dimensions, and characteristics (Fig. A2) in order to properly perform comprehensible and accurate observational studies and night-time field experiments.

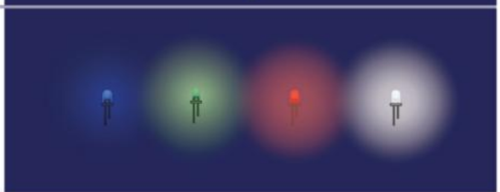
Category of artificial light and light source	Type	Abbreviation	Examples
ALAN	indirect or skyglow	ALAN (ind.)	
ALAN	direct or point source	ALAN (dir.)	
Ceramic-Metal Halide lamp	-	CMH	
Compact Fluorescent lamp	-	CFL	
High-pressure Sodium lamps	-	HPS	
Light Emitting Diode	-	LEDs	
Linear Fluorescent lamp	-	FL	
Low-pressure Sodium lamp	-	LPS	

Figure A2. A schematic diagram illustrating the different dimensions of ALAN: ALAN (ind.) in the form of indirect illumination or skyglow in urban and rural areas, ALAN (dir.) in the form of point sources, and six different light sources often used for outdoor night-time illumination: a low-pressure sodium lamp (LPS) and a high-pressure sodium lamp (HPS), a ceramic metal halide lamp (CMH), a compact fluorescent lamp (CFL), light-emitting diodes (LEDs), a linear fluorescent lamp (FL), and a neon and cold cathode lamp. Source: Authors' figure.

Table A3. Overview of various types of electric light sources commonly used in urban settings in the past and present. Source: author's elaboration based on [299,300,301,302,303,304,305,306].

Terminology	Definitions
Standard incandescent lamp	An artificial light source where the filament in the lamp is heated to increase the temperature of the filament so that it emits light. A black body radiator with a CCT. Not in common use any more.
Tungsten-halogen lamp (TH)	An artificial light source with a tungsten filament that is sealed in a transparent housing and filled with a mixture of inert gas and a small amount of halogen to allow higher operating temperatures than standard incandescent lamps. A black body radiator with a CCT of ca. 3000 K. Not in common use any more.
Linear fluorescent lamp (FL)	An artificial low-pressure mercury gas discharge lamp that uses an electrical current to activate the phosphor coating on the interior of the lamp to glow. (The light that is emitted is rich in short and ultraviolet wavelengths.) FLs are commonly used.
Compact fluorescent lamp (CFL)	An artificial low-pressure mercury gas discharge lamp with a curved or folded tube (smaller in size when compared to fluorescents to fit household light sockets) and an integrated ballast. A CFL uses an electrical current that makes the phosphor coating on the lamp's interior glow. (The light that is emitted is rich in short and ultraviolet wavelengths.) CFLs are commonly used.
Cold cathode (CC) and neon lamp	A gas-discharge source that produces artificial light via electricity emitted from a cathode to ignite mercury vapour through the scattering of kinetic energy. CC and neon lamps are commonly used.
High-pressure mercury vapour lamp (HPM)	An artificial light source in a double compartment bulb (a quartz discharge tube with mercury vapour at high pressure and an outer bulb coated with phosphor). The light that is emitted is rich in short ultraviolet wavelengths and visible light. This light source has been banned due to its negative impact on the environment. Not in common use any more.

Table A3. Overview of various types of electric light sources commonly used in urban settings in the past and present. Source: author's elaboration based on [299,300,301,302,303,304,305,306].

Terminology	Definitions
Ceramic metal halide lamp (CMH)	An artificial high-intensity discharge lamp (HID) that uses ceramic material to allow mercury, argon, and metal halide salts to heat at stable but high temperatures to produce light. This light source produces a colour rendering index (CRI) and a correlated colour temperature (CCT) close to daylight, dependent on the mixture of metal halide salts. CMHs are commonly used.
Low-pressure sodium lamp (LPS)	An artificial low-pressure gas discharge light source that uses sodium in the discharge arc tube to warm the lamp in order to produce light. The light that is emitted is from a narrow band of the spectrum (589 nm), a near-monochromatic amber colour unique to sodium lamps. While highly energy efficient and favoured around astronomical observatories, it is not in common use any more and is being phased out in many countries.
High-pressure sodium lamp (HPS)	An artificial high-intensity gas discharge lamp (HID) that produces light through sodium vapour at high pressure. The light that is emitted is broader in spectrum compared to an LPS, with a peak at a wavelength of 586 nm. CCT ca. 2000 K. Still in use but is being phased out.
Light-emitting diode (LED)	An artificial light source that uses a chip of semiconductor material that emits light when an electric current pass through it. It is highly energy efficient, comparable to an LPS, but offers a full spectrum in the visible range and high CRI values. In use and rapidly replacing older light sources, such as LPSs, HPSs, and CMHs. The vast majority of LEDs currently in use for outdoor lighting around the world emit the whole visible spectrum, with peaks of blue wavelengths.

While performing research studies related to artificial lighting and its impact on flora and fauna, it is important to use appropriate metrics/definitions of the units, as presented in Table A4 and in a graphical format in Figure A3. Otherwise, none of the research outcomes can be understood by lighting professionals and integrated into their projects.

For a long time, the lighting industry used the CCT as the only parameter to describe the colour appearance of light sources for urban lighting, which can be considered as an insufficient and often-misleading parameter. There is a different, more important parameter, called the SPD (Figure A4). This parameter can define the energy and wavelengths of an artificial light source that might have a biological impact on living organisms.

Table A4. Overview of radiometric and photometric quantities of light and units. Source [300,301,302,303,304,305,306].

Terminology	Definitions
Radiant energy (Q_e); luminous energy (Q_v)	Energy of electromagnetic radiation, unit J (joule); example, energy of a photon. Luminous energy is the photometric equivalent (i.e., perceived energy referenced to luminosity function); unit (lm s).
Radiant flux (ϕe); luminous flux (ϕv)	Radiant energy per time, unit W (watt); example, all light (photons per second) emitted by a lamp in all directions (Figure A3). Luminous flux is the photometric equivalent; unit lm (lumen).
Radiant intensity (Ie); luminous intensity (Iv)	Radiant flux per solid angle; unit W/sr. Luminous intensity is the photometric equivalent; unit cd (candela, lm/sr).
Radiance (E_e); luminance (E_v)	Radiant flux emitted, reflected, transmitted, or received by a surface per solid angle per projected area; unit W/m2sr. Luminance is the photometric equivalent; unit cd/m2 (lm/m2sr) (Figure A3).
Irradiance (E_e); illuminance (E_v)	Radiant flux received by a surface per area; unit W/m2; example, horizontal irradiance (Figure A3). Illuminance is the photometric equivalent; unit lx (lm/m2).
Spectral irradiance (E_e, λ)	Irradiance per unit wavelength (also frequency); unit W/m2nm.
Luminous efficacy of a light source (Ksource)	Ratio of luminous flux to electrical power of a light source; unit lm/W; a measure of how well a light source produces visible light; not to be confused with the luminous efficacy of radiation.
Electrical power of a light source (Pi)	The rated electrical power consumed by a light source (including ballast, driver, control gear, etc., if applicable); unit W (watt).
Spectral power distribution (SPD)	Distribution of any radiant quantity (radiant energy, radiant flux, radiance, irradiance, etc.) as a function of wavelength, most commonly given in spectral irradiance, ideally provided in nm resolution.
Correlated colour temperature (CCT)	Temperature of a Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution; unit K (kelvin). The CCT can be roughly categorized as warm (<3300 K), neutral (3300–5300 K), or cool (>5300 K) in colour appearance.

Table A4. Overview of radiometric and photometric quantities of light and units. Source [300, 301, 302, 303, 304, 305, 306].

Terminology	Definitions
Color rendering index (CRI)	Measure of the degree to which the psychophysical colour of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant. The CRI is given in 0–100, with 100 being the most accurate.
Reflectance (ρ)	The effectiveness of a material in reflecting radiant (or luminous) energy.
Flicker	Light source with a temporal change in radiant flux that can, e.g., be perceived as a stroboscopic effect.
Lamp survival factor (LSF) or lamp life	The estimated lifespan of a light source once installed and operating, measured in hours. Operating temperature, frequency of usage and switching, failure of electrical components, the supplied voltage, and vibrations are some factors that may shorten the estimated length of lamp life.
Operating time	The management and control of operating lighting systems for a determined geographical location to specify the hours a luminaire or a lighting system may operate and consume energy (for instance, hourly, daily, weekly, monthly, annually, or seasonal or for cultural events, religious events, or holidays).
Scene setting	The control of illuminance levels and/or colour temperatures to set scenes at a determined time for a determined location.
Dimming	The manual or automatic control that manages light output with a programmable timer or sensor installed on-site to provide the gradual decrease of illuminance during a determined period at night or to perform a gradual increase of illuminance levels after dusk.

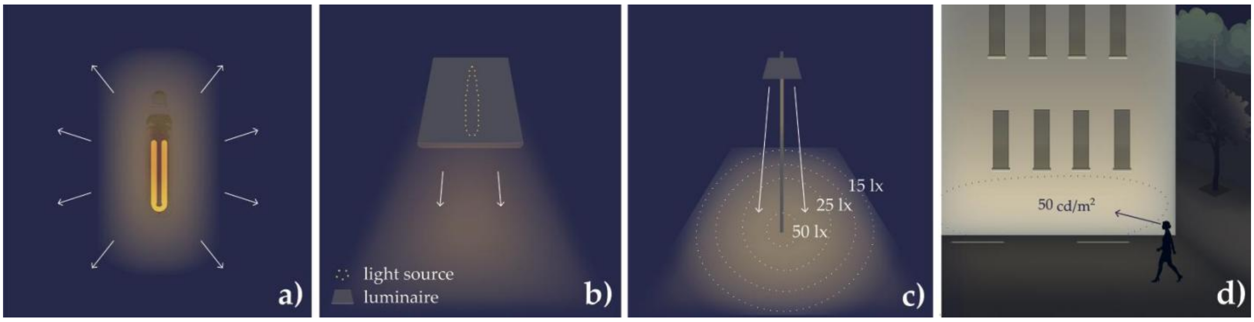


Figure A3. A schematic diagram that illustrates four typical metrics considered by urban lighting professionals: (a) luminous flux radiating in all directions, (b) luminous flux radiating at a determined area, (c) illuminance, and (d) luminance. Authors' figure.

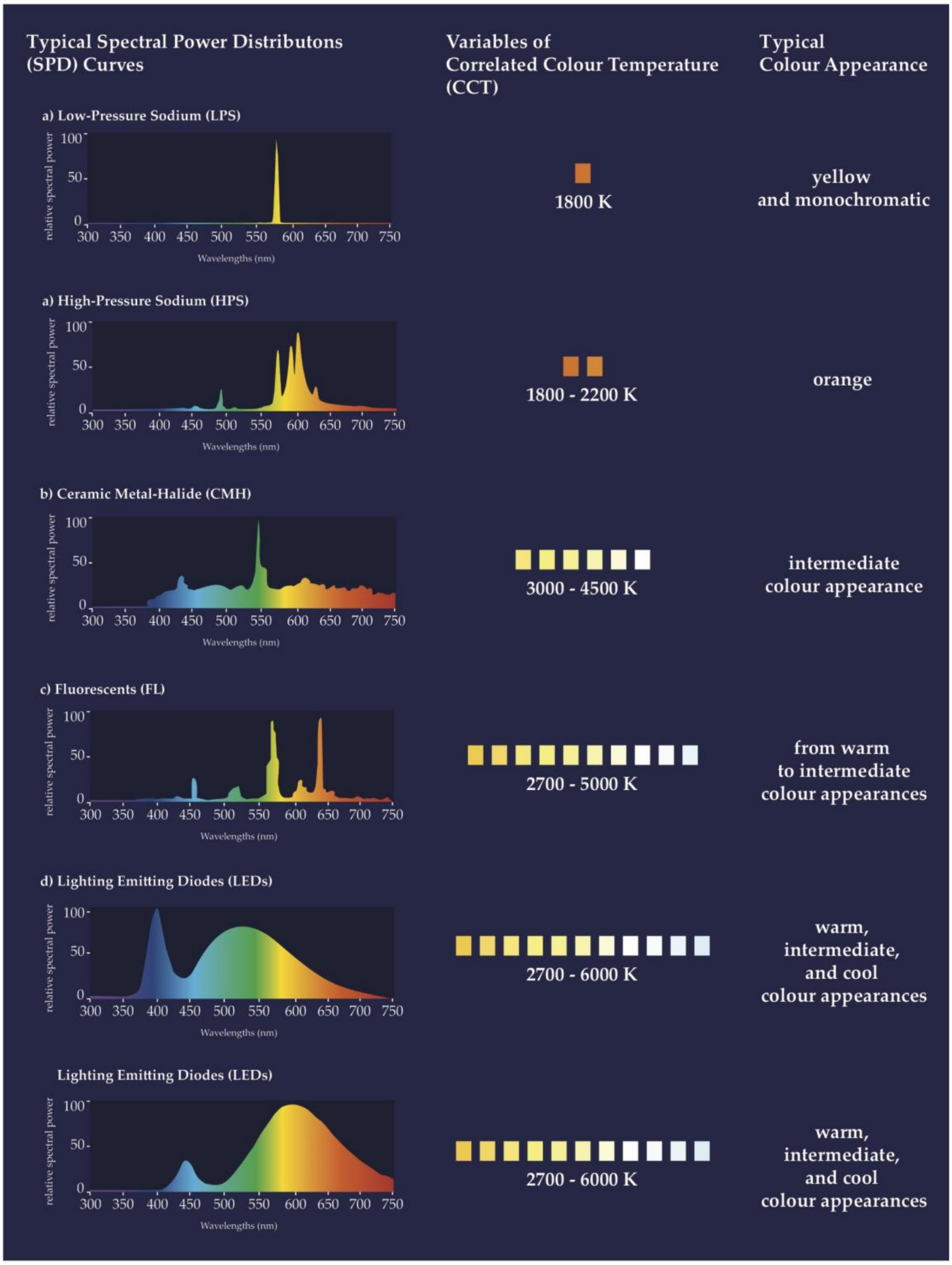


Figure A4. A schematic diagram that illustrates the colour appearance of five commonly used types of electric light sources in urban environments: (a) low-pressure sodium lamps (LPSs) (amber colour appearance) and high-pressure sodium lamps (HPSs) (orange colour appearance); (b) ceramic metal halide lamps (CMHs), with an intermediate colour appearance; (c) fluorescent lamps (FLs) with warm to an intermediate colour appearance; (d) light-emitting diodes (LEDs), which range from warm to intermediate and cool colour appearance. Source: Authors' figure.

Over time, many terms and definitions have been established that relate to artificial light at night as a pollutant. Some of them are only used by ALAN researchers and a few of the ones listed in Table A5 are included in lighting standards. This should change in the future so that ULP will be better understood and these aspects can be addressed in night-time projects of illumination.

Table A5. Overview of terminologies and definitions of artificial light at night (ALAN) as a pollutant. Source: author's elaboration based on [6,9,10,307].

Terminology	Definitions
Artificial light at night (ALAN)	A phrase used as a broad term to summarize all forms of artificial lighting (e.g., electric and gas lighting sources), most commonly used to address the unintended consequence of artificial lighting when improperly managed as a form of anthropogenic pollution, which may affect a wide range of environmental processes. ALAN can be described as direct when the source of light is considered a point light source and the parameters of the mentioned source can be modified and as indirect when it addresses the skyglow effect, as it integrates multiple light sources that are reflected from other surfaces.
Astronomical light pollution (ALP)	Mismanaged artificial light that prevents the visibility of starlight and a naturally dark sky.
Ecological light pollution (ELP)	The adverse effect or negative impact of artificial lighting on living organisms and ecosystems.
Glare	The visual and physical discomfort caused by luminance levels that exceed the threshold our eyes can manage.
Light pollution (LP)	The widespread use of artificial illumination in the night-time environment and the unwanted consequence of improperly managed and poorly controlled lighting properties of artificial light sources and luminaires. Artificial light that is polluting the natural light. Light pollution occurs in four ways, skyglow, glare, light trespass, and clutter, all of which prevent visibility of the naturally dark sky and stars and is defined as astronomical light pollution. Light pollution also has an adverse effect on aquatic and terrestrial ecosystems and living organisms and is defined as ecological light pollution.

Table A5. Overview of terminologies and definitions of artificial light at night (ALAN) as a pollutant. Source: author's elaboration based on [6,9,10,307].

Terminology	Definitions
Light trespass	Objectionable light from an artificial light source that intrudes into indoor settings and private property, illuminating spaces not meant to be illuminated. The term "light trespass" has been commonly used to describe the intrusion of light into settings where it is not meant to be, such as gardens or natural habitats.
Visual light clutter	Visual light clutter in the urban environment at night is defined as the state in which too many items lead to a degradation of the performance of a visual task at night.
Obtrusive light	The quantitative, directional, or spectral properties in light, which can cause visual discomfort and distraction and also hinder the perception of nearby environments.
Over-illumination	The presence of unnecessary artificial lighting caused by excessive brightness, too many luminaires, and the varied coloration of artificial light from different sources, which blends together and forms an unnatural gleam.
Skyglow	Glow from light radiated upward that is then scattered within the atmosphere and diverted back to the Earth. It often results in a diffuse light dome above densely populated areas and extends across landscapes. A consequence of luminaires improperly directing light upward toward the sky or from reflected light. Skyglow depends on the weather and atmospheric conditions. Skyglow used to have orange colour from LPSs and HPSs, but today, skyglow can have a cool, white appearance from LEDs.

3.11. References for Chapter 3

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Chapter 4:

Light pollution from illuminated bridges as a potential barrier for migrating fish — linking measurements with a proposal for a conceptual model

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4.1. Abstract

Illuminated bridges have become important assets to navigable aquatic systems. However, if artificial light at night (ALAN) from illuminated bridges reaches aquatic habitats, such as rivers, it can threaten the river's natural heterogeneity and alter the behavioural responses of migratory fish. Here, via a pilot study, we quantified levels of ALAN at illuminated bridges that cross a river and, propose a conceptual model to estimate its potential implications on two migrating fish species with contrasting life histories. Night-time light measurements on the river Spree in Berlin were performed continuously along a transect and in detail at seven illuminated bridges. Photometric data of the pilot study showed rapidly increased and decreased light levels at several illuminated bridges from which we derived several model illumination scenarios. These illumination scenarios and their potential effect on migrating Atlantic salmon smolts (*Salmo salar*) and European silver eel (*Anguilla anguilla*) are presented as a conceptual model, considering illuminated bridges as behavioural barriers to fish migration. ALAN's adverse effects on freshwater habitats must be better researched, understood, managed, and properly communicated to develop future sustainable lighting practices and policies that preserve riverscapes and their biodiversity.

4.2. Introduction

Bridges are permanent landmarks that can cross navigable aquatic systems such as rivers, lakes, streams, canals and sometimes even parts of the sea. When located in urban areas, these structures often integrate lighting systems that span the gamut from functional to aesthetic illumination [1]. However, illuminated bridges can cause an impact of artificial light at night (ALAN) on aquatic habitats.

ALAN directly incident on a land or water surface is direct light pollution and can reach illuminances up to 1,000 times brighter than during full-moon [2]. Indirect light pollution originates from ALAN scattered in the atmosphere as skyglow, which creates light domes far beyond its source, depending on cloud cover and atmospheric conditions [3]. Because both direct ALAN and skyglow can reach aquatic realms [2, 4], it can cause a wide range of responses in freshwater organisms, and thus present a threat to aquatic biodiversity [5]. For example, light pollution can alter diel vertical migration in zooplankton [6], disrupt drift in arthropods [7], and induce attraction [8] or avoidance behaviour in fishes [9] and has been shown to disrupt dispersal in Atlantic salmon fry (*Salmo salar*) [10].

Bridge illumination can alter behaviour in bats [11] and insects [12, 13]. For migrating fishes such as eel (*Anguilla anguilla)* and salmonids bridge illumination has been reported to interrupt their movements [14, 15, 16], and thus increasing the spatial resistance of a landscape. Consequently, migration may take more time and energy and impact the reproductive success of fish [17]. However, the mechanism by which the unnatural presence or absence of light (e.g. due to bridge structure or improperly managed of ALAN) forms a behavioural barrier for fish migratory behaviour remains unclear.

To address this knowledge gap, we therefore, (i) quantified ALAN along a transect of the river Spree (Berlin, Germany) by continuous sky radiance and camera measurements at seven illuminated bridges. We then used this as a basis to (ii) identify different types of potential light barriers at illuminated bridges and estimate the potential effect of two light barrier types on fish migration behaviour by (iii) proposing a conceptual framework based on a literature review for vulnerable life stages of two migratory fish taxa with contrasting life histories — Atlantic salmon smolts (*S. salar*) and European silver eel (*A. anguilla*).

4.3. Materials and Methods

The night-time measurements were performed during cloudy sky conditions on the 24th of February 2020 on a route of about 10 km from West to East (Fig. 1a) on the river Spree in Berlin (Germany) from an engine boat between ca. 19:30 and 21:49 local time (GMT +1), with the new moon setting at approximately 18:20 (GMT +1). At each bridge, we stopped at three points before, under, and after the bridge to measure in three directions with the camera. An all-sky image with the camera pointing towards the zenith, and two images in opposite directions with the camera imaging in the vertical plane, pointing towards the horizon, were obtained (Figure 1b).

A calibrated digital single-lens reflex camera (DSLR, Canon EOS 6D) with a wide-angle fisheye lens (Sigma EX DG f = 8 mm, F3.5) with a 180° field of view was used to perform night-time light measurements. The camera measures the radiance in three spectral channels (red, green, blue–RGB). However, we relied on the Sky Quality Camera software (SQC, Euromix, Ljubljana, Slovenia) that utilises the green channel for a (near) photometric calibration. The software provides luminance, correlated colour temperature (CCT) maps (Fig. 1b), and calculated illuminance. CCT is extracted by the software by transforming the three spectral channels (RGB) to CIE XYZ colour space. For details, see a recent review paper [18]. The camera was placed on a tripod to add stability as measurements were performed from a boat. The camera method is relatively precise, but the pointing error from the orientation and the movement and rocking of the boat induces an error of about 10% [19]. ISO settings were fixed at 3200, and the shutter speed varied between 0.3 seconds at the darkest location and 1/13 of a second at the brightest location.

Additionally, the sky radiance at zenith was monitored continuously during the transect with a mobile night-sky radiometer equipped with a data logger (Sky Quality Meter, SQM-LU-DL, Unihedron, Ontario, Canada) in magnitude per square arc second, $mag_{SQM}/arcsec^2$, which is a negative logarithmic unit, where low values represent high radiance, and high values represent low radiance. Furthermore, a difference of 2.5 is a factor of 10 in the linear scale, and a 5 magnitude difference is a factor of 100. A rough approximation of luminance can be done using $L_v \approx 10.8 \cdot 10^4 \cdot 10^{(-0.4 \cdot mag_{SQM})}$, but it must be treated cautiously.

A clear night sky reference is about 21.6 $mag_{SQM}/arcsec^2$ (approximately 0.25 mcd/m^2) [20]. The primary GPS device, intended to record boat position, failed. Thus, positions had to be estimated with a second camera (Canon EOS 6D with a 50 mm lens) equipped with a GPS on the boat to record images of the illuminated locations around the measurement sites.

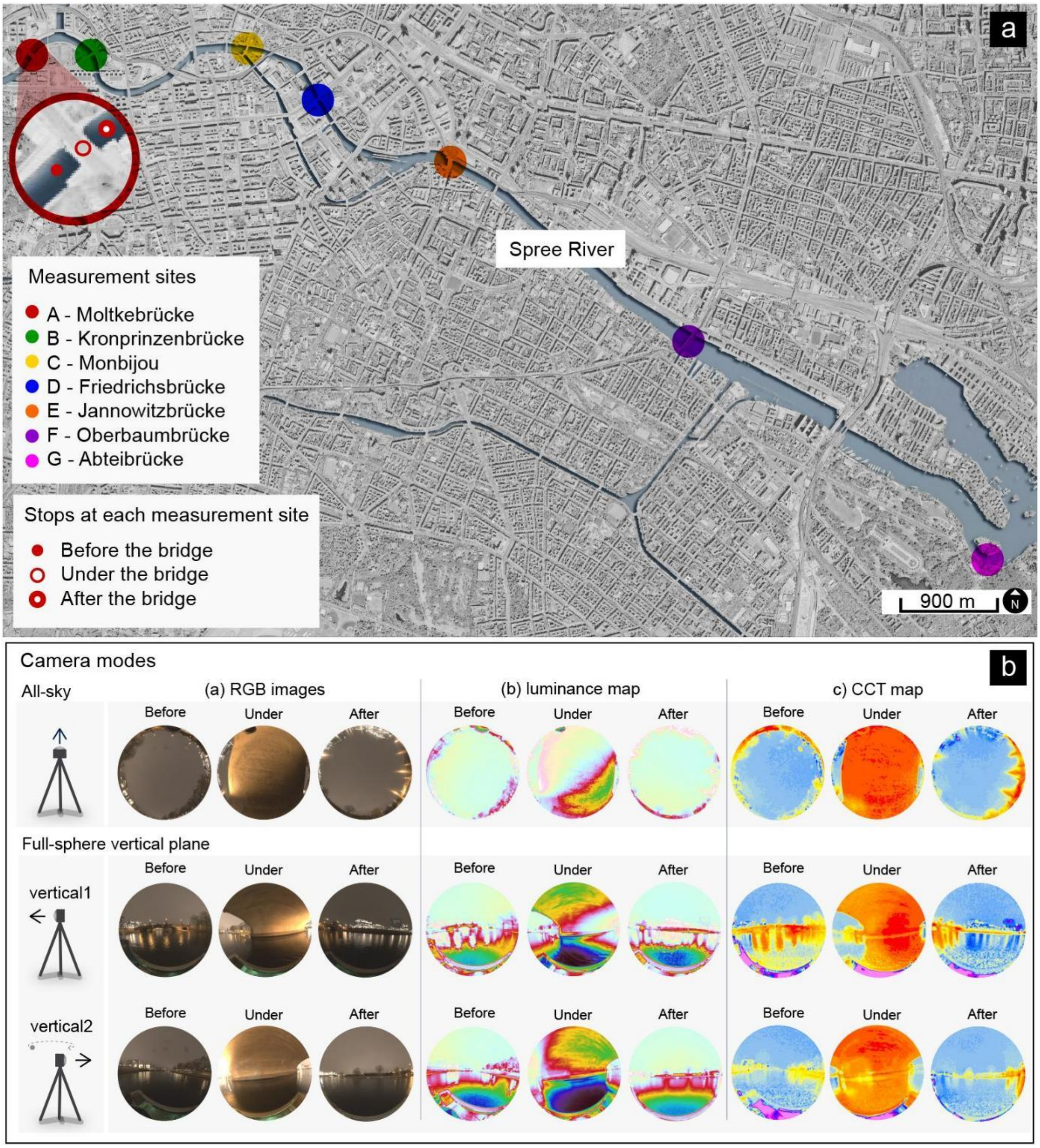

Figure 1. Overview of measurement sites and camera planes for measurements. (A) Map of the measurement sites, seven illuminated bridges along the river Spree in Berlin, Germany. At each bridge, measurements were performed at stops before, under and after the bridge. (B) At each stop, one all-sky and two vertical plane camera measurements were performed, from which the luminance map and CCT map were calculated. Example measurements from site A (Moltkebrücke) are shown in the full data set in the appendix.

4.4. Results

From the luminance data of the all-sky images, horizontal illuminance and the two opposing vertical plane images of total spherical scalar illuminance were calculated. The full imaging dataset (see Appendix A), and the illuminance results are summarised in Table 1 and 2. Fig. 2a shows the horizontal illuminance, and Fig. 2b the scalar illuminance for each site, showing a gradual decrease along the transect for horizontal illuminance and slightly more heterogeneity but the same trend for scalar illuminance. At most bridges, the lowest values in illuminance were measured under the bridge, except for measurement site A–Moltkebrücke, the only bridge lit underneath. Thus, at Moltkebrücke, the highest horizontal illuminance (ca. 1100 mlx) was measured under the bridge compared to the other six measurement sites (170 mlx to 9 mlx). The lowest illuminance under the bridge, of only 9 ± 1 mlx, was measured at site E (Jannowitzbrücke), which is ca. 120 times darker than site A (Moltkebrücke). Furthermore, the maximum illuminance ratio (R_{max}) was determined by dividing illuminance under the bridge by the highest illuminance obtained before or after the bridge to illustrate the largest step in light level change from open waters to the bridge or vice versa, shown in Table 1. The R_{max} values ranged from 0.88, indicating brighter conditions under the bridge (A – Moltkebrücke) to 105, indicating darker conditions under the bridge (E – Jannowitzbrücke), showing the strong heterogeneity among these bridges.

The scalar illuminance was always lowest under the bridge when comparing all site measurements (positive R_{max}). The R_{max} values ranged between factors of 1.4 (G – Abteibrücke) to 12.8 (E – Jannowitzbrücke), giving a smaller range than for horizontal illuminance.

Table 1. R_{max} of horizontal and scalar illuminance obtained from the multispectral imaging data at three stops on Measurement sites A–G. Rmax is determined by dividing illuminance under the bridge by the highest illuminance obtained before or after the bridge. It represents the maximum illuminance ratio and the largest step in light level change from open waters to under the bridge or vice versa.

Horizontal Illuminance E_v, (*all-sky*) (mlux)							
Measurement sites	**A**	**B**	**C**	**D**	**E**	**F**	**G**
$\mathbf{R_{max}}$	0.88	5.9	11.4	12.5	105	21.3	1.3
Scalar illuminance $E_{v,\,scal}$ (*vertical 1 and vertical 2*) (mlux)							
Measurement sites	**A**	**B**	**C**	**D**	**E**	**F**	**G**
$\mathbf{R_{max}}$	2.1	2.8	3.9	4.7	12.8	8.2	1.4

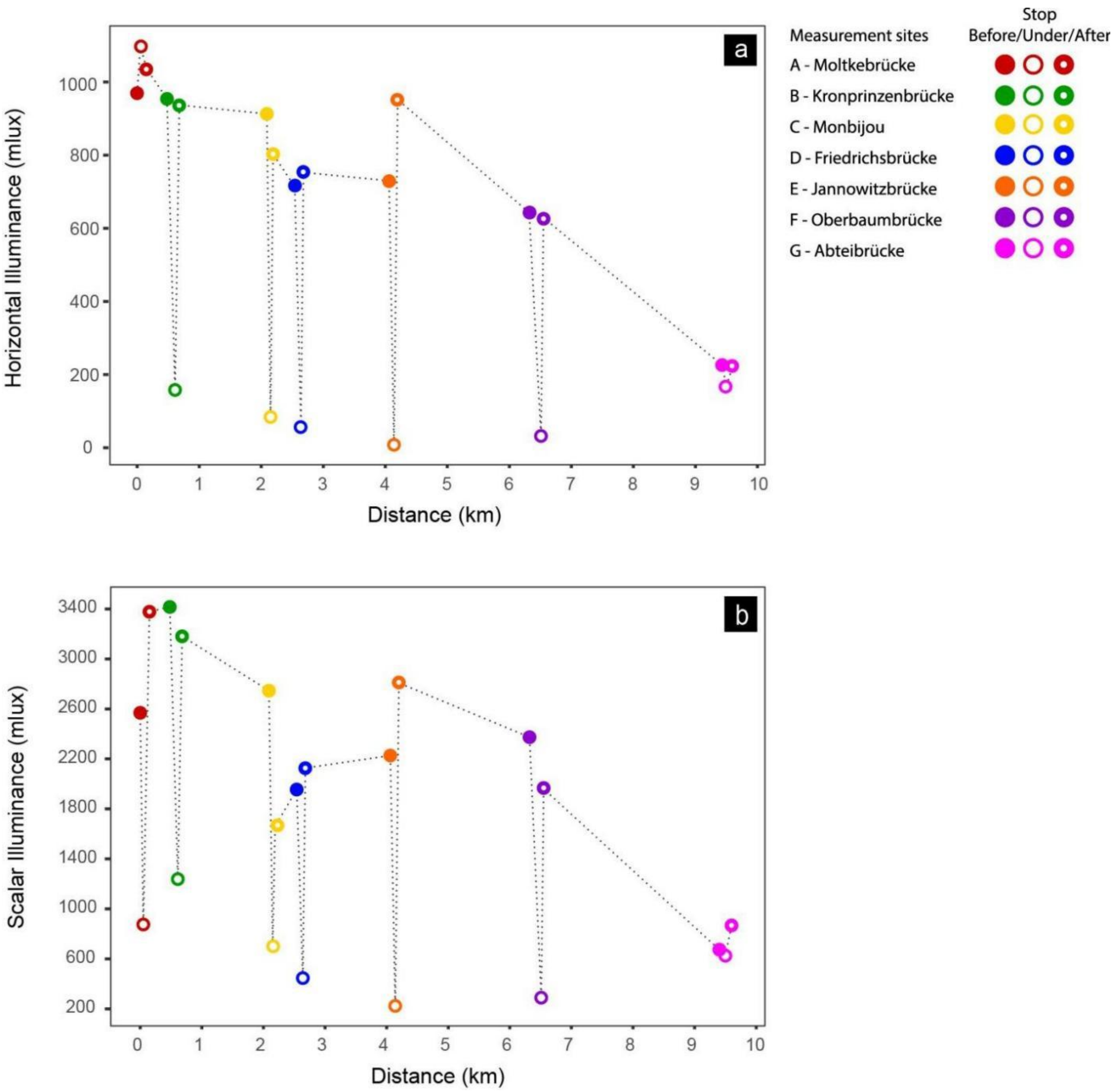

Figure 2. Photometric data obtained from the A–G measurement sites with all-sky camera mode at three different stops: before, under, and after the bridge (see Fig. 1b). (A) Horizontal illuminance as a function of distance. (B) Scalar illuminance as a function of distance.

The continuous sky radiance measurements obtained along the transect with the SQM are shown in Fig. 3. The bridges can be identified as rapid changes in sky radiance (or radiance above the boat as direct or straylight will also be picked up by the sensor, and creates extraordinarily high readings). Skyglow over the transect ranged from approximately 14 $mag_{SQM}/arcsec^2$ in the urban zone (ca. 270 mcd/m², about 1000 times brighter than a reference clear sky) to 17 $mag_{SQM}/arcsec^2$ (ca. 17 mcd/m²) towards the peri-urban area.

Direct ALAN was present at the bridge – Mühlendammbrücke (site 12 in Fig. 3) and at the locks – Mühlendammschleuse (site 13, in Fig. 3), which creates radiance values of approximately 10 - 12 $mag_{SQM}/arcsec^2$ that cannot be used quantitatively because it is unclear what is the contribution of direct ALAN, straylight or real sky radiance. Under most bridges, a reduction in radiance occurred. However, radiance was increased at measurement site A – Moltkebrücke (site 1 in Fig. 3 and Appendix A) and several other lit bridges (sites 3, 6, 19 in Fig. 3). Radiances at these lit bridges reached 12 $mag_{SQM}/arcsec^2$. At one bridge, Ebertbrücke (site 6 in Fig. 3), only increased radiance was observed, indicating that the bridge was lit underneath. Interestingly, a reduction of radiance was observed at the three other lit bridges. At Moltkebrücke (site 1 in Fig. 3), the bridge was lit underneath, and the bridge illumination did not cover the whole arch and left a dark section. At the other two lit bridges, Marschallbrücke (site 6 in Fig. 3) and Abteibrücke (site 19 in Fig. 3), an increase of radiance was observed before and after the bridge most likely caused by spill light from road lighting intended to illuminate the bridge above.

Sky radiance variations of two measurement sites with contrasting sky radiance values occurring when approaching the bridge are shown in Fig. A8 and A9 (see Appendix A). Measurement site A – Moltkebrücke exhibits uninterrupted skyglow along the river transect, which becomes brighter as the boat passes under the bridge, subsequently darkens, and then rather rapidly returns to the skyglow radiance values after crossing the bridge (see Fig. A8). Luminance maps of Moltkebrücke shown in Fig. A1 (see Appendix A) confirm that one half of the underpath is illuminated, while the other half is not. Meanwhile, measurement site E – Jannowitzbrücke shows a consistent skyglow over the river transect, which is reduced in radiance as the boat reaches the bridge. The attenuation of skyglow becomes pronounced under the bridge as no luminaires were observed at the underpath and due to the bridge's width, confirmed with the luminance maps shown in Fig. A5 (see Appendix A). Subsequently, after crossing the bridge, the darker section under the bridge rapidly returns to skyglow radiance values. The exact function how rapidly the level changes could not be obtained and would require a higher temporal resolution (and/or finer spatial resolution, respectively) of measurement.

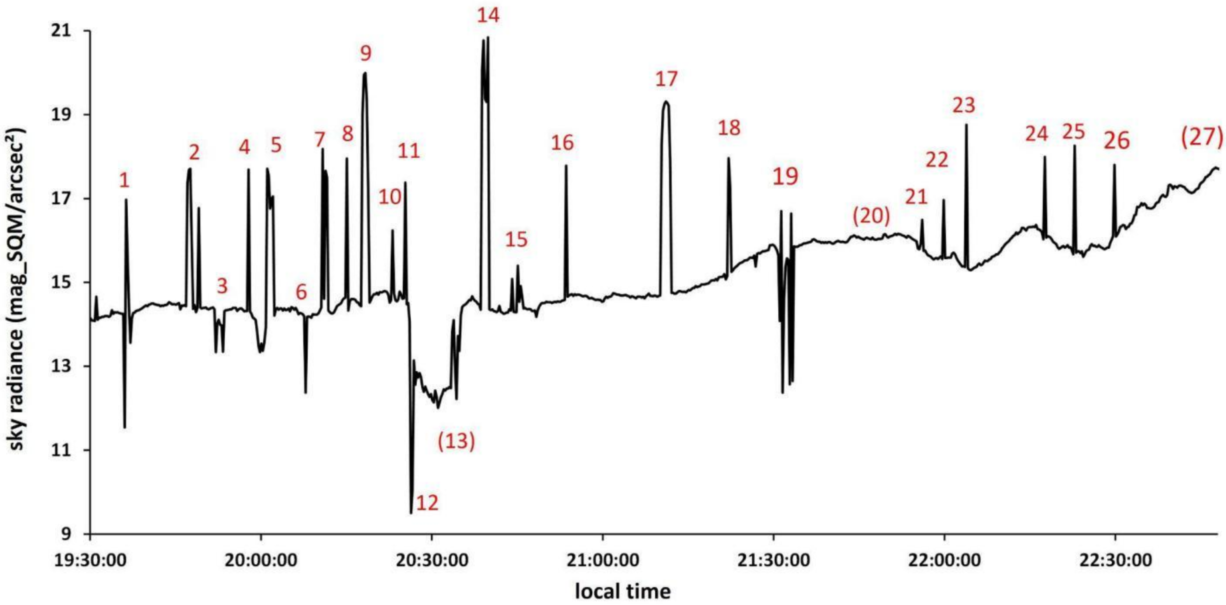

Figure 3. Continuous sky radiance SQM measurements while the boat moved along the transect. Note the negative logarithmic scale (see Methods). Bridges are perceivable as rapid changes in radiance and indicated with numbers (numbers in brackets indicate ALAN-specific sites that are no bridges): 1- Moltkebrücke, 2 - Kronprinzenbrücke, 3 - Marschallbrücke, 4 - Bahnhof Friedrichstraße, 5 - Weidendammer Brücke, 6 - Ebertbrücke, 7 - Monbijoubrücke, 8 - S-Bahn Brücke Hackescher Markt, 9 - Friedrichsbrücke, 10 - Karl-Liebknecht Brücke, 11 -Rathausbrücke, 12 - Mühlendammbrücke, (13) - Locks Mühlendammschleuse (direct ALAN), 14 - Jannowitzbrücke, 15 - Michaelbrücke, 16 - Schillingbrücke, 17 - Oberbaumbrücke, 18 - Elsenbrücke, 19 - Abteibrücke, (20) - Plänterwald (no ALAN), 21 - Minna-Todenhagen-Brücke, 22 - Alte Stubenrauchbrücke, 23 - Treskowbrücke, 24 - Wilhelm-Spindler-Brücke, 25 - Dammbrücke, 26 - Salvador-Allende-Brücke, (27) - Müggelsee (no ALAN).

4.5. Conceptual framework of light barriers

This section proposes a conceptual framework for illuminated bridges as barriers potentially impacting fish migration. From the measurement data, several bridge illumination types depend on the surrounding skyglow and the illumination under the bridge. As no comprehensive data on light colour was obtained, the conceptual framework focuses only on the changes detected by the SQM.

In this context, a light barrier is described as an encountered dark-to-bright (a positive step function) or bright-to-dark section (a negative step function) when passing under a bridge. This conceptual framework considers only one parameter of light — its brightness (light levels). The conceptual framework highlights an example of light step functions (Fig. 4) and light step functions resulting from each bridge illumination type (Fig. 5). These are linked to potential behavioural responses of migrating fish (Fig. 7).

4.5.1. Light step functions and bridge illumination types

Figure 4 (a - c) shows imaging measurement data (luminance maps) of Jannowitzbrücke. The bridge is unlit underneath, and the surroundings show strong direct and indirect ALAN. Thus, the illuminance under the bridge (Fig. 4b) is much lower than before and after the bridge (Fig. 4 a,c; see also Table 1). Therefore, illuminance decreases when moving from the open waters towards the underpath of the bridge, representing a negative light step function; when moving from the underpath of the bridge towards open waters, illuminance increases, which represents a positive light step function (Fig. 4d).

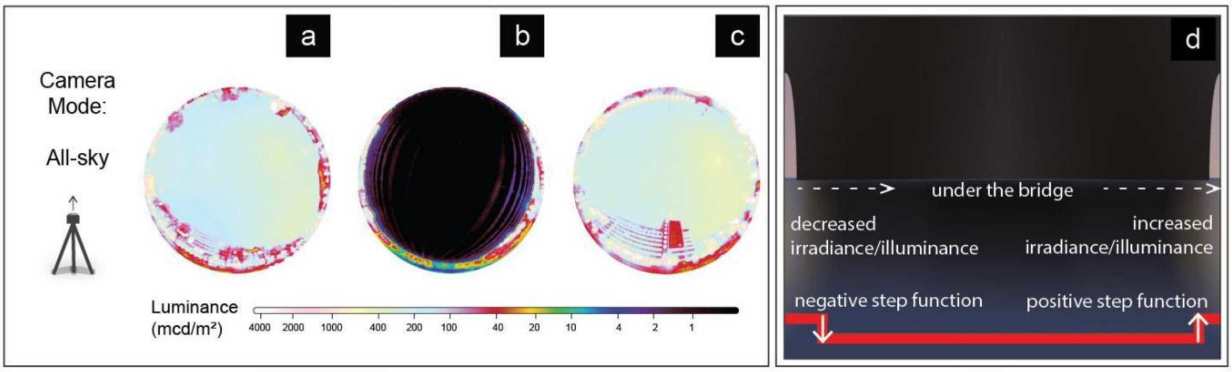

Figure 4. Luminance maps and cross-section of measurement site E–Jannowitzbrücke. (a-c) Luminance maps for stops (a) before, (b) under, and (c) after the bridge at measurement site E–Jannowitzbrücke. The all-sky luminance maps of Jannowitzbrücke exhibit higher luminance in open waters (a,c) when compared to luminance levels under the bridge (b). (d) Cross-section of the bridge arch structure that exhibits changing light step functions (when moving from left to right) when crossing from open waters towards the underpath of the bridge and again to open waters. A decrease in irradiance or illuminance indicates a negative step function, and an increase in irradiance or illuminance indicates a positive step function.

R_{max} represents the change in illuminance of the step function (see Table 2), with values below 1 indicating a negative step function and above 1 indicating a positive step function when moving from the brightest location outside the bridge towards underneath the bridge.

Four bridge illumination types were derived from camera and SQM measurements and previous work by Jechow & Hölker (2019) [2]. These bridge illumination types were simplified to consider only illumination above (roadway illumination) and underneath the bridge (underpath illumination).

Depending on the location of the bridge (e.g. surroundings and the light pollution context), the illuminated bridge will form a potential light barrier composed of multiple negative or positive step functions. Fig. 5 illustrates a cross-section and a side view of eight illuminated bridge scenarios. Four simplified bridge illumination types are set in rural areas with no skyglow (Fig. 5 a - d). The other four simplified bridge illumination types are set in urban areas with skyglow (Fig. 5 e - h). Real-world bridge illumination types and scenarios will depend on the geometry of the bridge and light levels, which can be very heterogeneous, consisting of skyglow, light spill from roadway illumination, architectural or functional lighting underneath and towards the bridge vertical surfaces, and direct ALAN sources located proximate to the water that often include advertisements, windows, lit building surfaces, light from adjacent roads or parks, etc. (Pérez Vega et al., subm).

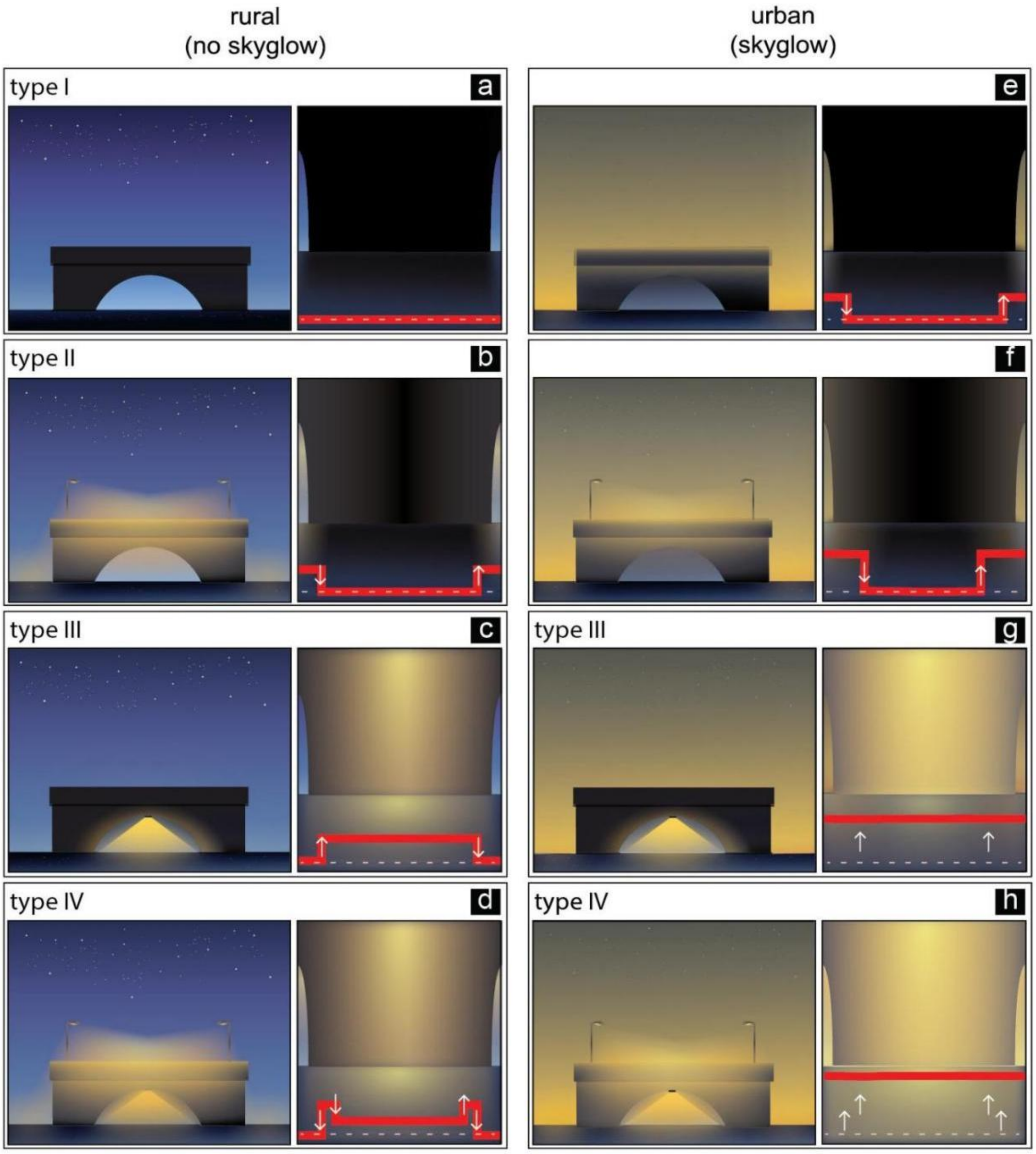

Figure 5. Side views and cross-sections of eight bridge illumination scenarios spanning rural and urban rivers. The side views show the perspective of the bridge as seen from a boat when approaching an arch. The cross-section shows the underpath of the bridge. The dashed lines represent the expected natural light levels typical in a river with a bridge. The red lines represent the varied levels of irradiance or illuminance of different illuminated bridge scenarios, which form multiple potential light barriers originating from multiple positive and negative light step functions, except for bridge illumination types (a) and (g). The white arrows highlight steps in illuminance/irradiance. (a,e) Type I has an unlit roadway and underpath. (b,f) Type II has an illuminated roadway and unlit underpath. (c,g) Type III has an illuminated underpath with no roadway illumination. (d,h) Type IV has roadway and underpath illumination.

4.5.2. ALAN and migrating fish

It is important to interpret the bridge illumination types with their light step functions as potential barriers for migrating organisms.

ALAN can aggregate and slow down migratory fish species. It has been previously reported that some salmonids and eels occasionally interrupt their migration at lit structures [14, 15, 16, 21, 22]. ALAN, particularly at bridges, may thus increase the spatial resistance of a landscape. Consequently, migration can take more time and energy, which could threaten natural synchronous reproduction and reproductive success [17]. However, it remains unclear whether bridge illumination is a behavioural barrier that disrupts fish migration. Furthermore, a fish's response to a positive or negative light step function is likely to depend on the fish’s life history. In the scenarios mentioned above, positive and negative light step functions might alter the information a migrating fish requires to accomplish their migration.

Migration is often defined as an adaptive and seasonal long-distance movement in a species' life cycle. It is also derived from the spatial and temporal distribution of resources and environmental conditions to breed, forage or find favourable climatic conditions [23, 24, 25]. Fishes like salmon smolts and eels migrate through various connected aquatic systems [26, 27]. However, eels and salmon have developed distinct migration strategies, which have resulted in very different combinations of behavioural and reproductive traits.

For example, eels are anadromous, i.e. they spend their adult life in freshwater and return to the sea to reproduce. They often migrate during fall, winter, rain or flooding events that might increase river flow and at night, when light levels are often low [28, 29, 30]. During migration, eels tend to swim in deeper parts of the water column and have been observed to avoid illuminated waters at night [28, 30]. Salmon, on the other hand, are catadromous, migrating from the sea to freshwaters during the day or at night in spring and autumn. Their nocturnal migration usually is closer to the water surface, and active behaviour, including positive phototaxis, has been observed near illuminated waters [31, 32].

Fig 6. provides an overview of demonstrated behavioural responses in eels and salmon upon exposure to ALAN and natural light, respectively. During their migration, eels and salmon are often exposed to unique optical aquatic environments modulated by turbidity, the presence of dissolved organic matter and further absorbing substances, and illuminated waters at night [2, 5, 9, 33].

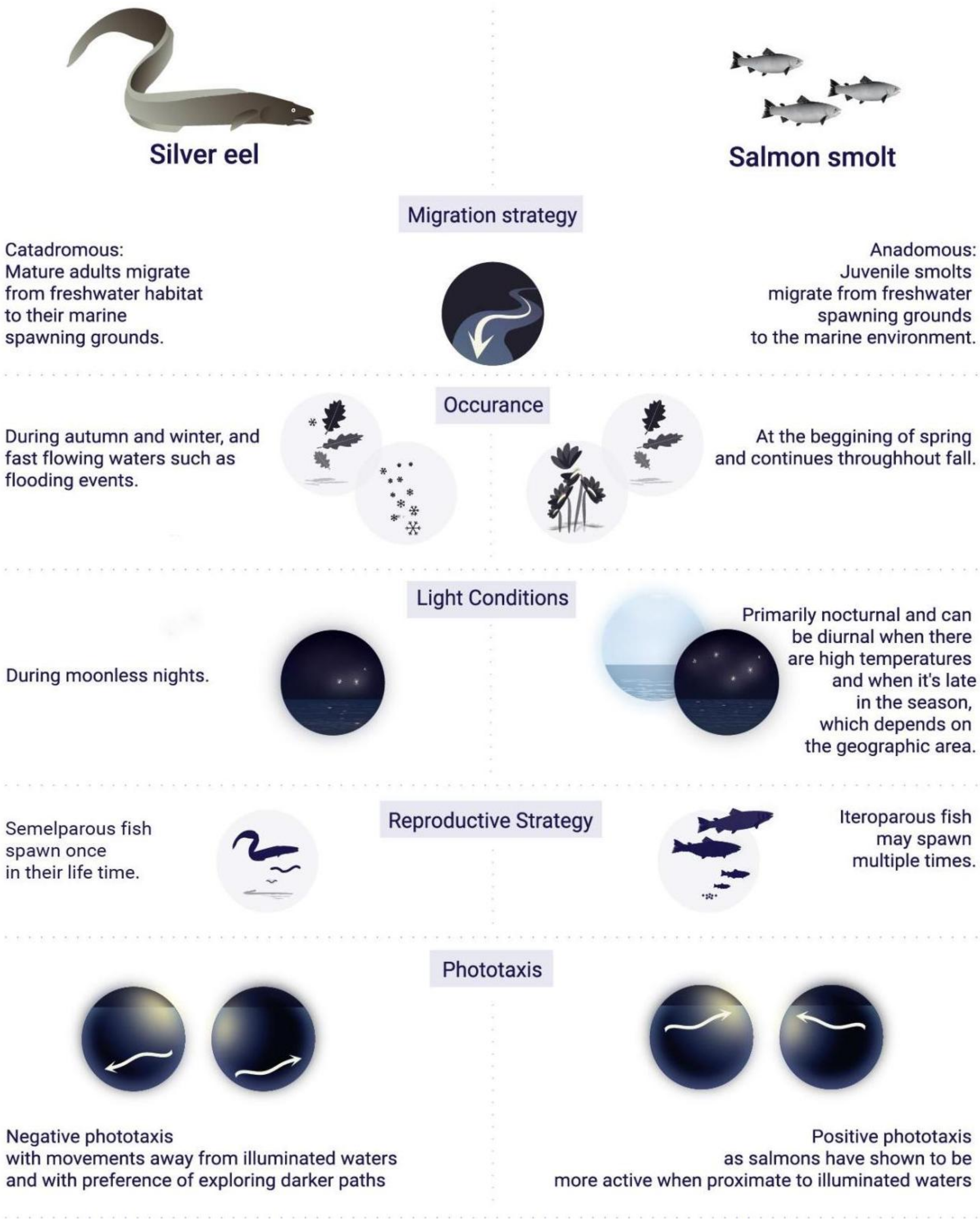

Figure 6. A summary on contrasting migration behaviours of silver European eel and Atlantic salmon smolt.

4.5.3. Bridge illumination as a behavioural barrier

The potential implications of light barriers on the migration strategies of silver eels and salmon smolts can include a pitfall effect — where fish are retained in a small area, resulting from their responses to light stimuli. However, the behavioural mechanisms driving this potential effect vary between salmon smolts and silver eels.

Naturally dark environments are ideal for successful eel migration (Fig. 7a) due to their preference for low light levels [34]. Any scenario in which light is introduced into the water column can potentially induce avoidance behaviour in eels (Fig. 7 b,d) [9, 15, 29, 35]. Furthermore, dark areas bounded by light may induce a pitfall effect (Fig. 7c), behaviourally constraining eels to the dark underpass of a bridge for some time. Lastly, as ALAN can attenuate rapidly with water depth, illuminated bridges may push migrating eels to the bottom of the water column as they pass (Fig. 7d).

Contrastingly, Atlantic salmon smolts can exhibit positive phototaxis, where ALAN exposure causes attraction and aggregation in illuminated areas [36]. In the case of the illumination scenarios with underlit bridges (Fig. 7 f,h), attraction to ALAN may result in a pitfall effect, causing smolts to aggregate directly under the bridge. Lastly, illumination scenarios with high levels of urban skyglow and unlit dark underpass may also present a barrier to migration (Fig. 7g). Ono & Simenstad (2014) observed that daytime shadows cast by overwater structures obstructed the outmigration movements of juvenile Salmon (*Oncorhynchus* spp.) [37].

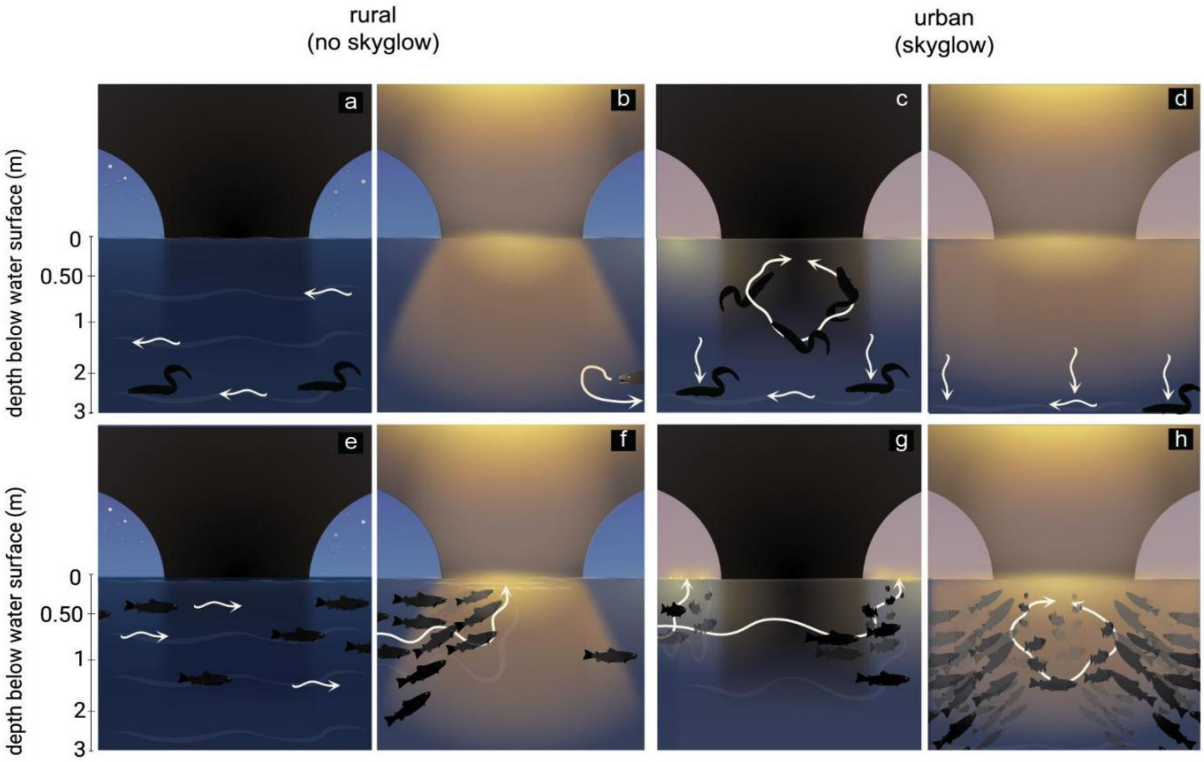

Figure 7. An overview of the expected behavioural responses to bridge illumination in two selected species, silver European eel and Atlantic salmon smolt. The two selected species represent vastly different life histories and migration behaviours. (a - d) During migration, eels have been shown to remain at the far end of the water column and have been observed to avoid illuminated waters at night [14,15 35]. (a) During their migration, Silver European eels can eventually reach their marine spawning grounds when navigating rivers with naturally low light levels at night. However, (b - d) if unnatural contrasting light scenarios at illuminated bridges are encountered, their migratory behaviour could be delayed, which can (b) change their migratory direction, (b) force eels to remain under dark paths (e.g. under unlit bridges), (d) orient eels closer to the bottom of the water column. (e - h) Meanwhile, Atlantic salmon smolts have been shown to migrate at night closer to the water surface with active behaviours when proximate to illuminated waters [31, 32, 38]. (e) They can eventually reach their freshwater spawning grounds when navigating waters that remain under naturally low light levels at night. However, if Atlantic salmon smolts encounter unnatural contrasting light scenarios at illuminated bridges, their migration could be altered or delayed due to their potential attraction to ALAN. This behaviour can potentially drift them away from their migratory paths into (f) illuminated corners under the bridge, (g) urban light polluted areas in the vicinity, or can possibly (h) trap and aggregate Atlantic salmon smolts in illuminated waters.

4.6. Discussion

River systems are often modified by natural and anthropogenic drivers that can lead to fragmentation or reduction of river heterogeneity [39]. Given the benefit illuminated bridges contribute to night-time route connectivity, their ecological impact is rarely questioned. To better evaluate a possible anthropogenic impact on a river ecosystem, it is always interesting to take a look at the pristine state of the Spree river before human settlement. Here, the aquatic communities of the Spree river were characterized by riverbanks with adjacent floodplains and densely forested areas [40]. Today's river landscape, however, bears little resemblance to its original state and often gives the impression of an urbanized waterway modulated by multiple stressors that challenges aquatic communities. The results of this study demonstrated that the river Spree in Berlin is heavily exposed to one of these urban stressors – ALAN, which is characterized by sky radiance variations (skyglow), ALAN gradients, and steep light contrasts. Illuminated bridges can thus cause novel types of nocturnal light by generating excessive light levels, limiting natural darkness and thus producing light contrasting ratios at rivers unprecedented in evolutionary history.

The continuous sky radiance and single-point illuminance measurements showed that

the proximity to urban elements (e.g. bridge structures), the composition of the bridges, and their integrated lighting systems can shift the light environment in a river. Skyglow (i.e. sky radiance) on the Spree was high due to cloudy skies (see also Jechow et al., 2020 [41]), with the highest values measured in the (urban) centre and a gradual decrease of skyglow (compared to the rapid changes in radiance observed at the bridges, the sharp peaks in Fig. 3) towards the less densely populated eastern part of Berlin was observed. The decrease in sky radiance was not following a strict inverse power law, but rather also showed local increase when being close to a sub-urban centre (i.e. Berlin Schöneweide near Treskowbrücke – 23 in Fig. 3 or Berlin-Köpenick near Dammbrücke – 25 in Fig. 3). This showed that the level of urbanization is not only linked to direct emission but also the skyglow background [2]. The sky radiance values align with studies performed in Berlin in a terrestrial context [3], where about the same elevated sky radiance and illuminance levels for cloudy skies were found. Furthermore, the change of sky radiance with distance from the urban centre were shown to differ inside and outside the city limits, particularly for cloudy skies [3]. In the same study, clear sky measurements were performed at the same locations showing much lower but still elevated values. Repeating our measurements under clear conditions would have most likely resulted in a different skyglow background. However, COVID lockdown in Germany had closed river locks [41] and banned us from repeating this transect in time.

In general, measurements in freshwater systems are sparse [2]; the only longer-term but static sky radiance measurements were done on a lake [42]. Analyses of nocturnal aerial photographs of Berlin show rivers and canals approximately six times brighter than lakes due to their large ratio of shore length to the water surface [43] and a multi-point study at Berlin waters using a precise underwater lux meter showed that illuminance ranged between 0.008 lx and 1.4 lx at 0.5 m below the surface [44].

It is difficult to disentangle the fractions of skyglow and direct ALAN from our measurements. However, in urban areas, there is always a contribution to the use of multispectral (RGB) all-sky images with a digital camera. This method provides spatially resolved radiance over the complete hemisphere in three spectral bands in one image by a single measurement. It involves the light field information from from all directions (horizontal illuminance and two opposing vertical plane images of total spherical scalar illuminance). With the use of this method, the results demonstrated lower values under most bridges, except for measurement site A–Moltkebrücke, and that the Spree river was prone to divergent light scenarios. Nevertheless, our data showed that a finer spatial resolution of direct ALAN measurements would be beneficial.

As discussed above, our measurements fit previous data obtained in Berlin central area under cloudy conditions [3]. Given the varying sky radiance (skyglow), ALAN gradients, and steep light contrasts, it is important to relate the potential effects of different lighting situations on migrating fish.. Thus, a conceptual framework is proposed to outline the multiple behavioural mechanisms that may delay fish migration in rivers with bridge lighting and to describe the impact of illuminated bridges as behavioural barriers for migratory aquatic species.

Although migratory delay caused by a single bridge may appear minor, urban migratory paths often consist of multiple illuminated bridges of varying types, which can potentially cause a large cumulative delay in migration. Understanding how variance in bridge illumination types and behavioural responses affects these delays is critical to estimate these cumulative impacts and potential fitness consequences. While little is known about the effect of migration timing on eel spawning, the river phase of this migration is discontinuous — involving expanded stopovers [45] and a few periods of locomotion, generally initiated by high discharge and low light conditions [34]. In the absence of favourable migration conditions, eels have been reported to postpone migration to the following year [46] and silvering — the physiological and morphological changes associated with sexual maturation — is assumed to reverse [47]. For migration routes with multiple illuminated bridges, cumulative migration interruptions resulting from ALAN exposure may be sufficient to trigger migratory postponement. Lastly, as eels tend to migrate when turbidity is high and under low light levels [34], and being negative phototactic during nocturnal migration [35], then the propagation of ALAN into the lower part of the water column may cause eels to orient even closer to the bottom or to become inactive. Therefore, illumination on bridges needs to be better shielded and reduced to low light levels, in order to mitigate the impact on eels.

In contrast, Atlantic salmon smolts may exhibit positive phototaxis when exposed to ALAN. This effect of smolt attraction to ALAN can be considered multi-faceted. First, the survival of smolts upon arrival in the sea is proposed to be dependent on the timing of arrival during the smolt window [48] — a short period where environmental conditions facilitate the rapid growth critical for their survival to the post-smolt stage. A delayed arrival in the sea may result from attraction to ALAN, negatively impacting the smolt's fitness. Secondly, migrating smolts are highly sensitive to predation. Predatory fish have been shown to aggregate towards ALAN, corresponding with higher predation rates of migrating salmonid smolts [49]. The pitfall effect illuminated bridges can have on smolts may prolong their exposure to high-predation areas during migration, reducing survival. Thus, also for smolts, bridge illumination would need to be better shielded and reduced to low light levels to mitigate impacts.

Lastly, all teleost species accomplish visual adaptation between light and dark conditions with retinomotor movements — movements of the rod, cone, and epithelial pigment cells within the retina [50]. While the time required for adaptation varies by species, life stage, and light levels, juvenile Atlantic salmon have been shown to require more than 25 minutes to adapt between light to dark conditions [38]. During this adaptation period, the fish may be impaired from may be unable to perceive crucial information about their environment, such as the presence of predators, and consequently, the ability to execute visually-mediated predator avoidance responses. Hence, adaptation to bridge illumination conditions may reduce fitness due to an increased and prolonged predation risk.

To date, the ecological status of a river such as the Spree accounts for the impact induced by human use associated with dams, locks, water mills, fish weirs, navigation, industrial pollutants, and human recreation [51]. The impact of illuminated bridges over rivers still remains understudied. Studies have shown that riverine wildlife, including insects and bats, can be affected by bridge illumination as their flying paths are interrupted by bridge ALAN [11, 12, 13]. Therefore, more studies are required to determine bridge ALAN as potential light barrier likely to alter the passage of species on riverine systems. Bridge architectural forms such as the beams, the truss, the arch, the suspension, the cantilever, and the cable stay, as well as reflectance of materials (e.g. stainless steel, white paint) could play an important role in the complexity of light distribution over the river. Therefore, illuminated bridges, or structures that cross any form of a natural waterbody, need to be studied in detail to identify light conditions that can potentially have negative impacts on migratory species in order to deliver recommendations that avoid ecological hazards. Future ALAN research should focus on the implications of ALAN on freshwater systems as rivers are an integral part of the urban realm in which light barriers can adversely affect freshwater habitats and biodiversity hotspots. More ALAN research could aid prevent the loss of nocturnal integrity in freshwater systems [5].

The conceptual framework presented here, proposes a simplified model of how potential illuminated bridges could impact the heterogeneity of a river by night, considering that actual bridges might have much more complex structures with complex sequences of step functions. Also, the model highlights the variability in bridge illumination scenarios, which can serve as a guide to shape future experimental designs examining the effects of bridge illumination on freshwater systems.

Even though there are only few studies that tested the effects of ALAN on migrating fish, still more studies on the impact of ALAN on freshwater is needed to involve decision makers and to create mitigation strategies that protect riverscapes and their biodiversity in an integrated manner with a broad appreciation of the night-time [5].

4.7. Limitations of the study

Due to the character of a pilot study, there are some limitations to the presented work. Here, we outline some issues that we would recommend to improve in future studies.

Although we used a tripod and short exposure time following our experience from previous work [19], we recommend the use of a gimbal camera stabilizer to compensate the movement of a moving and rocking boat in future studies.

Furthermore, the number of stops per measurement site was limited by the scheduled closure of the locks during our study. However, with more time at hand we would recommend more stops per bridge, underneath the bridge itself and in open waters nearby the bridge, and ideally also multiple passes. In total, a higher spatial resolution would be desirable and ideally a two-dimensional mapping of the irradiance and radiance distribution. However, this goes with the compromise of the number of bridges that can be quantified per night and the distance that can be covered. For an individual bridge, a high spatial resolution should be the target, which could potentially provide a finer resolution on the exact function of the decrease or increase of light levels.

For future studies it is recommended to also use a wider set of measurement tools, like a continuously measuring illuminance meter, a spectroradiometer to obtain spectral power distribution and potentially multiple cameras to obtain vertical and horizontal plane data in parallel, ideally also obtaining data continuously and potentially under the water surface or from water samplings (see [2] for proposed measuring platforms), Additionally, one could obtain more information on the bridge geometry, as well as other characteristics of the bridge illumination, including the type of light source, the distance between luminaires, etc.

4.8. Future ALAN research in freshwater ecosystems

Future ALAN research in freshwater ecosystems should involve a wide array of measurements including cameras, sky radiance meters, lux meters, spectrometers and the use of drones above the water surface to develop a finer spatial resolution of the illuminated areas that also consider light planning approaches (the distance between luminaires, the distance between the river bank and the luminaire, if luminaires are shielded, etc). Also, tools that could measure light even underwater. Such data can be linked with remote sensing data from aerial measurements or satellites [2].

To effectively tackle the existing knowledge gaps within the different disciplines of ALAN, we propose the link between measurement results and a conceptual model. This approach aims to address the missing ecological knowledge on the potential effect of light changes that might alter the behaviour of migratory fish, as it is crucial information for policy-makers and the lighting industry, to understand issues and develop potential solutions to minimize light pollution in a comprehensive manner.

Adhering to the use of illumination sustainably, exclusively in the passage area, remains still an uncommon approach, nonetheless a needed one [5]. Still, typically applied lighting systems could be better controlled to avoid light barriers in aquatic habitats by night. However, the current conceptual framework could be a communication tool to sensitize citizens and decision makers on how illuminated bridges affect rivers and aquatic biodiversity.

4.9. Conclusion

Our measurements show that bridges can induce varied and different types of unnatural illumination scenarios that may deteriorate or fragment aquatic habitats after dusk. Additionally, the conceptual model presented here demonstrates how typical bridge illumination conditions may induce different behavioural responses in migrating fish and the possible fitness implications for these migratory species.

The results of this study highlight the need for further studies on the impacts of ALAN on freshwater systems, as well as more detailed assessments of light environments in aquatic habitats [5]. Given the wide array of disciplines involved in the issue of light pollution, it is imperative to address this with an inter-and transdisciplinary approach [52, 53]. Better descriptions of ALAN in rivers can support the development of sound transdisciplinary solutions, ideally as an emerging collaboration between practice, research, production, decision-making and planning [53, 54, 55]. Establishing such transdisciplinary approaches can help professionals involved in light planning and design to address the United Nations Sustainable Development Goal (SDG14, 2015) [56] for the integrity of life below water, the assessment of new and existing lighting design, and to facilitate the evaluation of new, existing, and sustainable lighting solutions [57, 58, 59].

4.10. Appendix A for Chapter 4

Table A1. Information about the position at which measurements were taken.

Measurement site	Bridges	Stops	Latitude, Longitude	Distance (km)	Time
A	Moltkebrücke	1	52° 31' 17.44" N, 13° 22' 6.18" E	0.0	19:30 - 19:37
		2	52° 31’ 18.60” N, 13° 22’ 7.85” E	0.05	
		3	52° 31' 21.18" N, 13° 22' 10.32" E	0.14	
B	Kronprinzen brücke	1	52° 31' 21.37" N, 13° 22' 27.44” E	0.48	19:42 - 19:47
		2	52° 31’ 18.81” N, 13° 22’ 32.88” E	0.61	
		3	52° 31' 16.54" N, 13° 22' 33.94" E	0.68	
C	Monbijou	1	52° 31' 20.7" N, 13° 23' 36.2" E	2.09	20:06 - 20:12
		2	52° 31' 20.9" N, 13° 23' 39.0" E	2.15	
		3	52° 31' 20.1" N, 13° 23' 40.1" E	2.19	
D	Friedrichsbrücke	1	52° 31' 16.3" N, 13° 23' 57.7" E	2.54	20:15 - 20:20
		2	52° 31’ 13.97” N, 13° 24’ 1.44” E	2.64	
		3	52° 31' 13.0" N, 13° 24' 02.8" E	2.68	
E	Jannowitzbrücke	1	52° 30' 52.3" N, 13° 24' 59.9" E	4.06	20:34 - 20:39
		2	52° 30’ 51.45” N, 13° 25’ 4.16” E	4.14	

Table A1. Information about the position at which measurements were taken.

		3	52° 30' 50.5" N, 13° 25' 06.4" E	4.20	
F	Oberbaumbrücke	1	52° 30' 09.6" N, 13° 26' 36.1"E	6.32	20:56 - 21:17
		2	52° 30' 07.2" N, 13° 26' 45.5"E	6.51	
		3	52° 30' 05.5" N, 13° 26' 46.2" E	6.55	
G	Abteibrücke	1	52° 29' 12.0" N, 13° 28' 47.10" E	9.43	21:39 - 21:33
		2	52° 29’ 10.97” N, 13° 28’ 50.40” E	9.50	
		3	52° 29' 11.7" N, 13° 28' 54.9" E	9.60	

Table A2. Technical information about the deck width, height, and length of each bridge

Measurement site	Bridges	Deck Width (m)	Height (vertical navigation clearance for boats) (m)	Length (m)
A	Moltkebrücke	26.70	4.50	77.00 - 92.00
B	Kronprinzenbrücke	23.40 - 24.00	7.50	74 - 76.26
C	Monbijoubrücke	15	4.50	62.00
D	Friedrichsbrücke	27	4.30 - 4.50	69.30
E	Jannowitzbrücke	35-36	4.0	73.50-80.00
F	Oberbaumbrücke	22 (useful width) 27.90	4.50	150
G	Abteibrücke	4.4	9	75.4

Table A3. Technical information about the distances between the bridges

Measurement sites	Distance between the bridges (km)
A to B	0.56
B to C	1.54

C to D	0.49
D to E	1.5
E to F	2.31
F to G	2.99

Table A4. Technical information about the distances between the stops.

Measurement site	Bridges	Distance between before and under (km)	Distance between under and after (km)	Distance between before and after (km)
A	Moltkebrücke	0.5	0.09	0.59
B	Kronprinzenbrücke	0.13	0.07	0.2
C	Monbijoubrücke	0.06	0.04	0.1
D	Friedrichbrücke	0.1	0.04	0.14
E	Jannowitzbrücke	0.08	0.06	0.14
F	Oberbaumbrücke	0.19	0.04	0.23
G	Abteibrücke	0.07	0.1	0.17

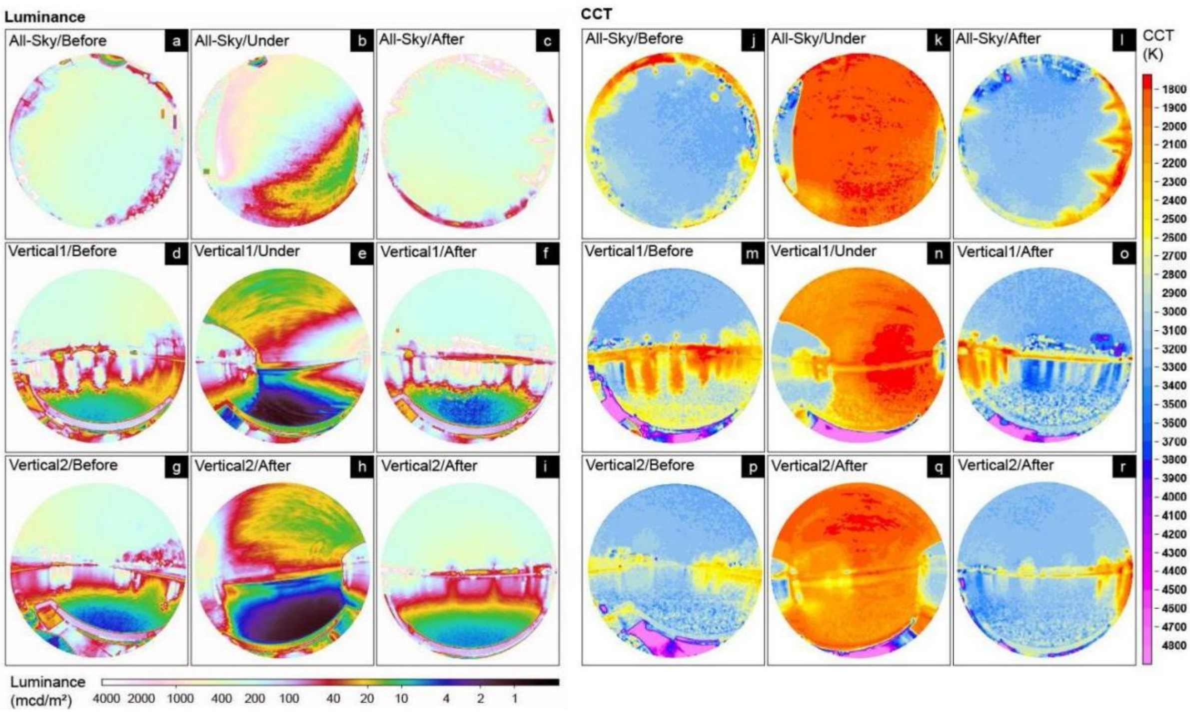

Figure A1. Luminance (a - i) and CCT (j - r) maps of measurement site A (Moltkebrücke). Overview of all-sky (a - c, j - l) and two vertical planes (d - i, m - r) camera modes.

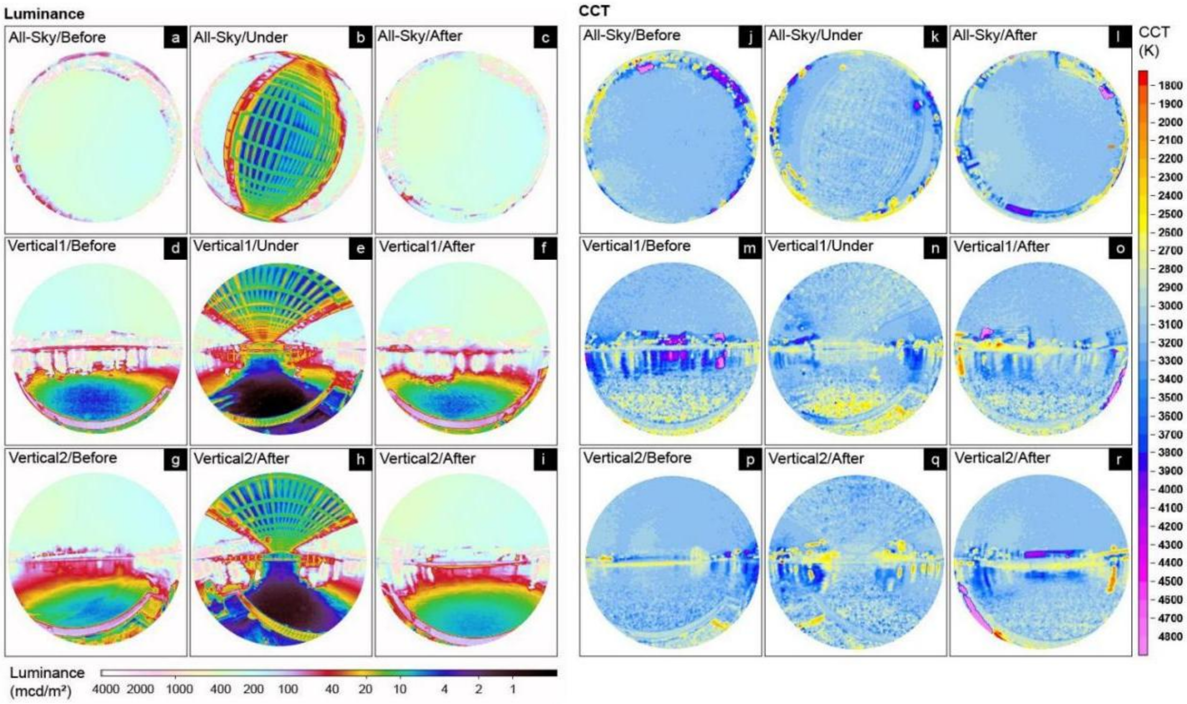

Figure A2. Luminance (a - i) and CCT (j - r) maps of Measurement site B (Kronprinzenbrücke). Overview of all-sky (a - c, j - l) and two vertical planes (d - i, m - r) camera modes.

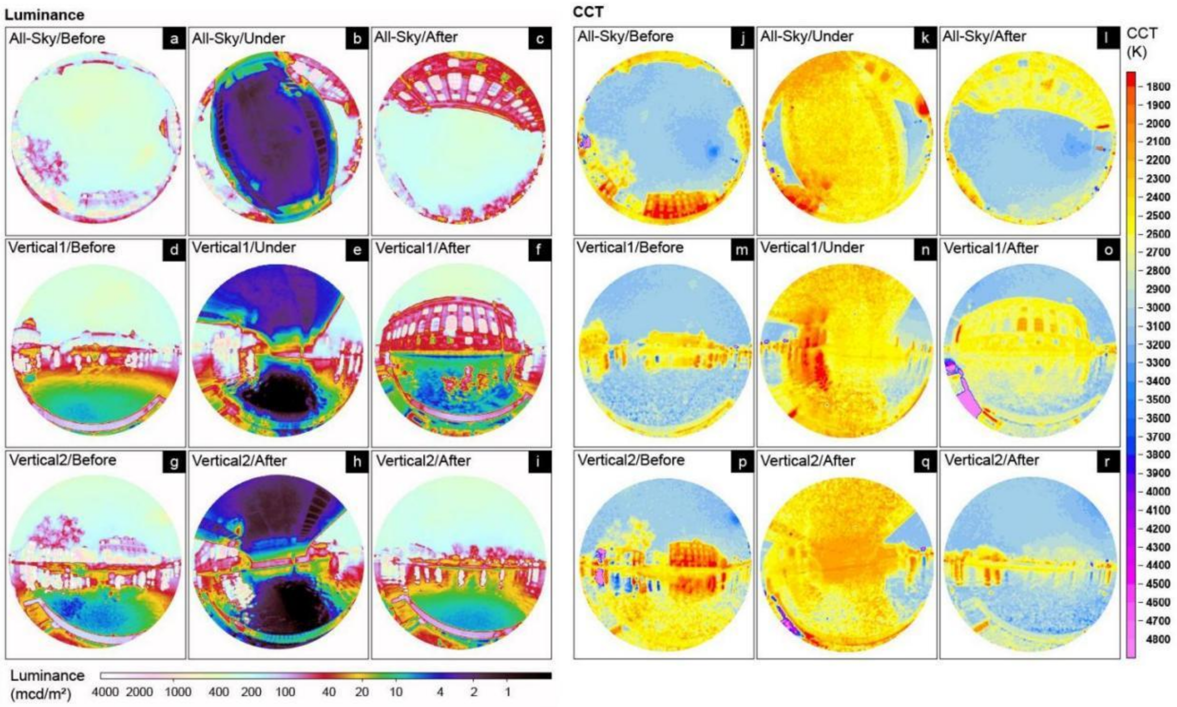

Figure A3. Luminance (a - i) and CCT (j - r) maps of measurement site C (Monbijou). Overview of all-sky (a - c, j - l) and two vertical planes (d - **I**, M - R) camera modes.

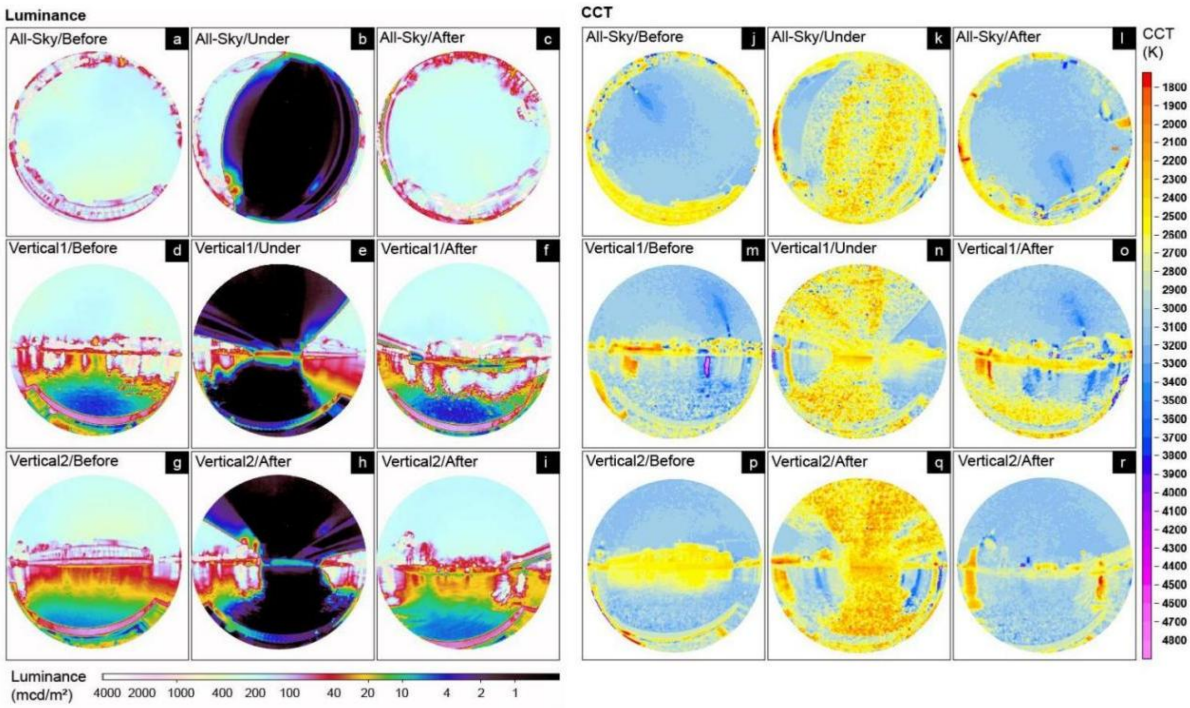

Figure A4. Luminance (a - i) and CCT (j - r) maps of measurement site D (Friedrichsbrücke). Overview of all-sky (a - c, j - l) and two vertical planes (d - i, m - r) camera modes.

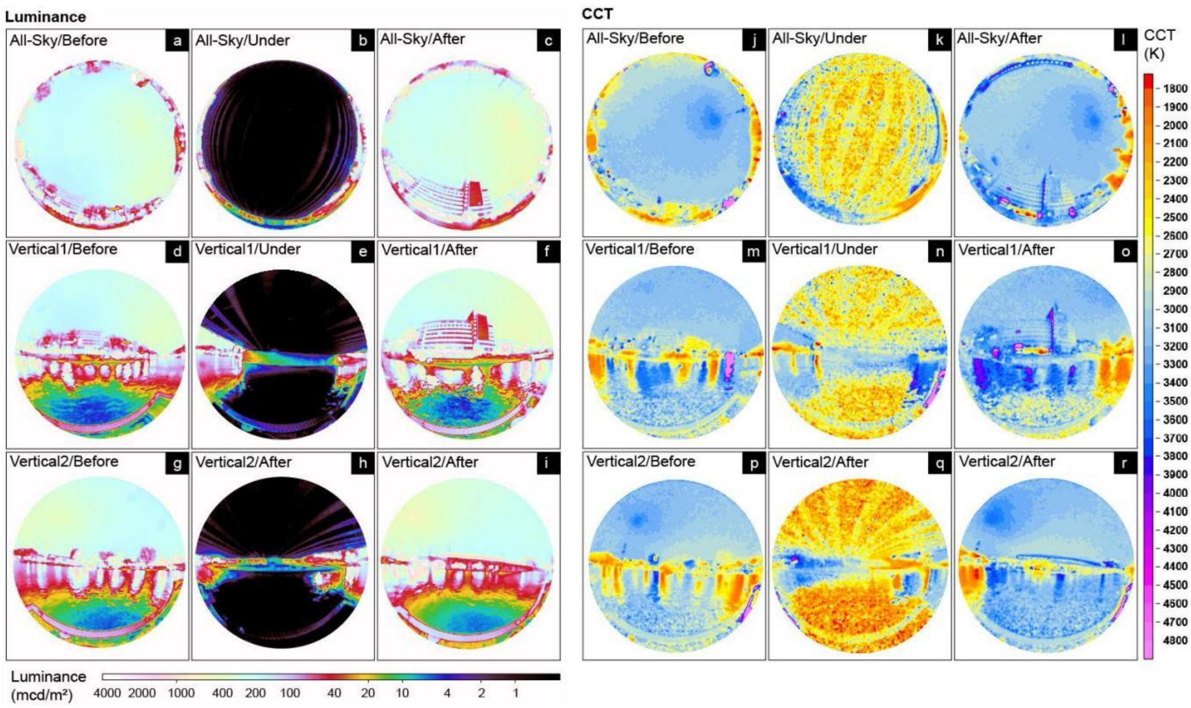

Figure A5. Luminance (a - i) and CCT (j - r) maps of measurement site E (Jannowitzbrücke). Overview of all-sky (a - c, j - l) and two vertical planes (d - i, m - r) camera modes.

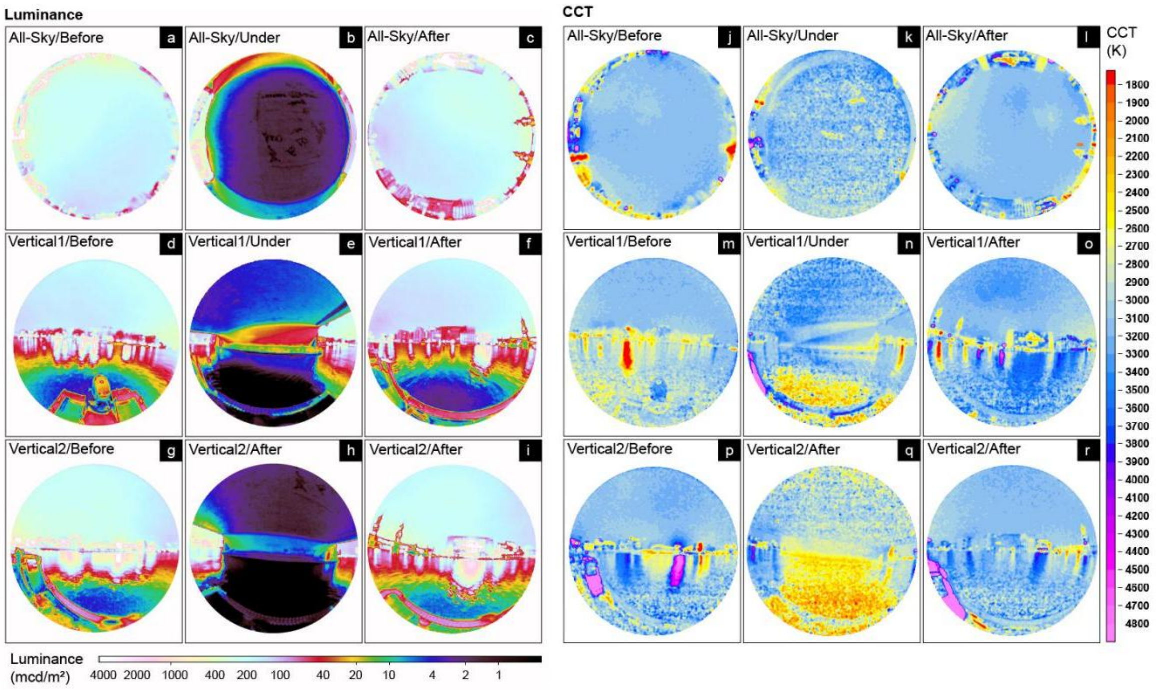

Figure A6. Luminance (a - i) and CCT (j - r) maps of measurement site F (Oberbaumbrücke). Overview of all-sky (a - c, j - l) and two vertical planes (d - i, m - r) camera modes.

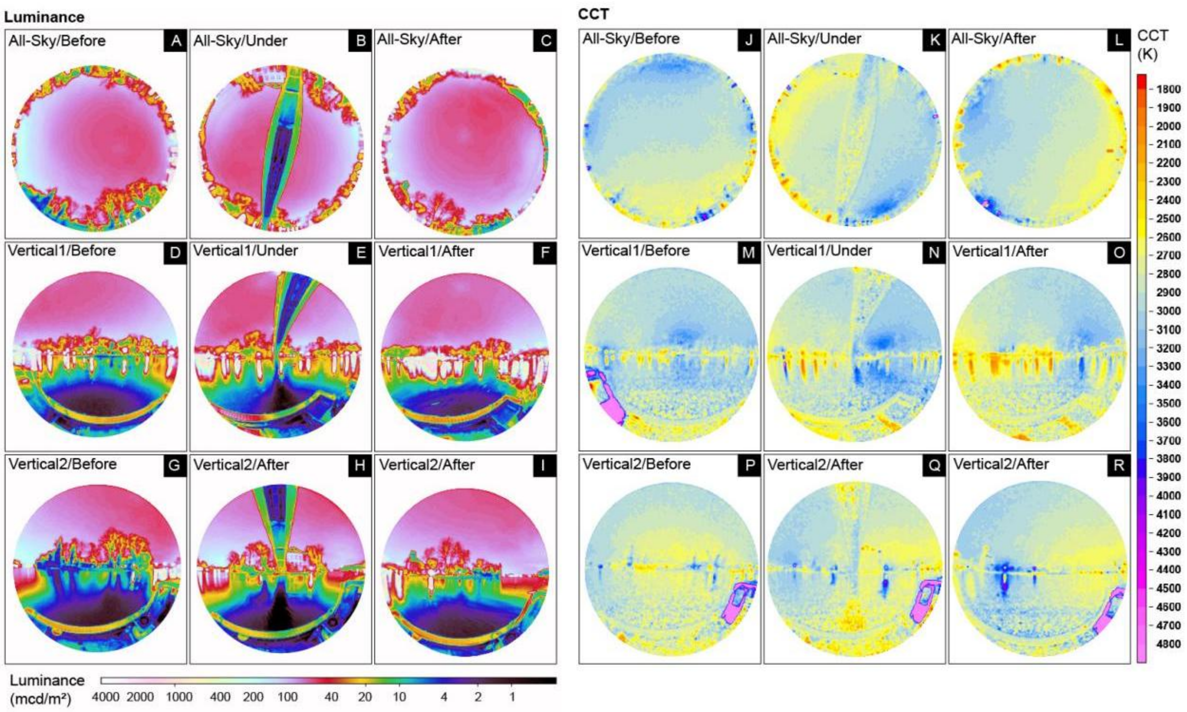

Figure A7. Luminance (a - i) and CCT (j - r) maps of measurement site F (Abteibrücke). Overview of all-sky (a - c, j - l) and two vertical planes (d - i, m - r) camera modes.

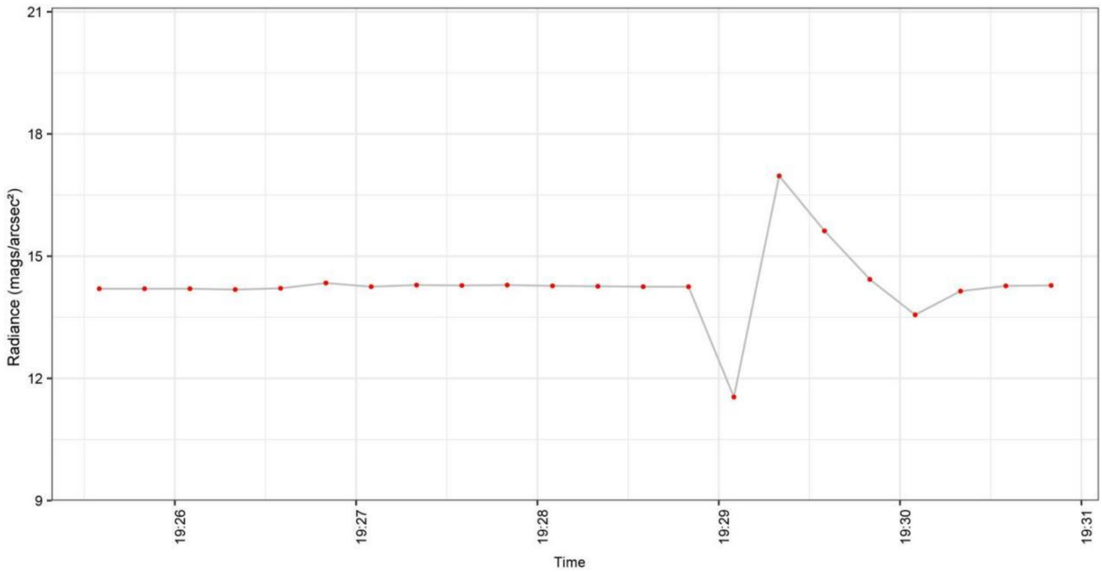

Figure A8. Sky radiance SQM measurements while the boat moved along measurement site A–Moltkebrücke. Note that sky radiance decreases when the mag/arc^2 values increases (see Methods). Red dots indicate a measured sky radiance and bridges are perceivable as rapid changes in sky radiance. Here, the time frame between 19:29-19:30 indicates a rapid change in sky radiance –an illuminated bridge. Skyglow brightness demonstrates continuous values at approximately 14 magSQM/arcsec^2 over the transect. A luminaire close to the underpath of the bridge emits light, which makes the light field brighter, at approximately 11magSQM/arcsec^2. Then, sky radiance values rapidly change within a range of about 15 seconds to approximately 17magSQM/arcsec^2 becoming dark before it gradually becomes bright again to values that range at 14 magSQM/arcsec^2).

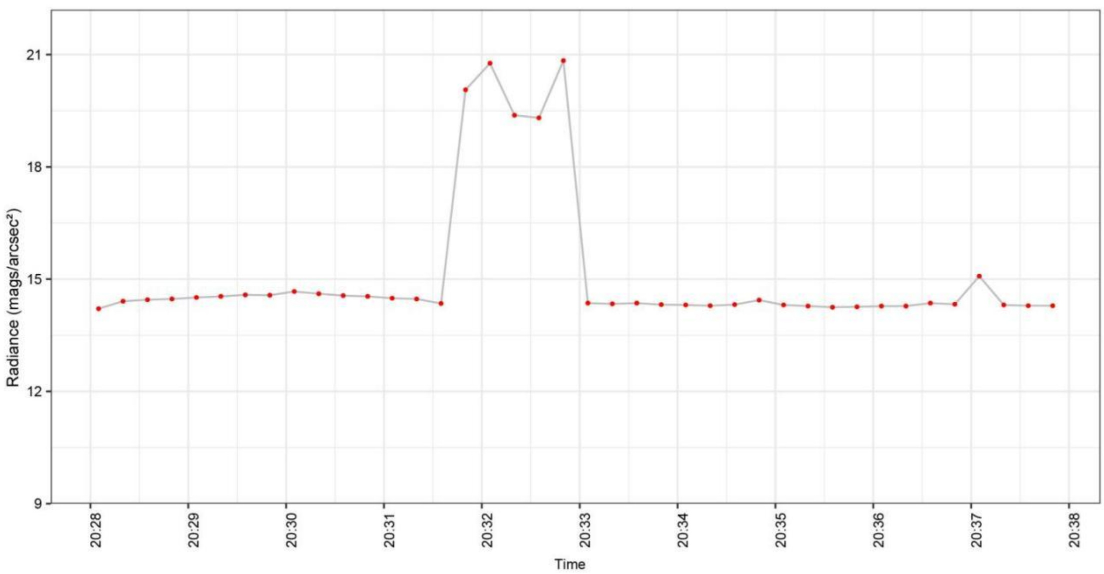

Figure A9. Sky radiance SQM measurements while the boat moved along measurement site E Jannowitzbrücke. Note that sky radiance decreases when the mag/arc^2 values increases (see Methods). Red dots indicate measured sky radiance and bridges are perceivable as rapid changes in sky radiance. Here, the time frame between 20:31-20:33 indicate a rapid change in sky radiance. Skyglow brightness demonstrates continuous values at approximately 14 magSQM/arcsec^2 over the transect. An decrease in sky radiance occurred when approaching the bridge with values between 20-21 magSQM/arcsec^2 indicating a darker section occurs at the river when compared to the skyglow at the river transect. Then, sky radiance values gradually reach 19 magSQM/arcsec^2 (under the bridge) indicating a wide bridge with an unlit underpath. These values then change to 21 magSQM/arcsec^2 indicating a darker section under the bridge that then gradually goes back to brighter values as it reaches radiances at approximately 14 magSQM/arcsec^2.

4.11. References for Chapter 4

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Chapter 5:

Polarised light pollution on river water surfaces caused by artificial light at night from illuminated bridges and surroundings

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5.1. Abstract

Bridge illumination gave rise to night-time illuminated paths across aquatic systems. However, if bridge artificial light at night (ALAN) reach waterbodies, it can result in polarised light pollution (PLP), which might alter the optical conditions of a river by night and potentially interfere with moonlight polarisation signals reflected off the water's surface. It is a night-time phenomenon that can detrimentally change the behaviour of organisms sensitive to horizontally reflected polarised moonlight, a navigational cue and signal known to be used by flying water-seeking insects to detect suitable aquatic habitats to reproduce and lay eggs. In this study, we quantify the reflection of ALAN-induced polarisation patterns at the water's surface near seven illuminated bridges crossing the river Spree in Berlin. The photometric data shows that bridge illumination induces PLP, which reflects from the water's surface when measured at specific locations in space considered as potential flying paths for polarotactic aquatic insects. ALAN-induced polarisation findings at illuminated bridges suggest that PLP is a pollutant that illuminates aquatic areas. It requires better research as it can potentially affect polarimetric navigation in flying aquatic insects. As the extent of light pollution reaches riverine systems and aquatic habitats, the potential effects of PLP on freshwaters need the proper development of sustainable lighting solutions that can aid in preserving riverine nightscapes.

5.2. Introduction

Light is the part of the electromagnetic spectrum visible to the human eye, and such electromagnetic waves can be polarised. Generally, humans are not able to perceive the polarisation of light, apart from some very specific situations [1], while some animals are able to perceive it [2]. Polarisation can occur when unpolarised light is reflected or transmitted at surfaces that have a preference for a specific polarisation direction or by scattering within a medium (e.g. the atmosphere or water) (see Supplementary Material) [2, 3]. The air and water interface (i.e. water surfaces in nature) is an example of a typical surface where light is reflected so that the resulting reflected light is (at least partly) linearly polarised. As other surfaces might not reflect the light of a specific polarisation like water, the polarisation information can be understood as encoded optical information about the surroundings (e.g. water or the absence of water), and it can change how surfaces and objects are perceived by organisms that can detect them.

In nature, polarisation is a property of light known to be abundant as it is often found in scattered skylights, the reflected light of the surface of waterbodies, rocks, soil, and vegetation [4, 5, 6]. Polarised light has been shown to be used by vertebrates and invertebrates as an optical source of encoded information about habitats and surroundings (e.g. as a celestial compass and aquatic habitat information). For instance, fish, birds, and marine invertebrates and invertebrates such as insects use polarised light to locate habitats [3,7–11]. Bees, ants, and arthropods make use of polarised light as a navigational cue to locate the sun‘s position (via polarised light in the sky) and as a reference to return to nesting sites [12]. Flying aquatic insects detect waterbodies during their flight through the polarised reflection of light at the water's surface [13]. Under natural light conditions, waterbodies are known to reflect horizontally polarised light and have been shown to attract so-called polarotactic organisms with visual systems that detect polarised light [14,15], which makes polarisation an advantage that reveals specific light conditions of environments, aids navigation and habitat selection [3,5–14]. Figure 1 shows a typical scenario in which the polarisation of reflected moonlight is expected to be used as a signal that aids mayflies during their flights to detect the water's surface.

Artificial light at night (ALAN) incident on inland waters (i.e. surfaces where ALAN is not intended to be) might create polarised light signals by reflection, potentially leading to polarised light pollution (PLP), which is likely to create artificial polarisation patterns on the water surface that can eventually turn illuminated waters and surfaces into an ecological trap at night [16,17]. Consequently, ALAN-induced polarisation patterns can potentially affect the behaviour of flying nocturnal species sensitive to polarised light [14,18,19].

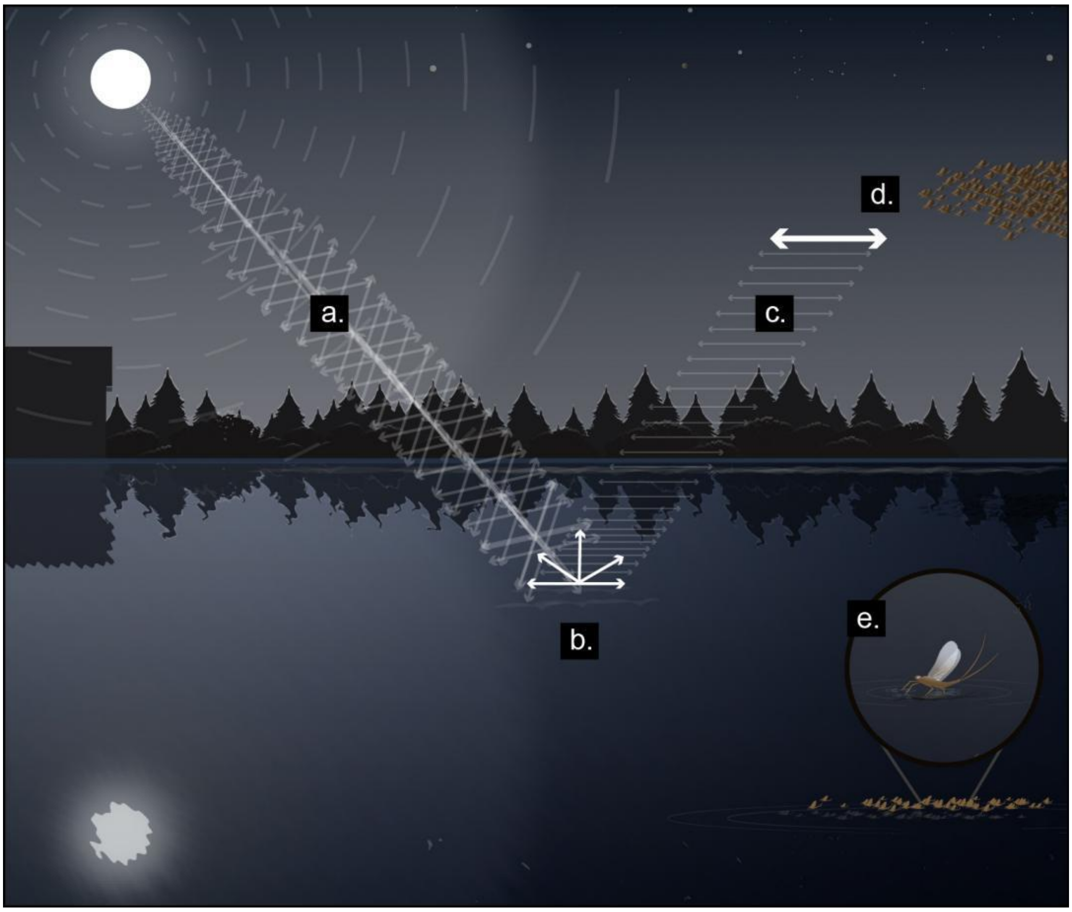

Figure 1. Overview of a naturally illuminated river at night during a full moon where the moonlight polarisation signals reflected at the water's surface are used as a navigational cue for reproductive behaviour. In natural conditions, moonlight is a distant single source that can also be used for navigation due to its large contrast within the relatively dark surroundings. At the same time, its position remains nearly constant within the sky for animals navigating on typical spatial scales (i.e. where the position of the moon in the sky remains almost fixed). During a full moon and a cloudless night, (a) unpolarised incident moonlight strikes (b) the boundary of air and water where mainly horizontally polarised light is reflected. The reflected linear polarised light becomes a source of optical information to locate the water surface and a reference for orientation and navigation used by (d) polarotactic-flying organisms, such as mayflies. The moon's reflected polarised light is often related to foraging and reproductive behaviours in nocturnal flying aquatic insects (see review in [3]). (e) Horizontally reflected polarised moonlight serves as optical information that indicates a potential habitat for mating or laying eggs. Source: authors' work.

Growing concerns about PLP [14,19] have become evident as ALAN continues to increase in radiance and extent [20,21]. ALAN directly incident on land or water can reach up to 1,000 times brighter than during a full moon [22], and when indirectly, it scatters in the atmosphere as skyglow [23], where it can reach polarising surfaces and induce maladaptive behaviours or affect the physiology of flora and fauna [24,25].

One study on the distinct polarisation properties of a dark lake suggests that PLP can influence the detectability of the water, which could potentially affect the behaviour of polarotactic insects [26,27]. Another study demonstrated that polarised ALAN and unpolarised ALAN at bridges could attract and trap mayflies [17,28]. This combination of unpolarised and polarised ALAN will likely contribute to the increased attraction of nocturnal flying species towards the bridge structure, which can veil the bridge into an ecological trap [27,29,30]. In mayflies, polarised ALAN at bridges has been shown to affect their natural behaviour and swarming dynamics [19].

Studies on polarisation signals have demonstrated that man-made surfaces, including asphalt roads [31], solar panels [29], black and grey horizontal reflectors [32], black and white cloth [33], cars [34,35], and dark glass surfaces [32,36] when illuminated with natural light (sunlight), have polarising properties comparable to those of water surfaces when illuminated [37] and have demonstrated reflected horizontally polarised light likely to turn these surfaces into ecological traps for attracted polarotactic organisms. We have recently raised the issue of ALAN from illuminated bridges in inland waters [38] and also mentioned the problem of PLP from ALAN in a review paper [39].

However, so far, no studies have considered PLP from ALAN being reflected at the water's surface. Most work was done on ALAN creating PLP on non-water surfaces mimicking the impression of water surfaces, and few studies have done that in the context of illuminated bridges [17,19]. PLP induced by bridge illumination remains a multi-faceted research question. Thus, measuring how ALAN is polarised is a crucial first step in our understanding of the vision of different animal groups, habitat selection [40], and ecological interactions of organisms with their environment.

In this study, we (i) quantify the reflection polarisation patterns of ALAN from illuminated bridges crossing a river and at potential flying path positions of polarotactic aquatic insects to (ii) explore if illuminated bridges crossing the Spree in Berlin are potential PLP hubs and to (iii) draw up potential implications for water-seeking insects. Furthermore, we identify the different sources of reflected polarised light in/near illuminated bridges to estimate the extent to which bridge ALAN becomes horizontally polarised by reflection at the water's surface. Furthermore, we identify the different sources of reflected polarised light in/near illuminated bridges to estimate the extent to which bridge ALAN becomes horizontally polarised by reflection at the water's surface.

5.3. Materials and Methods

The night-time measurements were performed during clear sky conditions on the 24th of March, 2022. Measurements were obtained between ca.18:30 and 23:30 local time

(GMT +1), with the moon setting at approximately 20:45 (GMT +1). The measurement area covers a 10 km route from West to East (Fig. 2a), which includes seven illuminated bridges crossing the river Spree in Berlin. Prior to the measurement night, the seven illuminated bridges were scouted by foot to determine one position at each bridge to obtain measurements considering potential insect flying perspectives over the river. Once the position at each bridge was set, a mapped route was established to perform one-night ground measurements over seven illuminated bridges. The measurements were used to determine if PLP occurred at illuminated bridges. The measurements do not cover all possible positions an insect might consider when flying over a river.

A digital single-lens reflex camera (DSLR, Canon EOS 6D), a 50 mm lens, and a linear polarising filter (polariser) were used to determine PLP. The camera measures the radiance for each pixel in the three colour channels RGB (red, green, blue). PLP is determined by capturing two RGB images with different polariser orientations, as shown in Fig. 2b. The polariser orientations were set by identifying the lowest and the highest light transmission at a defined polarising reference surface. The lowest light transmission is equivalent to the polariser oriented at 0° (vertical), and the highest light transmission is equivalent to the polariser oriented at 90° (horizontal). Both orientations were marked with a pencil on the camera lens to note the stops at which the rim should no longer move to obtain measurements.

The camera was placed on a tripod at each measurement site to add stability, as no difference should occur from one frame to the other. The camera is then pointed towards the illuminated bridge. Note that the measurement (a linearly polarised map) should include the water surface in front of the illuminated bridge and the bridge itself. Also, the camera should remain in the set position for both orientations. Once the camera's position is determined, the polariser is set at 0°, and a measurement is obtained. The procedure is also repeated for the polariser set at 90°. A remote control is used to avoid moving the camera from position and to avoid misalignments. The polariser must be carefully moved to avoid abrupt changes between the frames. ISO settings are fixed at 6400 and the shutter speed at 1/30 seconds. The camera was equipped with a GPS to record images of their corresponding locations within the 10 km transect. For comparing images, orientations 0° and 90° were considered enough to determine the PLP at the water surface. To calculate the PLP, the custom-written software R with the packages named raster and sp for image processing was used. The RAW (or CR2 format) files are then organised by measurement sites to extract RGB channels from each image. RAW files with the polariser at orientations 0° and 90° were used throughout this work. However, the full dataset also includes orientations 45° and 135°, which were shown to be not necessary due to the relatively straightforward determination of the polarising plane (horizontal water surface).

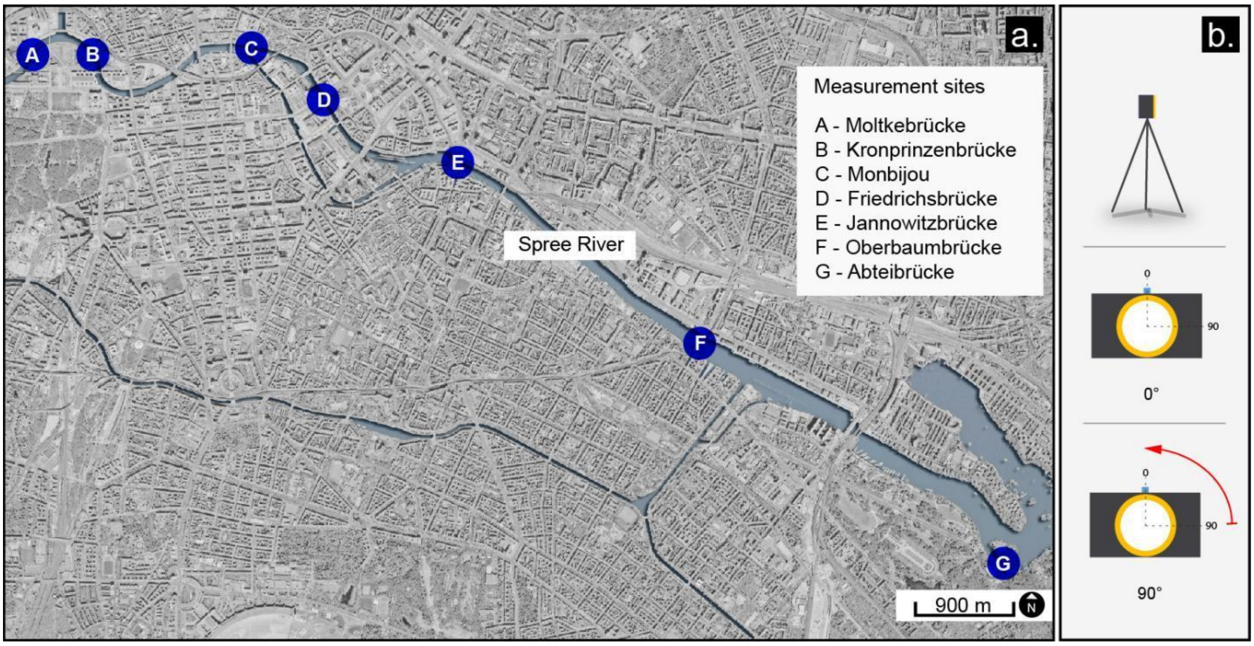

Figure 2. Map of the measurement sites along the river Spree in Berlin, Germany and an overview of the two different orientations the camera was oriented. (a) Map of the measurement sites, seven illuminated bridges along the river Spree in Berlin, Germany. (b) At each measurement site, an RGB camera is pointed at the illuminated bridge to obtain two images with a linear polariser in two different orientations: at 0° (vertical polarisation) and 90° (horizontal polarisation). The yellow rim indicates the position of the polariser on the camera, the blue line indicates the position of the outlined mark on the 50 mm lens. Source: authors' own work.

The images taken at orientations 0° and 90° are used to determine the degree of linear polarisation (DoLP) of ALAN.

DoLP is given by:

$$DOLP_{0/90} = \left|\frac{I_0 - I_{90}}{I_0 + I_{90}}\right| \qquad (1)$$

And re-written as stokes parameters considering that

$$S_0 = I_0 + I_{90} \qquad (2)$$

$$S_1 = I_0 - I_{90} \qquad (3)$$

Therefore,

$$DOLP_{0/90} = \left|\frac{S_1}{S_0}\right| \qquad (4)$$

DoLP is represented in % to show how much of the light wave's electric field is aligned in a defined direction. A perfectly polarised light wave has a DOLP equivalent of 100%, while an unpolarised light wave has a DoLP equivalent of 0%. As the study aims to quantify horizontally reflected polarisation patterns of bridge ALAN on the water surface of a river, the water-to-air power coefficient, Fresnel equations, and Brewster's law must be considered (see Supplementary Information).

5.4. Results

Polarisation imaging was performed at each of the seven bridges and both RGB images and calculated DOLP maps (see methods) are presented here. Figure 3 shows the results for Friedrichbrücke as an example of the complete dataset of results for measurement site D. Figure 3 (a,b) shows two RGB images for the two linear polarisations in which (a) corresponds to 0° (vertical polarisation) and (b) to 90° (horizontal polarisation). Also, RGB images show with magenta arrows the position of visible luminaires on the bridge, while the magenta squares indicate their reflected light at the water's surface. Blue arrows indicate the position of luminaires on the bridge for boat passage, while the blue squares indicate their reflected light at the water's surface. Figure 3 (c,d,e) shows the resulting calculated DoLP where equation (4) (see Materials and Methods section) was applied for each pixel for the three colour channels of the camera (c, red; d, green and e, blue). The false colour code of each data image works as follows: greenish pixels have a high DoLP of nearly 1, yellowish pixels are nearly 0.5 DoLP, and reddish pixels have a low DoLP of nearly 0. White pixels are removed data points where the original radiance was too low to properly extract a DOLP signal.

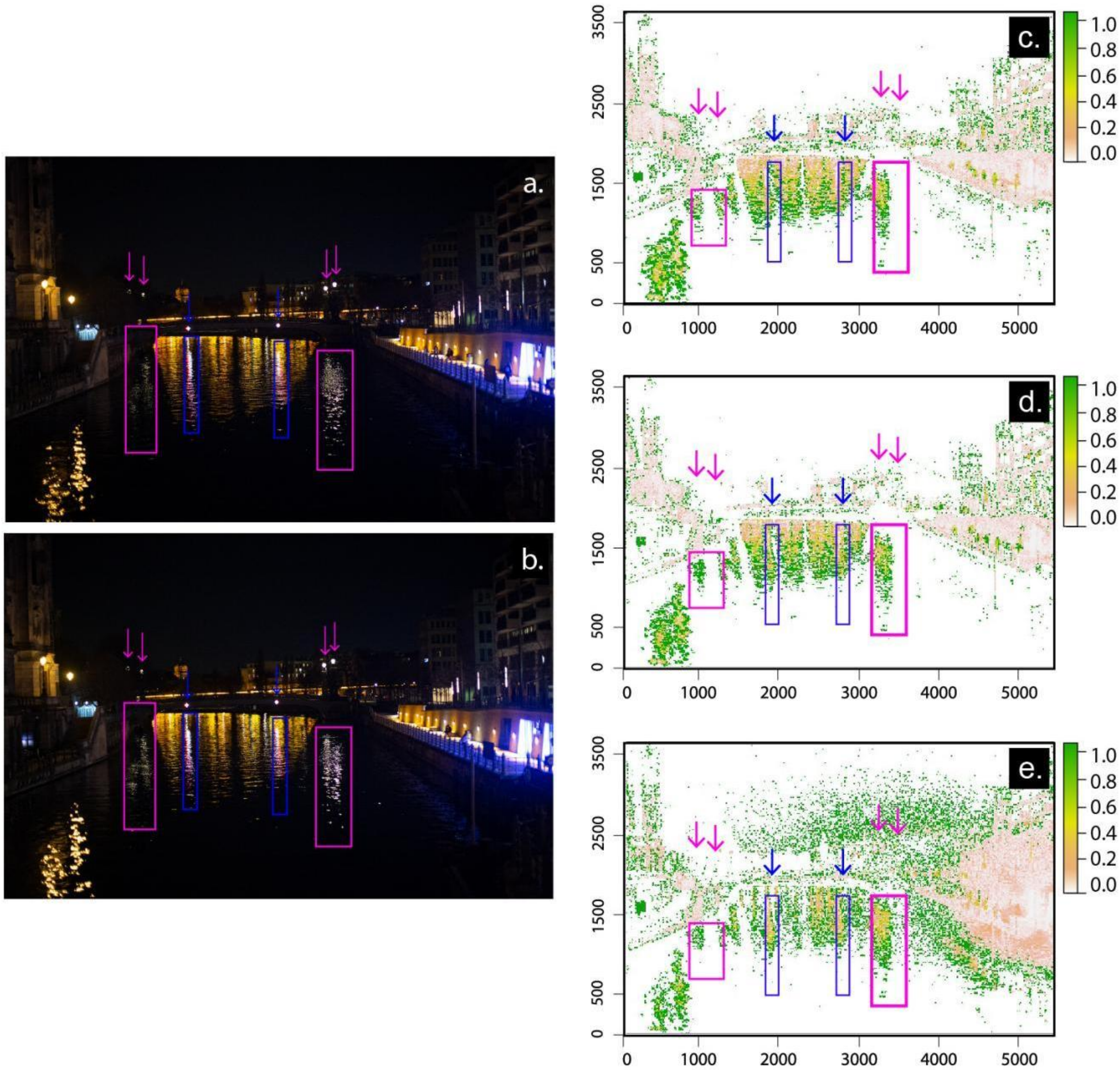

Figure 3. (a,b) RGB images of measurement site D — Friedrichbrücke where (a) shows a polariser set at 0° (vertical polarisation) and (b), a polariser set at 90° (horizontal polarisation). (c, d, e) Calculated DOLP for each imaging pixel for the red channel (c), green channel (d), and blue channel (e). (a-e) Arrows show dominant light sources and boxes show the reflected light on the water's surface. Source: authors' own work.

Figure 3 shows Friedrichbrücke with two types of illumination that consist of luminaires for pedestrian (magenta arrows) and boat passage (blue arrows). Both illumination types horizontally polarised light by reflection (a degree of polarisation ranging between 0.2 – 1.0) on the water's surface. Also, the sources for both illumination types were directly visible from the measurement position.

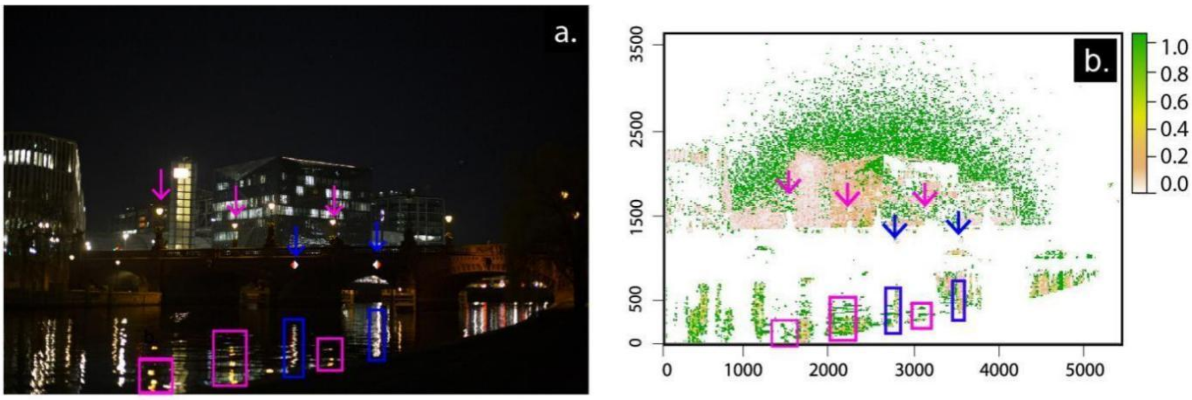

Figure 4. (a) RGB image of measurement site A — Moltkebrücke with the polariser set at 90° (horizontal polarisation). (b) Calculated DOLP for each imaging pixel for the blue channel (e). Arrows show dominant light sources and boxes show the reflected light on the water's surface. Source: authors' own work.

Figure 4 shows the reduced dataset for Moltkebrücke with only one RGB image and calculated DOLP for each pixel of one colour channel. Both bridge illumination intended for pedestrian passage (magenta arrows) and bridge illumination intended for boat passage (blue arrows) induce horizontally polarised light by reflection (DOLP ranging between 0.2 – 1.0) on the water's surface. Both pedestrian and boat passage illumination had light sources visible from the measurement position. Also, indoor illumination from buildings in the vicinity of Moltkebrücke showed to induce horizontally polarised light reflected at the water's surface (DOLP ranging between 0.2 – 1.0). However, these light sources were not directly visible from the measurement position.

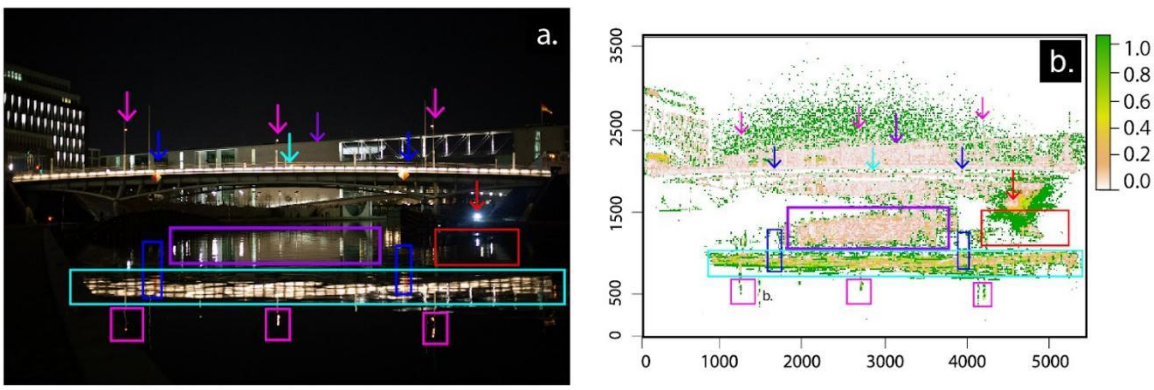

Figure 5. (a) RGB images of measurement site B — Kronprinzenbrücke with the polariser set at 90° (horizontal polarisation). (b) Calculated DOLP for each imaging pixel for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

Figure 5 shows the same reduced dataset as in Fig. 4 for Kronprinzenbrücke. Three illumination types (in magenta, blue, cyan, purple, and red) with different functionalities (magenta for pedestrian and vehicular passage; blue for boat passage; cyan for bridge decorative lighting; purple, for the vertically illuminated building behind the bridge; red, floodlight under the bridge) were identified. Functional and decorative bridge lighting produced horizontally polarised light (DOLP ranging between 0.2 – 1.0). At the bridge, three illuminating sources intended for pedestrian and vehicular passage, located on the opposite site of the measurement position and across the bridge (magenta arrows), were directly visible from across the bridge and induced horizontally polarised light (DOLP ranging between 0.8 – 1.0) at the water‘s surface. Two illuminating sources intended for boat passage (blue arrows), located at the bridge, were directly visible from the measurement position and also induced horizontally polarised light (DOLP ranging between 0.2 – 1.0) at the water surface.

Moreover, decorative lighting on the bridge (cyan arrow) created the most apparent horizontally polarised light by reflection (DOLP ranging between 0.2 – 1.0), shown in the cyan box, when compared to functional luminaires intended for pedestrian, vehicular, and boat passage (magenta and blue arrows) at Kronprinzenbrücke. The light sources for decorative lighting (cyan arrow) were also visible from the measurement position. In addition, far behind the bridge, a vertically illuminated wall (purple arrow) and a floodlight in the vicinity (red arrow) also created horizontally polarised light by reflection on the water‘s surface. The light source of the vertically illuminated building was not visible from the measurement position (purple arrow), while the floodlight‘s light source was visible and unshielded (red arrow). The building vertically illuminated upwards (DOLP ranging between 0.0 – 0.4) presented a lower DOLP when compared to the floodlight with a visible light source (DOLP ranging between 0.2 – 1.0) from the measurement position.

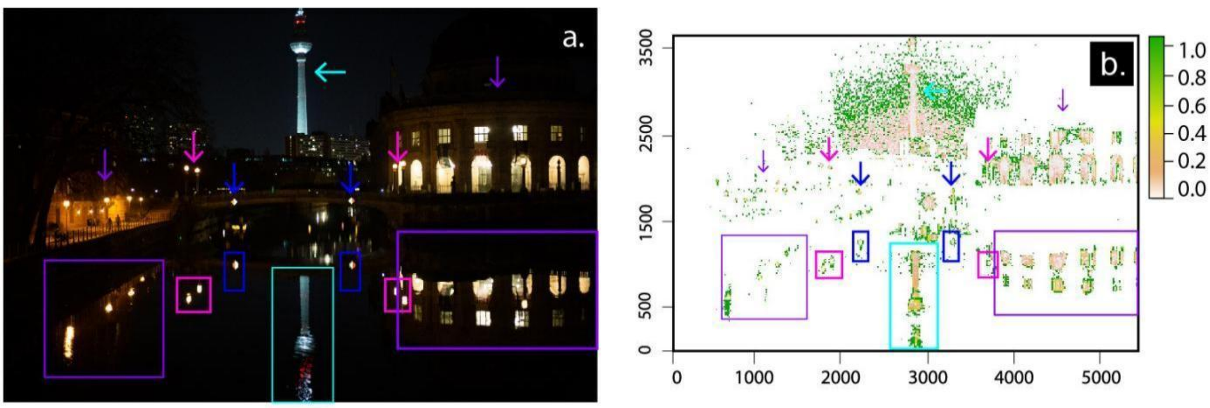

Figure 6. (a) RGB images of measurement site C — Monbijoubrücke with the polariser set at 90° (horizontal polarisation). (b) Calculated DOLP for each imaging pixel for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface. Source: authors’ own work.

Figure 6 shows the reduced dataset for Monbijoubrücke. Four illumination types: pedestrian path lighting of the bridge (magenta arrows), luminaires intended for boat passage (blue arrows), the TV tower with decorative lighting (cyan arrows), illuminated paths that surround the boroughs of the Monbijoubrücke (purple arrows), were identified as main sources of ALAN. Illumination for pedestrian and boat passage were directly visible from the measurement position, and both induced horizontally polarised light at the water‘s surface (DOLP ranging between 0.2 – 0.6). Far behind the bridge lies the TV tower (cyan arrows), which is vertically illuminated upwards, but had no directly visible light sources from the measurement position (apart from the red blinking lights used at the top of buildings for plane navigation) and is induced horizontally polarised light by reflection at the water‘s surface. The illuminated TV tower presented a higher DOLP signal on the water‘s surface (DOLP ranging between 0.2 – 1.0) when compared to bridge ALAN (magenta and blue arrows). In addition, surrounding illuminated paths that connect the bridge network (purple arrows) present a fainted DOLP signal. The light sources at these surrounding paths were on the left path while they remained non-visible on the right side path.

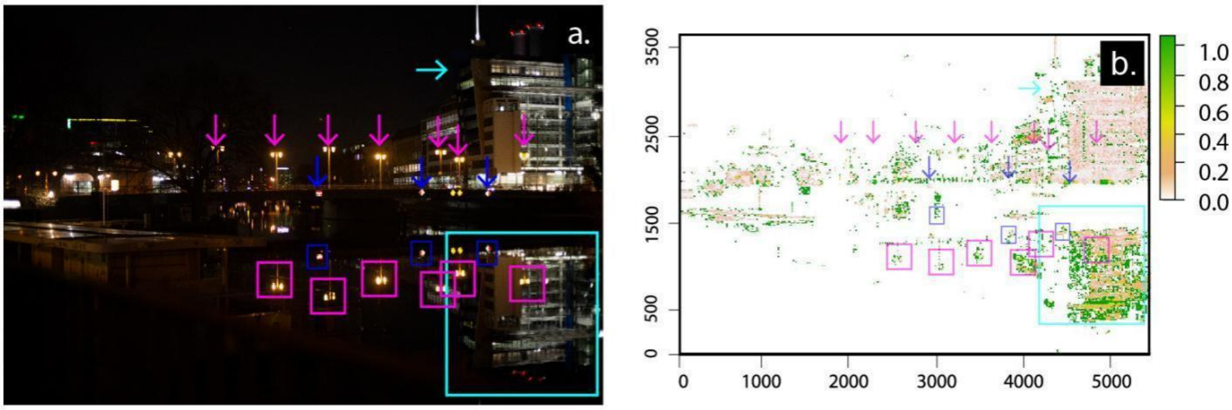

Figure 7. (a) RGB images of measurement site E — Jannowitzbrücke with the polariser set at 90° (horizontal polarisation). (b) Calculated DOLP for each imaging pixel for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface. Source: authors' own work.

Figure 7 shows the reduced dataset for Jannowitzbrücke. Three illumination types, pedestrian and vehicular lighting on top of the bridge (magenta arrows), luminaires for boat passage (blue arrows), and surrounding illumination from a building were identified. All three types cause horizontally polarised light reflected (DOLP ranging between 0.2 - 1.0) at the water‘s surface. The surrounding illumination showed a broader DOLP signal when compared to luminaires on the bridge for pedestrian, vehicular and boat passage. The light sources of both pedestrian, vehicular and boat passage were visible from the measurement position while the light sources of the bridge were not visible.

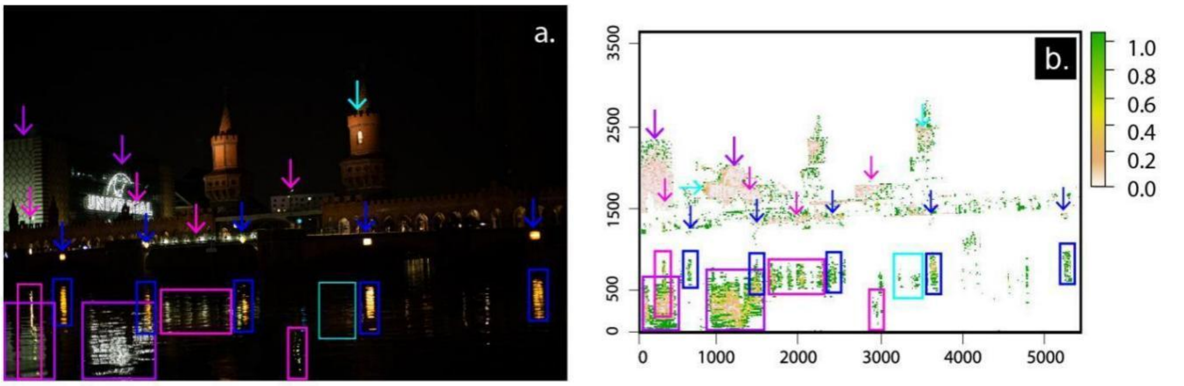

Figure 8. (a) RGB images of measurement site F — Oberbaumbrücke with the polariser set at 90° (horizontal polarisation). (b) Calculated DOLP for each imaging pixel for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface. Source: authors' own work. Source: authors' own work.

Figure 8 shows five illumination types at Oberbaumbrücke with luminaires intended for vehicular passage (magenta arrows), boat passage (blue arrows), decorative purposes that include light projected on the walls of a tower to show its architecture and textures (cyan arrows), and the Universal building that included a backlit (illuminated from behind) logo and a vertical uplit (luminaires directed upwards) wall (purple arrows). Luminaires intended for vehicular passage were not visible from the measurement position and horizontally polarised light by reflection (DOLP ranging between 0.4 – 1.0) at the water's surface. Luminaires intended for boat passage were visible from the measurement position and caused horizontally polarised light by reflection (DOLP ranging between 0.4 – 1.0) at the water's surface. The light sources that projected light on the two top towers were not visible from the measurement position and its DOLP signal was faded when compared to other illuminated structures. Still, it showed a low signal that horizontally reflected light at the water's surface (DOLP ranging between 0.6 – 1.0). The illumination from the Universal building (both the Universal logo and the uplit wall) produced that broadest DOLP signal (DOLP ranging between 0.2 – 1.0) that horizontally polarised reflected light at the water's surface when compared to other sources at Oberbaumbrücke. The light sources of the Universal logo were somehow visible from the measurement position due to the glass structure while the light sources of the uplit wall remained not visible.

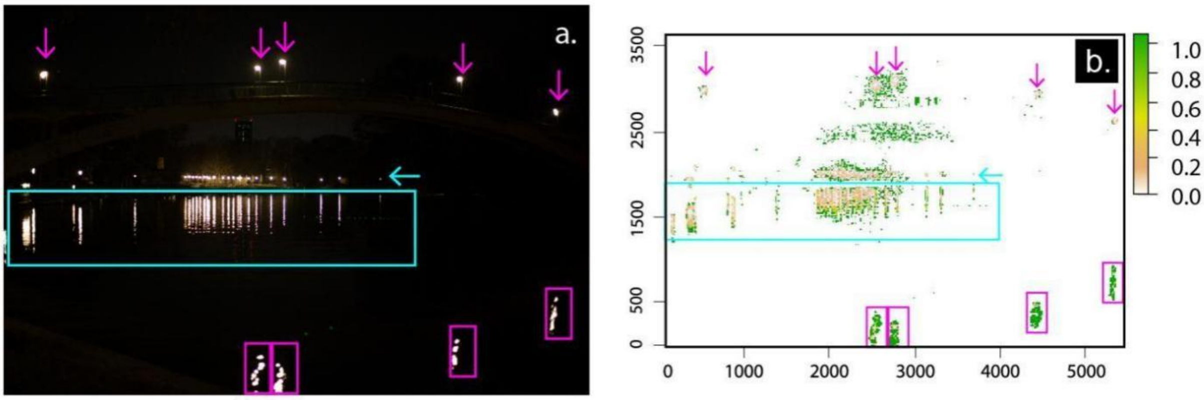

Figure 9. (a) RGB images of measurement site G — Abteibrücke with the polariser set at 90° (horizontal polarisation). (b) Calculated DOLP for each imaging pixel for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface. Source: authors' own work.

Figure 9 shows two illumination types at Abteibrücke with luminaires located at the bridge‘s pedestrian path (magenta arrows) and luminaires for pedestrian passage (cyan arrows) close to the land along the edge of the river that connects the bridge with the surroundings. Both types of pedestrian illumination showed to horizontally reflect polarised light at the water‘s surface (DOLP ranging between 0.2 – 1.0). The light sources of both illuminating scenarios were visible from the measurement position. In both scenarios, the light sources have a shield that does not properly cover the light source, making it visible from the measurement position. All measurement sites demonstrated a strong DOLP signal from illuminated surroundings, present for the blue channel, while the red channel reported a weak DOLP signal.

5.5. Discussion

The results of this study, obtained at the river Spree in Berlin, show that illuminated bridges and the illuminated urban surroundings create PLP that can mask the natural polarisation signal of natural light incident on rivers by night. Moreover, surrounding illuminated areas showed, when the 3-RGB channels were observed separately, that a strong DOLP signal was present for the blue channel while a weak DOLP signal appeared for the red channel, which could indicate short wavelengths from surrounding illumination that diffused when compared to longer wavelengths.

At the bridges, we mainly detected unshielded bridge ALAN, including individuals and groups of luminaires (e.g. luminaires for pedestrian, vehicular, or boat passage), that produce a high amount of PLP. This occurred when the head of a post-top luminaire had no shielding or the source of emission was exposed. Bridge illumination, intended for vehicular passage, at Oberbaumbrücke, was the only illumination type in which luminaires were not directed towards the water surface, making the light source not visible from the measurement position and showed a lower horizontally reflected polarised signal on the water's surface. Our measurement results were mainly in line with our anticipation that the bridge ALAN induces PLP, particularly if luminaires are unshielded. However, the result might differ if the viewing position at each bridge changes.

Surprisingly, ALAN from the surroundings produced more PLP at the water surface than ALAN from the bridges and the bridge structures, apparent in Figs. 3 – 9 (b). ALAN from buildings in the vicinity created PLP, even when the point sources were not directly visible from the measurement position. For example, the vertically illuminated or light emitted upwards of the building behind Kronprinzenbrücke in Fig. 5 (purple arrow), the TV tower far behind Monbijoubrücke in Fig. 7, the building illuminated next to Jannowitzbrücke in Fig. 7., and the two light projected towers at the top of Oberbaumbrücke in Fig. 8. PLP was induced at both illuminated bridges and pathways in the proximity of the water's surface, as well as in urban areas not immediately adjacent to the water's surface. Other illumination scenarios, apart from bridge ALAN, that created PLP included nearby indoor building illumination (Fig. 4, 6), decorative bridge lighting (Fig. 6) and floodlights in the vicinity (Fig. 6).

In the past, most studies on PLP mainly focused on artificial surfaces (e.g. concrete, paint, glass, etc.) and even on daytime illumination, showing that man-made structures can become ecological traps (studies reviewed in [37]). Recent literature has demonstrated that artificial light sources, particularly at or near roadways close to waterways, are likely to disrupt natural light at night, as asphalt roads are also reflecting ALAN of a specific polarisation direction [41,42]. PLP is a phenomenon that has been shown to attract insects by luring them away from their typical trajectories into unsuitable habitats that can lead into an ecological trap towards reproductive failure or death [28–30]. These are just some of the known behavioural consequences for aquatic polarotactic insects when man-made structures appear to be polarising water surfaces [17,19,37].

Sensory ecology on polarisation signals of aquatic insects dates back to the 1980s [40], and research on polarisation signals in the hydrosphere dates back to the 1950s [41], making the field a very recent one. In recent years it has gained the attention of the ALAN community and ecologists [14,17,26] as it has been shown to be related to behaviours in the insect organism group. In recent studies, ALAN, as a source of PLP and a potential nocturnal evolutionary trap for aquatic insects, has become a subject of concern [19,27,28]. In this study, we filled this research gap by showing that PLP also occurs in urban aquatic nightscapes, induced by luminaires close to the water's surface (e.g. bridge ALAN) that are improperly shielded and by surrounding illumination that creates light pollution due to the improper management of its light distribution.

Please note that our procedure (taking multiple images in a row) has the drawback that the water surface undergoes small changes from one image to the next (e.g. small ripples due to wind or movement of animals or boats). Therefore, the (more correct) use of all four images 0°, 45°, 90° and 135° created more noise than additional information would have been included when using all Stokes parameters [2]. However, a test run with a still water surface comparing the DOLP with all four and the reduced two Stokes parameters showed equivalent results because of the known horizontal orientation of the water surface (which cannot be easily omitted for built structures like concrete). Studies have demonstrated different approaches to measuring polarised light. Shashar et al., 1995 demonstrated an approach to polarisation sensors, imaging polarimetry with DSLR cameras and a polarising filter [42,43], and most recently, Szaz et al. 2023 used drones for imaging polarimetry [26]. In our study, the process is hindered by the removal and placement of the polarisation filter, which is not recommended. This would change if multiple cameras or a specific polarisation measurement camera [26] that can obtain all polarisation orientations in a single image would have been used. In such a case, the use of all Stokes parameters to unravel even more information is recommended.

Like sunlight, moonlight produces polarised light patterns at night (though more than six orders of magnitude weaker than sunlight) that can be perceived ideally on cloudless nights [44]. Moonlight polarisation has been described as a band of highly polarised light across the sky at a 90-degree angle from the moon that, if masked by light pollution, is likely to affect the navigation system of nocturnal animals [44,45]. In a natural pristine river, where only the moonlight may be visible starlight, lunar polarisation not only in the sky but also from reflected light is expected to be an important orientation cue, as shown in Fig. 1. If the moon polarisation signal is masked by ALAN (often multiple light sources of ALAN), then ALAN can misinform polarotactic organisms as shown in Fig. 10. Insects can thus be attracted to street lamps that emit unpolarised light, but also be misled by polarised light reflected from the water surface. Thus, PLP can interfere with optically encoded polarimetric signals and thus affect the perceptibility and interpretation of information about the night sky and adjacent aquatic habitats for polarotactic organisms.

Wetlands and waterbodies are important interfaces that aquatic insects need to detect to complete their life cycles successfully. Both fully (adults and larvae are mainly aquatic) aquatic insects and insects with terrestrial adult stages, but aquatic larvae or nymphs use horizontal polarisation of light by means of reflection to detect their habitat (reviewed in [46]). Non-biting midges, particularly female chironomids, use horizontally polarised light by reflection to detect breeding habitats [47,48]. Coleoptera, Heteroptera, Ephemeroptera and dragonflies swarm and mate over surfaces that are horizontally polarised light by reflection [34,49]. Deteriorating the natural polarisation signals can misinform specific light conditions, habitat location, detection of water surface, selection of habitats and oviposition sites, alter communication, predator and prey detection and even affect reproductive success [13,15,17,19,35,47,48].

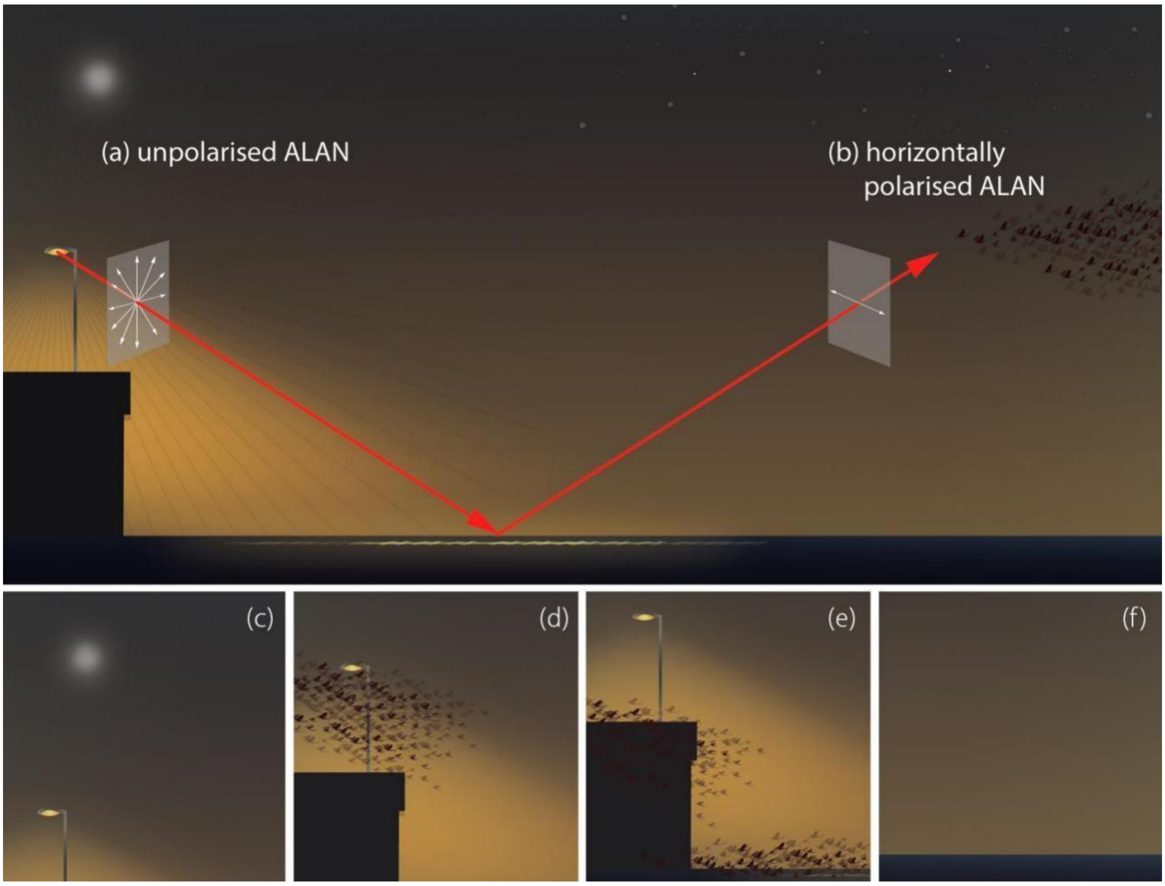

Figure. 10. (a) Any source of light emits unpolarised light, and it becomes polarised when such light comes in contact with a particle or surface. (b) Surface polarisation by means of reflection is a result of Fresnel reflection at the interface of air and water, which is when unpolarised light (in the air) reaches the surface of the water and is horizontally polarised by means of reflection. If ALAN emits unpolarised light and reaches a surface that can polarise ALAN (e.g. water, asphalt), then this phenomenon can induce reflected ALAN, which can occur at a particular angle, known as Brewster's angle, where the reflected light is fully polarised parallel to the surface it made contact with. For water, Brewster's angle occurs at 53°. When horizontally polarised ALAN occurs, (c) it can mask lunar skylight polarisation, (d) it might lure flying aquatic insects into the source of ALAN due to positive phototaxis and positive polarotaxis, potentially inducing a vacuum effect [50] at the artificial source of illumination. (e) Flying aquatic insects, potentially blinded by ALAN, while others manage to escape from the source of attraction, could be misinformed by the polarising surfaces illuminated (e.g. asphalt and the water). If the illuminated asphalt structure of the bridge manages to reach a degree of linear polarisation higher than the threshold of the flying organism, then landing can occur on the asphalt road instead of the water, which can lead to reproductive failure or death. (f) ALAN can potentially

deteriorate the movement and flux of flying organisms across a riverine system [51]. Source: authors' own work.

5.5.1. Recommendations for Future ALAN Research and Urban Lighting

PLP remains a pollutant reported only in few biological studies as polarisation is a novel entity rarely considered in night-time environments, and our knowledge of the negative implications of PLP is still very limited [14,39]. Therefore, future ALAN research should explore polarisation as a property of light, as various animals are able to perceive it. Also, polarisation should be further explored to properly assess the use and application of ALAN and materials to avoid masking the natural polarisation signal of moonlight after dusk.

Furthermore, the urban lighting design field is still centred on parameters that solely consider human visual orientation and visibility based on daytime vision and apply light in that manner across nightscapes [52]. ALAN becomes present in areas where it is not needed, as the practice still remains unaware of properties of light, such as polarisation, that are not used by humans but that are crucial for other organisms to survive.

Lastly, to protect organisms sensitive to reflected polarised light, it is recommended that the emission of luminaires shall not exceed the intended functional range, and, if possible, the water bodies should remain in darkness throughout the night by shielding solutions for luminaires [39]. This is to avoid flying aquatic insects being lured into a PLP zone, the boundaries between the bridge structure, or into the asphalt road, all unsuitable places to lay eggs [19,31,43,53].

The perception of water bodies by flying aquatic insects has been shown to be related to the properties of polarised reflected light of short wavelengths - ultraviolet (UV) radiation [15,27], blue wavelengths and green wavelengths [54]. Luminaires near water bodies could, therefore, be adapted to reduce critical wavelengths in order to mitigate the attraction of positively phototactic insects that are sensitive to UV and polarised light. However, it should be noted that many fully aquatic animals use the entire visible spectrum [39]. Consequently, protective measures such as improving luminance distribution or reducing light intensity and duration are likely to be more effective in minimising the negative impacts of polarised light on freshwater biodiversity.

5.6. Conclusions

Our study highlights bridge ALAN as a source of PLP for aquatic habitats even when the source is not directly visible from the observation point. If ALAN reaches the water's surface, this can induce polarised light that can mask natural polarisation cues, which probably can become an ecological hazard for flying aquatic insects and other polarotactic organisms sensitive to changes in polarised light. Our literature scan unravels a large knowledge gap on PLP and ALAN in the context of aquatic systems. More research on this optical pollutant is required to aid professionals in the lighting field and representatives of the lighting industry in addressing the United Nations Sustainable Development Goal (SDG14) [55] for the protection of aquatic life and habitats. Moreover, to raise awareness on PLP with the overall goal of avoiding emissions of ALAN on waterbodies and to consider less light in the path of flying insects.

While our pilot study is limited to single-point measurements, more comprehensive measurements across different environments and urban gradients are required. This can be achieved with better imaging tools [26] from aerial vehicles [17] or from boats [38]. While our knowledge of ALAN as a pollutant has increased, the behavioural responses of organisms sensitive to polarised light still need more research to be better and properly understood.

5.7. Appendix for Chapter 5

Electromagnetic radiation is a transverse wave where the electromagnetic field oscillates perpendicular to the wave's propagation direction. Thus, this oscillation can be directional as well, which is called polarisation. Light is unpolarised when the electric field has equal amplitude in all directions, the direction of the electric field oscillates equally in all spatial directions and randomly in time (i.e. with random phase), as shown in Fig. S1(a) (left). If the oscillation of the electric field aligns along a single plane, then it is defined as linearly polarised, as shown in Fig. S1a (right), as an example, after passing through a linear polariser, resulting in linear polarisation in the y-axis. Unpolarised light can become polarised when it is reflected or transmitted at surfaces that have a preference for reflecting or transmitting polarised light due to their material properties [2]. When the electric field oscillates perpendicular to the incidence plane (which is confusingly not the material surface plane itself but the normal plane in the incidence direction of the light beam), this is called s-polarisation. When the electric field oscillates parallel with respect to the incidence plane, then it is known as p-polarisation. This is illustrated in Fig. S1 (b,c).

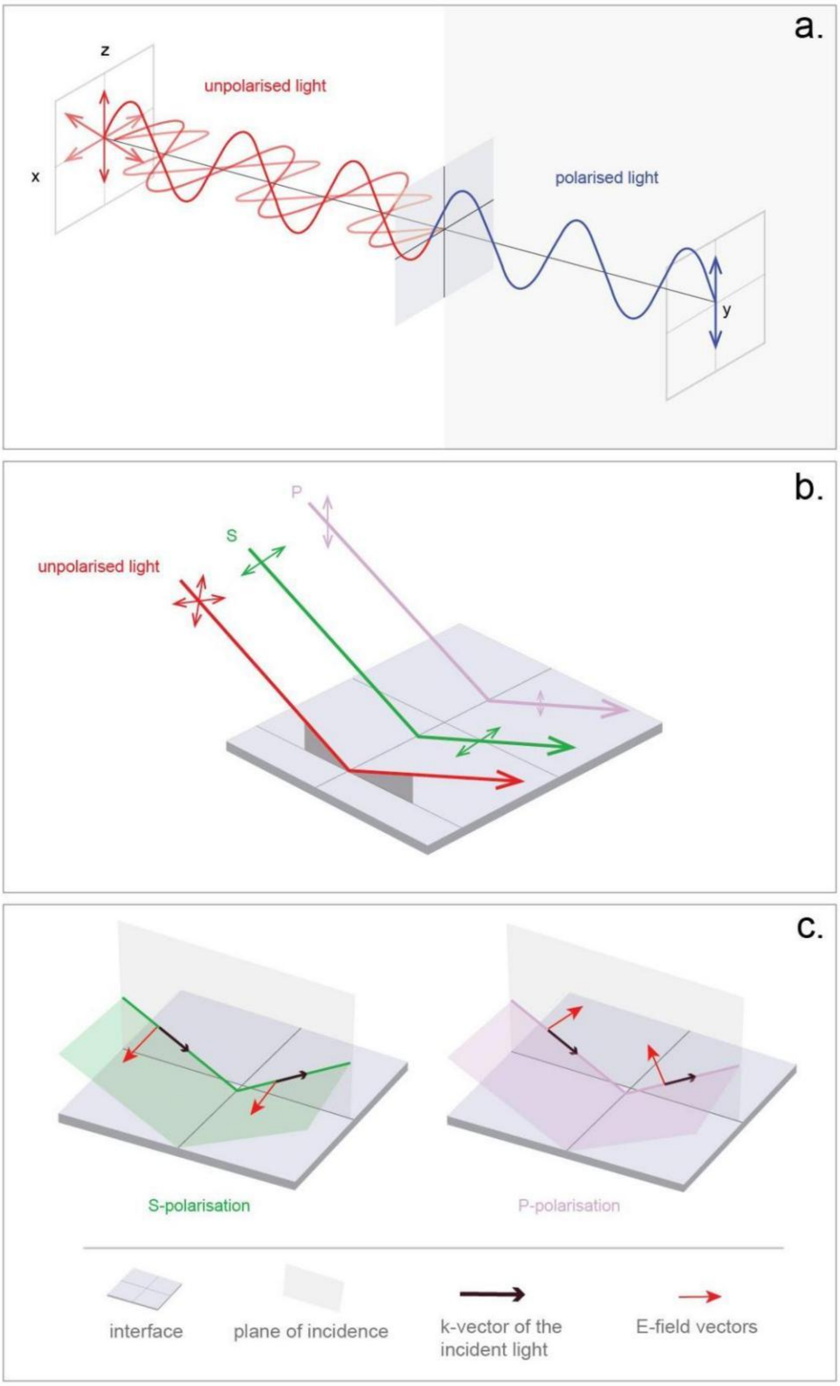

Figure A1. (a) Unpolarised (red, on the left) and linearly polarised light reflected after passing through a polariser (blue, to the right). (b,c) Comparison of reflected s- (green) and p- (purple) polarised beams at the surface. S-polarisation (in green) polarises its beam parallel to the surface and has the electric field oscillating perpendicular to the water (S for senkrecht/perpendicular to the incidence plane). P-polarisation (in purple) polarises its beam perpendicular to the surface and has the electric field oscillating perpendicular to the water surface (P for parallel/parallel to the incidence plane). Source: author's own work and modified from (Foster et al., 2018) [2].

When an incident ray of light travels through air and reaches the water, light can change by reflectance, transmission, or both at the boundary of these two materials (as shown in Fig.S2, with incident (θ_I) reflected (θ_R), and transmitted (θt) angles to the normal line (the dashed line) perpendicular (90° angle) to the surface at the point of incidence, as shown in Fig. S1. Incident and reflected angles are equal:

$\theta_I = \theta_R$ (Eq-S1),

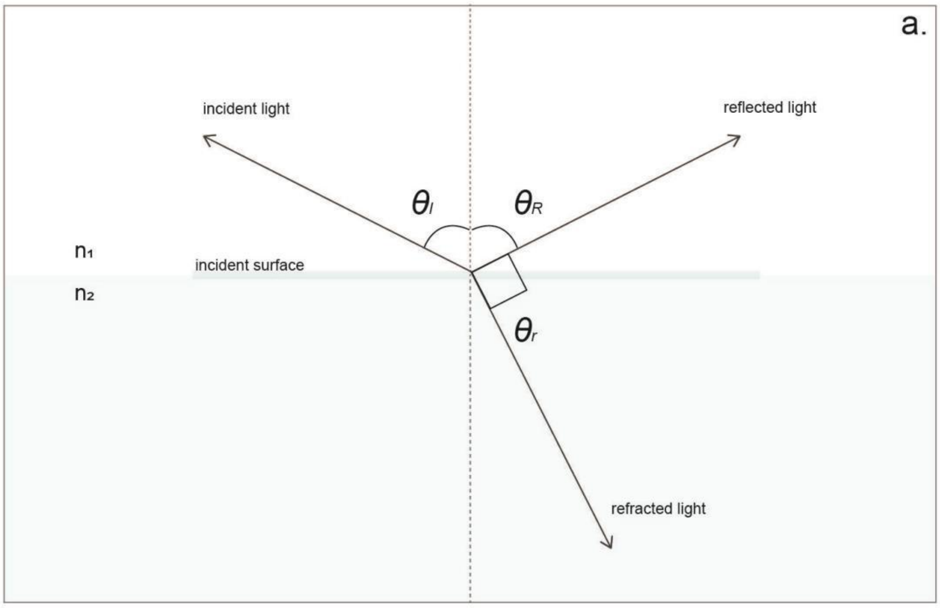

Figure A2. Overview of incident light being polarised when travelling from air and striking at the water, in which n1 is air and indicates the index of refraction of the incident medium, n2 is water and indicates the index of refraction of the striking medium, and the angle of incidence from the normal (dashed line).

The angle of refraction at this boundary is governed by the refractive indices of the involved materials. The index of refraction (*n*) is a property that indicates the ratio of the speed of light in a vacuum to the speed of light in the interested medium.

Snell's law:

$n_1 \sin \theta_I = n_{12} \sin \theta_{tR}$ (Eq-S2),

determines the angle of refraction. Here, the first material is air (n_1≈1) and the second material is water (n_2≈1.33). This results in what is called Snell's window, with light incident almost horizontally (θ_I =90°) being refracted to an angle of 48.7°, which means that the full hemisphere

with a 180° opening angle above the water is collapsed into a cone with an opening angle of only 97.4° underwater (see, e.g. Fig. 3 a,b in Hölker et al. 2023). Depending on the angle of incidence and the linear polarisation direction of the light (s- or p polarisation), the reflection coefficient R will differ following the Fresnel equations (Eq, 3 and 4), with the resulting coefficients shown in Fig. S3.

$$R_{\mathrm{s}} = \left|\frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \cos\theta_{\mathrm{t}}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \cos\theta_{\mathrm{t}}}\right|^2 = \left|\frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2}}\right|^2,$$

$$R_{\mathrm{p}} = \left|\frac{n_1 \cos\theta_{\mathrm{t}} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \cos\theta_{\mathrm{t}} + n_2 \cos\theta_{\mathrm{i}}}\right|^2 = \left|\frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} + n_2 \cos\theta_{\mathrm{i}}}\right|^2.$$

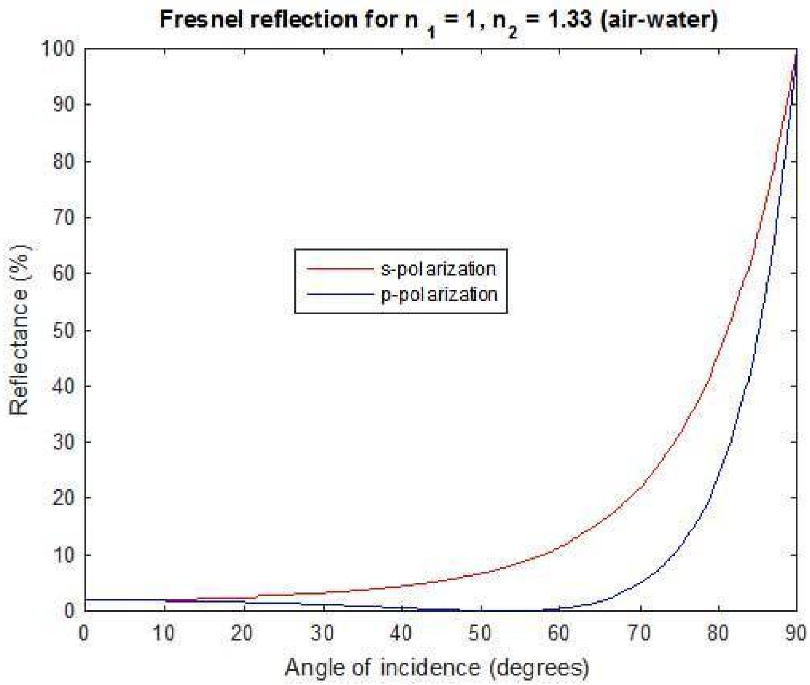

Figure A3. Plot of the reflection coefficients as a function of angle of incidence, where total polarisation of reflected light (s-polarisation) occurs at approximately 53°.

If unpolarised light is incident at the water surface, the reflected light is partially polarised for most incident angles. For example, for light incident from the normal (i.e. 90° from the water surface), both polarisations are reflected equally, resulting again in unpolarised light. Maximum polarisation is reached for Brewster's angle (θ_B)

$$tan\,\theta_B = \frac{n_2}{n_1} \qquad \text{(Eq-S5)}$$

$$\theta_p = 53.06° \qquad \text{(Eq-S6)}$$

Table A1. Supplementary table on the position at which measurements were taken at each measurement site.

Measurement site	Bridges	Latitude, Longitude	Time
A	Moltkebrücke	52° 31' 17.44" N, 13° 22' 6.18" E	19:21 - 19:35
B	Kronprinzenbrücke	52° 31' 21.37" N, 13° 22' 27.44" E	19:42 - 19:47
C	Monbijou	52° 31' 20.7" N 13° 23' 36.2" E	20:06 - 20:12
D	Friedrichsbrücke	52° 31' 16.3" N 13° 23' 57.7" E	20:15 - 20:20
E	Jannowitzbrücke	52° 30' 52.3" N, 13° 24' 59.9" E	20:34 - 20:39
F	Oberbaumbrücke	52° 30' 09.6" N, 13° 26' 36.1"E	20:56 - 21:17
G	Abteibrücke	52° 29' 12.0" N, 13° 28' 47.10" E	21:39 - 21:33

To mathematically represent light polarisation, the stokes parameters are often used where I will represent the total light intensity and I_α the light intensity when its beam passes through a polarisor with a defined transmission axis (e.g. S_0, S_1, S_2, S_3) in which,

$$S_0 = I$$
$$S_1 = I_0 - I_{90}$$
$$S_2 = I_{45} - I_{135}$$
$$S_3 = I_{left} - I_{right}$$

S_1 and S_2 are often used for linear polarisation.

5.8. References for Chapter 5

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Chapter 6: General Discussion

The awareness of LP is becoming a knowledge of interest across disciplines thanks to the efforts of ALAN researchers, who have clarified an imperative change in urban lighting design approaches that must shift to protect the nightscapes of natural environments [1,2]. In recent years, more studies have highlighted the importance of reducing LP, particularly for inland waters [3,4], as they cover freshwater habitats such as rivers, streams, ponds, lakes, and wetlands. Although they make up only 1% of the Earth's surface, they act as biodiversity hotspots supporting approximately 10% of all known species and around a third of freshwater-adapted vertebrate species [5]. Globally, inland waters have encountered steadily increasing difficulties due to anthropogenic stressors [6,7]. The irradiance from ALAN and its LP signal has become a major pollutant that can trespass the surface of waters and become present in the water column of waterways [3,8], interfering with the optical signal of natural light at night (e.g. moonlight) that can consequently affect the behaviours of species in aquatic systems [9–11].

This thesis emphasizes the urgent need for transdisciplinary collaborative strategies between experts involved in the research, practice, production inputs, and policy-making and planning of light (in Chapter 2). As a solution to the existing communication and knowledge gap between the experts involved, the intent was to create awareness of the different disciplines and skills and to propose the first steps to establish communication when interests might differ, which can incite the discussion on a collective goal towards reducing LP.

Moreover, this thesis also addressed the relevant knowledge to transfer between fields that can aid shifting from current lighting practice perspectives and approaches, solely focused on human day-time vision for nightscapes, towards practices inclusive of organism groups and natural environments. The most relevant parameters of artificial lighting were investigated to evaluate impacts on different organism groups that ALAN researchers should use in their research studies and by lighting professionals in their day-to-day practice were investigated. The aim was to create a knowledge blueprint that can facilitate an overview of the problem of LP and gather results on six organism groups with information tailored for lighting practitioners and transferable to the lighting practice. The aim was to minimize the negative effects without turning off lighting and to propose a translation of ALAN research for the lighting practice addressing environmental concerns (Chapter 3).

Furthermore, this thesis also investigated ALAN along a river transect. The aim was to identify different types of potential light barriers at illuminated bridges to estimate the potential effect of two light barrier types on fish migration behaviour and to propose a conceptual framework based on a literature review for two migratory fish with contrasting life histories — Atlantic salmon smolts (*S. salar*) and European silver eel (*A. anguilla*) (Chapter 4).

Additionally, the reflection polarisation patterns of ALAN from illuminated bridges crossing a river at potential flying path positions of polarotactic aquatic insects were investigated to propose its potential implications for aquatic insects (Chapter 5).

6.1. Key findings

Through this doctoral research project, I found that LP and its environmental impact are complex matters with knowledge gaps, communication and light measuring challenges that require considering a lighting practice, often needing more evidence-based approaches, and urgently needing sustainable urban lighting solutions.

I found that to address the knowledge gap, the fields of ALAN research and the lighting practice must collaborate. However, this challenge calls for not only measuring light as a potential pollutant and exhibiting the evidence; it is a challenge that requires translating the knowledge into a common lingua franca that can aid the experts of both disciplines in discussing current approaches and exchanging potential solutions.

In **Chapter 2**, I provided an overview of the perspectives of the fields involved, the challenges and the reasons behind a lighting practice that continues to apply artificial illumination that pollutes despite the evidence gathered by ALAN researchers. A dual perspective of the night was developed to describe (i) outdoor illumination evolving simultaneously with ALAN research, (ii) scientific findings that did not reach the lighting practice, and (iii) the need for collaboration to speed efforts that address environmental concerns and meet the evolving demands to reduce LP across nightscapes.

Moreover, a discussion was held with representatives of ALAN research and the lighting practice to propose collaborative initiatives, highlighting conferences as potential arenas to establish collaboration.

Furthermore, I proposed the Urban Lighting Research Transdisciplinary Framework (ULRTF) to define the stakeholders involved and a four-step process to facilitate collaboration among experts from the practice, production, research, policy, and planning of light and lighting. I found that the awareness of perspectives can aid the domains.

In **Chapter 3**, a collaboration between representatives of ALAN research and the lighting practice was set to translate the parameters of artificial illumination used in research and the lighting practice and the parameters in artificial illumination that can induce a negative outcome on six organism groups. 1417 studies on the exposure of ALAN for six different categories of organism groups were systematically reviewed. I presented the evidence reported in the 216 studies, which varied in their categories, reported responses, the applied physical properties of ALAN used in each study, and in the type of light source integrated. Via this collaboration, relevant parameters of artificial lighting for evaluating the impacts on different groups were defined.

I found that varied of the reported studies differed on the studied organism group. Birds, with 76 reported studies, was the most studied group compared to the other five organism groups, representing approximately 35% of the total studies. Arthropods, insects and spiders, as an organism group, with 43 reported studies out of 216, constituted the second most studied group and represented approximately 20% of the total studies. The organism group of non-human mammals, including bats, primates, rodents, and marsupials, with 30 studies reported out of 216, represented approximately 14% of the total studies. Plants represented about 8.8% of the total, with19 studies. Amphibians represented approximately 5.6% of the total with 12 studies, and reptiles represented approximately 3.7 % of the total studies with eight studies. With this, it was found that most ALAN research is currently focused on the impact of ALAN on terrestrial organisms such as birds.

Nineteen studies on the impact of ALAN on plants showed that ALAN can boost growth and increase the foliage, stems, density and cover of plants. Also, ALAN was found to disrupt varied plant processes, including an earlier initiation of budburst, an accelerated and heightened flowering process, delayed flowering, altered plant-herbivore interactions, modified leaf litter decomposition, and disrupted pollen transport.

Forty-three studies on the impact of ALAN on arthropods, insects and spiders highlighted behavioural and physiological responses to ALAN. The behaviours impacted orientation, navigation, resource finding, foraging, courtship, reproductive behaviour, species interactions, and predator avoidance. Most studies demonstrated a positive phototactic response (attraction to light). Additionally, one study suggested that horizontally polarized light intensity may interact with structures, inducing attraction to illuminated areas. Nevertheless, some studies indicate negative phototactic responses (avoidance to light).

Twenty-eight studies on the impact of ALAN on fish revealed distinct responses. Fish demonstrated either positive or negative phototaxis (attraction or avoidance) of illuminated waters in fish species such as lance, three-spined stickleback, Pacific herring, great sculpin, and soft sculpin with positive phototaxis. At the same time, European eel, American eel, vendace, and bogues presented negative phototaxis and avoided illuminated water sections. Changes in dispersal, movement, and migration patterns were evident, including delayed fry dispersal and disrupted diurnal patterns in Atlantic salmon. One study suggested using artificial light to guide eels into safer waters. Fish exposed to illuminated waters showed alterations in foraging behaviour, habitat use, and the arrangement of invertebrate prey at specific locations. Modified predator-prey interactions were observed in zooplanktivorous juvenile rudd and their prey. Fish exposed to ALAN experienced suppressed melatonin production in Eurasian perch, roach, golden rabbitfish, and zebrafish. Atlantic salmon displayed low cortisol rates, indicating altered stress perception, while juvenile bonefish exhibited elevated blood glucose concentrations. Roach and Eurasian perch exposed to ALAN demonstrated reduced blood concentrations of sex steroids and lowered gonadotropin mRNA expression. Larvae surgeonfish showed reduced thyroid hormone levels. Regarding growth rhythms, two studies reported changes, with larval Nile tilapia displaying low growth and feed conversion efficiency and Atlantic salmon showing increased growth and body weight, potentially reducing the incidence of sexual maturation. Although one study found no significant impact on the growth rate of Atlantic salmon, it revealed accelerated oocyte reabsorption, suggesting a potential alteration in their fundamental growth pattern.

Twelve studies on the impact of ALAN on amphibians demonstrated that ALAN disrupts nocturnal aquatic and terrestrial habitats. ALAN was found to diminish the resilience of amphibians and elevate susceptibility to other human-induced stressors. The effects of ALAN on amphibians‘ behaviour included shifts in shelter preferences, attraction toward urban edges leading to altered habitat choices, modified vocalization calls, adjusted detection and consumption of prey, changes in attempts to capture prey, heightened activity levels, and impacts on mate selection and reproductive success. Meanwhile, physiological responses to ALAN exposure in amphibians involve diminished growth and heightened production levels of neutrophils, alongside altered ratios of neutrophils to lymphocytes.

Eight articles highlighted the impact of ALAN on reptiles. ALAN was observed to attract reptiles away from dark areas and disrupt their typical nocturnal behaviours. The emergence of reptiles in illuminated areas at night demonstrated that wavelength composition can influence the visual sensitivities of reptiles, particularly luminaires with broader SPD. Moorish geckos foraged in illuminated areas and presented increased foraging activity. Four studies were focused on turtles and the impact of ALAN on coastlines and turtle nesting sites. ALAN was shown to draw turtles away from nesting sites into illuminated shore areas, altering their typical nocturnal trajectories and hatching behaviour. Both terrestrial and aquatic reptiles were shown to have behavioural changes when exposed to ALAN.

Seventy-six articles on the impact of ALAN on birds showed varied effects that altered bird behaviour during flight, migration, rest, and breeding. Physiological changes reported in birds exposed to ALAN include altered reproduction, development, body mass, and hormone levels. Disorientation during flight, altered foraging and active patterns, changes in singing timing, and altered sleep were some of the behavioural responses birds demonstrated when exposed to ALAN. Meanwhile, the physiological responses included advanced reproductive maturity, altered gonadal development, and hormonal changes.

Eleven studies on the impact of ALAN on non-human mammals, including bats, primates, rodents, and marsupials exhibited varied responses. Bats were shown attracted to illuminated areas, with altered foraging behaviours, while some bats avoided illuminated areas and responded with altered flight paths when exposed to ALAN. Primates such as female Japanese monkeys and gray mouse lemurs showed suppressed melatonin, delayed nocturnal emergence and changed core temperature at night under ALAN. Other responses in primates include altered use of space and increased testes size. Marsupials including Tammar wallabies, showed increased foraging activity and lowered melatonin levels when exposed to ALAN. However wombats showed no changes in behaviour when exposed to ALAN. The impact of ALAN on non-human mammals varied across the reported species, however it showed that ALAN can affect the behaviour and physiology.

The studies exhibited an unstandardized report of physical properties and quantities of light, which varied in terminologies across studies. At least one physical property of ALAN (e.g. illuminance in lux) was reported across all studies and taxa. The physical quantity of light used to describe light intensity across studies was found to be illuminance across all taxa. In contrast, irradiance was found in studies that concerned fish, birds, and plants. Luminance and radiance were found to be uncommon physical quantities. SPD and CCT were found to be the physical quantities reported in almost all taxa. The continuous exposure of ALAN from dusk to dawn was found to be reported in most studies across taxa, while the periodic exposure of ALAN was found to be considered only in a few studies. For the organism group of birds, flicker was commonly reported in various articles as a component to consider in light that can potentially alter avian responses. Moreover, in Chapter 3, it was also found that the most studied organism group — birds were studied when they were exposed to direct ALAN and LEDs. Most studies across all oraganism groups were exposed to LEDs (64 studies), followed by HPS (21 studies) and FLs (15 studies). It was also found that only one study reported an exposure to natural light conditions, such as moonlight at night, which was compared to the exposure to artificial illumination —LEDs. When studies compared the exposure of two light sources, FL and LEDs were the reported light sources. A total of 18 studies were found to compare the exposure to different light sources. Approximately 8.3% of the studies compared two different light sources.

Furthermore, with this systematic review, I found that the communication gap exists as there is no common language on ecology or environmental conservation between the fields involved. I proposed a communication framework and knowledge infrastructure diagram to define a ceiling and a foundation of knowledge needed on the flow of information between both domains to create a common language between the experts.

In **Chapter 4**, I presented evidence of LP, which was induced by surrounding and bridge illumination, along a transect of a river with seven crossing illuminated bridges. At the measured bridges light barriers were created. At the seven bridges, lower illuminance values were found under the bridges, except for one, Moltkebrücke. Moltkebrücke presented high horizontal illuminance values due to one luminaire located at the underpath of the bridge. The lowest illuminance, was approximately 120 times darker under the bridge when compared to Moltkebrücke, which occurred at Jannowitzbrücke due to the width and height of the bridge‘s structure. In addition, continuous sky radiance measurements were evidenced and revealed a variation from the urban zone to the peri-urban area. The sky radiance maps of the Moltkebrücke (bright) and Jannowitzbrücke (dark) showed light contrasting scenarios occuring under the bridge. These two scenarios showed that illuminated bridges and their artificially induced light scenarios (bright/dark) could imply a potential light barrier for a migrating fish. Based on these findings, a conceptual model on illuminated bridges as potential light barriers was created to determine the light scenarios that could affect migratory fish. This conceptual model was centred on brightness parameter changes (light levels) detected by the SQM when obtaining measurements. A light barrier was characterized as transitioning from dark to bright (a positive step function) or bright to dark (a negative step function) when passing under a bridge. This framework was then linked to the potential behavioural responses of migrating fish. The bridge‘s location and the LP context could determine that an illuminated bridge and its surrounding illumination may form a potential light barrier with multiple negative or positive step functions. However, real-world bridge illumination types will vary as they depend on bridge geometry, light levels, surrounding environment, skyglow, roadway illumination, architectural elements in the surroundings and the bridge structure, ALAN sources in the vicinity, etc.

I found that the interpretation of bridge illumination types could aid to associate the potential impact of light as a barrier for migrating organisms. ALAN could induce spatial resistance, leading to increased time and energy during migration at the illuminated bridges, potentially threatening natural reproductive success for migratory fish. Despite the current literature on the impact of ALAN on fish migration, it remains uncertain whether these light barriers induced by bridge and surrounding illumination serve as a behavioural barriers disrupting fish dispersal, movement, and migration. The response of fish to different light step functions is likely to depend on their specific life history.

The literature reviewed (on Chapter 4) on migratory fish presented that Salmon smolts and eels, for instance, migrate through various connected aquatic systems, each exhibiting distinct migration strategies and combinations of behavioural and reproductive traits. Salmon, as catadromous species, migrate from the sea to freshwater during the day or night in spring and autumn. Their nocturnal migration is typically closer to the water surface, and positive phototaxis has been observed near illuminated waters [10]. In contrast, eels, being anadromous, spend their adult life in freshwater and return to the sea for reproduction. They often migrate during fall, winter, or rainy events, frequently at night, with low light levels. Eels tend to swim in deeper parts of the water column and have been observed avoiding illuminated waters during migration [11].

In **Chapter 5**, I presented evidence on the calculated degree of linear polarisation that horizontally polarised at the water's surface by reflection. For most bridges, I found that illumination types for pedestrian, boat, and vehicular passage horizontally polarised light by reflection at the water's surface. Also, most luminaires intended for these three illumination types were visible from the measurement position site. Moreover, decorative lighting from the bridge (e.g. Kronprinzenbrücke illuminated structure) and surroundings (e.g. TV tower visible from Monbijoubrücke) was found to horizontally polarised light by reflection at the water's surface. For instance, for decorative lighting on the bridge Kronprinzenbrücke, the luminaire and light source were visible from the measurement site; however, for Monbijoubrücke, the luminaire and light sources from the surrounding decorative lighting of the TV tower were not visible from the measurement site. Furthermore, surrounding illumination from buildings in the vicinity is also horizontally polarised by reflection at the water's surface of most bridges.

In **Chapters 4 and 5**, I found that artificial illumination is an intricate pollutant to measure when occuring in urban aquatic systems as the water interface, or what occurs to light when it reaches the water surface, must be considered. Often, LP is measured above Earth's grounds via satellite imagery or on land close to luminaires. However, little attention is given to what occurs to light when it enters the water column or as it reaches the water's surface. I found that understanding physics and awareness of light beyond the areas is required to perform proper light measurements to describe what occurs at the frontiers of land and water. **Chapters 4 and 5** showed that bridge illumination, inducing LP and PLP, is often overlooked when it concerns aquatic systems. More attention needs to be given to ALAN particularly when it reaches waterways, aquatic habitats as it can affect its biodiversity.

6.2. Transdisciplinary lighting research and practice for the future of cities at night

To frame a complex problem (ALAN, LP, ELP, PLP) within a complex system (with experts from different fields and perspectives), varied communication frameworks, transdisciplinary research and collaborations between ALAN researchers and lighting practitioners are needed. Transdisciplinarity was used as a problem-driven and solution-oriented field to consolidate knowledge and methodologies among the two fields [12].It is an agenda suggested by ALAN researchers in 2010 [13] to provide meaning to diverse viewpoints, to meet the environmental needs and demands of modern societies, and to instigate information flow between the fields involved to reduce LP. Polh (2005) describes that the synergy between the natural and social sciences has to be contextualised within a framework of a specific environmental issue in need of investigation as collaboration will not evolve in a context-free space [14], implying that in order to solve the problem of LP, the communication between the experts needs to be resolved to mitigate the problem.

The existing research on ALAN and the work by Rich and Longcore (2013) [15], Gaston et al. (2013) [16], Schroer & Hölker (2017)[17], Grubisic et al. (2019)[18], Hölker et al. (2023)[4], Sanders et al. (2021)[19], must be apprehended by the lighting practice as it has set the grounds for ecological knowledge on the consequences when artificial light is not carefully designed. Their work emphasizes the importance of gathering, reviewing and translating scientific findings into practical content and that the responsibility of lighting is one not to take lightly. Research findings must be understood by many outside the academic realm so that the requested changes are implemented. Rethinking the human-centric approach in the urban lighting practice, improving communication between ALAN researchers and lighting practitioners, creating transferable knowledge between the fields and establishing relevant environmental parameters are some of the challenges to address via communication frameworks. In this thesis, the Urban Lighting Research Transdisciplinary Framework (ULRTF) (see Section 2.6.) and the communication framework and knowledge infrastructure scheme (see Section 3.9.) comprised the different frameworks to aid the shift from disciplinary thinking into transdisciplinary perspectives — to think beyond the boundaries of individual disciplines to aid solve challenges related to sustainable planning.

The proposed communication frameworks and collaborative efforts (e.g., systematic review in Chapter 3) mark a new chapter in transdisciplinary communications between the fields. However, more effort is still needed from both fields to integrate ecological awareness into the education of lighting professionals so that a shift of approaches starts from the formation years of a lighting designer. Transdisciplinarity should aim for standardised parameters in practice and when performing measurements and that night-time illumination does not harm organism groups.

6.2.1 Standardization of relevant parameters of artificial lighting

In Chapter 3, the 216 studies that were systematically reviewed presented an unstandardized approach when defining the pollutant - ALAN, particularly the exposed properties, quantities, or parameters used to diagnose a response in the behaviour or physiology of an organism. The evidence gathered by ALAN researchers has helped comprehend how complex ALAN is as a pollutant. However, the need for standardized physical light parameters for both ALAN research and the lighting practice can facilitate the understanding of findings by lighting practitioners. Standardizing physical light parameters is essential to align a common language between the fields of ALAN research and the lighting practice, which can aid in transferring the current lighting approaches causing LP. For instance, this can aid in assessing a take-away message on the physical light quantities and parameters to consider when illuminating if a study presents a complex finding.

Moreover, the evidence gathered by ALAN researchers indicates that a paradigm shift must happen in the lighting approaches currently used in urban lighting practice. However, more effort is required on how scientific content is transferred. Standardizing lighting parameters can rather become a common ground where the two fields can meet to transfer relevant knowledge. Standardizing physical parameters implies providing sufficient information on the applied light sources used in a study instead of addressing it as ALAN. Another example includes providing sufficient information on the used wavelength when describing the SPD. Properly informing the light component of studies can adequately inform the urban lighting practice of the effects of a determined light source used and if it needs to be avoided.

The physical quantity of light used to describe light intensity across studies was found to be illuminance across all taxa. It was also found that most studies reported a response induced in behaviour or physiology when exposed to one or multiple properties of ALAN at night. Most studies explored the potential impacts of LEDs (solid-state lighting) across organisms and have understood the shift from conventional lighting (e.g., incandescent lamps, tungsten halogen lamps, and high-pressure mercury vapour) to solid-state lighting as a total of 64 studies reported exposing an organism to lighting conditions with LEDs.

6.2.2. The importance of measuring LP in aquatic environments

Today, aquatic systems are under the pressure of multiple stressors [4–6], and artificial illumination has become one that can alter the optical conditions of waterbodies by night [3,4]. Few studies have presented quantitative measurements on how freshwater systems are affected by ALAN [3,8,20,21]. In these systems, the turbidity of the water plays an important role as it can determine how light is absorbed towards the water column. It has been shown that longer wavelengths scatter less into the water column of clear waters when compared to shorter wavelengths, which is a factor dependent on the irradiance level (light level) above the water, the optical properties of the water that typically vary seasonally, and the depth of the waterbody [22,23]. Another condition to consider in aquatic systems involves light polarisation, as the presence of ALAN can become polarised by reflection at the water's surface or asphalt structures near the water. This phenomenon can potentially induce PLP in aquatic habitats and affect the behaviour of organisms that rely on natural light/dark cycles [24,25].

Light field measurements are often performed using SQM, illuminance meters, digital cameras, and VIIRS/DNB satellite data [3,26]. The water column's light profile of freshwater systems by night is still largely unexplored and remains an important scenario to quantify light at night.

In Chapter 4, ALAN was measured as spatially resolved radiance over the complete hemisphere with a digital camera and using multispectral (RGB) all-sky images at the water's surface from a boat—one single measurement captured light field information from all directions and on three spectral bands. Chapters 4 and 5 exhibited a riverine system exposed to sky radiance variations (skyglow), ALAN gradients, steep light contrasts, and PLP due to surrounding illumination and Illuminated bridges. DSLR cameras and multispectral (RGB) all-sky images helped understand the light field of the bridges. This method can serve lighting practitioners as a tool to measure the light field to define luminaires that induce unnecessary light emissions, avoid illuminating areas that should remain at low levels at night, and detect point sources that require shielding. Measuring the light profile of inland waters by night could help understand potential consequences induced by ALAN, such as light barriers, for aquatic species.

6.2.3. The importance of ALAN studies on migrating aquatic species

Studies on aquatic species exposed to ALAN have revealed that behaviours involving movement, dispersal, distribution and migration have been shown to be detrimentally affected when waters are illuminated at night [9–11,27,28]. The movement of individuals and species in space and time is crucial in maintaining ecological balance. It can affect species distribution, dispersal, species interactions, prey and predator interactions, and species richness [29–31]. As ALAN can disrupt the natural movement of aquatic species, other behaviours, such as foraging and breeding, which are essential for the survival of aquatic species, can alter their fitness and survival [32,33]. Therefore, more studies are needed to understand the potential impact of ALAN from structures such as bridges that can potentially emit ALAN into aquatic realms.

6.3. Perspectives on the future of sustainable urban lighting design

The reduction of LP to protect the night skies across environments has been closely linked with the terms attributed to less applied light, such as responsible outdoor illumination, sustainable urban lighting design, and environmentally friendly lighting [34-37]. These terms are often used to describe when illumination is used responsibly considering the environment (surroundings), energy-efficient (costs), and conductive of human well-being [38].Dark Sky and the Illuminating Engineering Society (IES) have developed five lighting principles for responsible outdoor lighting, describing how artificial illumination should be:
(i) useful — with purpose while considering how the light might impact the area, habitat and

their inhabiting flora and fauna;
(ii) targeted — with the help of shields and careful aiming to target the direction at which the emission of light is aimed so it reaches the areas needed to illuminate;
(iii) with low level and no brighter than necessary;
(iv) controlled — with the use of timers, motion detectors, dimmed when possible and turned off when not needed; and
(v) warm-coloured — by limiting the short wavelengths to the least amount possible with no ultraviolet radiation [34].

Moreover, ALAN researchers and lighting practitioners have raised different arguments and evidence, contributing to a new perspective on the future of nightscapes. For instance, Schroer et al. [36] demonstrated that sustainable and responsible lighting also involves improving luminaire design with appropriate shielding to plan outdoor illumination properly at night. Zielinska-Dabkowska mentions that the shift to solid-state lighting and the awareness of unintentional harm induced to natural environments caused by LP led towards a new methodology addressed as Dark Infrastructure, which implies designing considering darkness and implementing artificial illumination only added to support nocturnal placemarking [39]. ALAN researchers have pleaded for a dark infrastructure by night and a green and blue infrastructure by day as a conservation strategy that should be accounted for night-time. This plea requests policies that reduce ALAN, which can help reduce the stress night-time illumination imposes on ecosystems [40,41]. Sordello et al. suggest a four-step-process towards implementing a dark infrastructure that can be considered for light planning projects [40]. Edensor & Dunn suggest that the engagement with dark skies and the sense of wonder and awe has been lost over the years [42]. Stone suggests that assigning contemporary values to darkness requires a broad understanding of LP and its consequences to articulate the night as an environmental value [43]. Responsible Outdoor Lighting at Night (ROLAN) Manifesto addresses to lighting professionals a list of ten principles, recalling the five Dark Sky principles for responsible outdoor lighting and mentioning the importance of considering United Nations Sustainable Development Goals as crucial efforts to be considered in current and future lighting practices, as a written declaration of the intentions that lighting practitioners should consider to reduce LP and towards sustainable approaches in lighting design [44]. However, a more in-depth description shall be attributed to the future of lighting design considering environmental conservation by injecting concepts of the balanced co-existence of humans and other organisms and the natural environment, which needs to be improved in the current lighting practice.

I find it crucial to extend this definition by adding that sustainable lighting design shall also refer to the responsible practice of designing lighting systems and master plans that minimize light emissions into the sky, greeneries, floodplains, and waterbodies.

Moreover, sustainable lighting design shall also prioritize the use of artificial illumination to render user paths visible at night by using the lowest emission possible, with shielded luminaires that direct their emission into the pathways and roads of passage, limiting spectral distributions rich in short wavelengths, avoiding ultraviolet radiance emission, and with night-time curfew based on user numbers when it concerns to outdoor illumination. The design of light at night should balance the need for adequate and necessary illumination by identifying the type of light source used and the physical quantities of artificial illumination that create lighting conditions that preserve the night and are favourable for people's needs.

Furthermore, to this definition, natural lighting conditions (e.g. lunar phases) shall be considered as well, particularly when illumination is proximate to freshwater systems where moonlight serves as a signal that can condition the behaviour of certain species at night.

Additionally, weather and atmosphere shall be considered with lowered light emissions during cloudy nights or in the presence of snow as it can alter the night sky's brightness.

6.4. Suggestions for future ALAN research

Future collaborative efforts between ALAN researchers and lighting practitioners should consider using communication strategies and frameworks to transfer ecological knowledge as required awareness for real-world projects efficiently. Collaborative efforts can also aid ALAN research in gaining insights into technological changes and lighting approaches that could be measured and tested before being applied to real-world projects.

Future ALAN studies should consider the radiometric and photometric characterization of the artificial light sources used based on the International System (SI) of units. Hence, research findings are easy to transfer into practical content for the lighting practice.

Moreover, as inland waters remain understudied, particularly when exposed to ALAN, the underwater light field must be considered for future quantitative studies on ALAN. Quantitative data of all potential forms of ALAN is currently needed to properly transfer the data as knowledge for the lighting practice so the dangers of illuminating waters are avoided.

Furthermore, as few studies compared natural light conditions (e.g. moonlight) with ALAN exposure, it is suggested that future ALAN research consider comparing behavioural and physiological responses across taxa when exposed to both — artificial and natural light scenarios.

Additionally, future studies on the impact of ALAN and PLP should consider aquatic organisms as their realm, and inhabiting species still need to be studied.

6.5. Suggestions for future sustainable lighting design

As the perspectives of ALAN research and sustainable urban lighting design should aim for the same common goal — to reduce LP and improve design approaches, it is an opportunity for both domains to have a seat at the table to make a change. This opportunity suggests using conferences and any socially engaging platform to share relevant findings and current illuminating projects.

Design skills are as crucial as research findings as they can aid in narrowing the takeaway message for a broader audience to gain interest in research studies. It is a skill as important as properly and carefully illuminating nightscapes. Involved experts are responsible for communicating and reshaping conventional perspectives on over-illuminated nightscapes. I consider that the lighting designer's challenge also involves embracing complex science and rethinking the systems illuminated, better navigating the conversations with ALAN experts responsible for sharing their findings, and collaborating towards ecology awareness.

As ALAN research and the lighting practice remain distant. More efforts are required to implement ecological awareness in the mindset of light planners and practitioners; the future of lighting design will require an educational approach in their pedagogic agenda focused on the conservation of ecosystems, acknowledgement of biodiversity thresholds and the different forms of ALAN and LP to build a sustainable lighting practice properly.

Figures 1 (a-c) present a list of recommendations lighting professionals should consider in their lighting design strategies. Figure 1(c) presents a guide on night-time illumination near inland waters..

6.8. Conclusions

To protect the natural optical conditions of the night from LP in floodplains and waterbodies, the approaches implemented by the lighting practice must align with research findings. Transdisciplinary collaborative practices should become a must in the lighting design agenda to balance the ongoing technological advancements of the lighting industry and the lighting strategies of light planners with ecologically conscious approaches for the future. Collaborative transdisciplinary practices can aid in rethinking conventional human-centric habits, bridge the existing communication and knowledge gaps, and develop platforms for translating and transferring information, which can aid in mitigating the impact of ALAN to protect the integrity of aquatic life below water.

The results of the studies that quantify ALAN in a freshwater context, Chapters 4 and 5, reveal that bridge illumination can create diverse lighting typologies and unnatural light scenarios that could alter aquatic habitats and induce PLP, which could consequently affect behaviours in the dispersal, movement and migration of aquatic species or induce ecological traps at illuminated areas. These findings highlight the need for further research on the impacts of ALAN on inland waters and call for the avoidance of illuminating waters at night. I recommend further research and comprehensive assessments considering varied lighting typologies to understand the environmental impact of lighting design approaches on the aquatic realm.

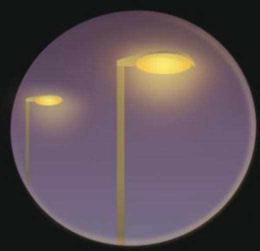
SUSTAINABLE LIGHTING DESIGN

Recommendations for lighting practitionners

MAP THE NIGHT SKY QUALITY

Identify the night-sky quality by measuring the light field to account the different forms of light pollution and ALAN.

IDENTIFY ARTIFICIAL ILLUMINATION INDUCING LIGHT POLLUTION



Identify luminaires that require shielding, light sources that require a post-top luminaire, and visible point sources in need of luminaire housing and shieding.

CONSIDER BIODIVERSITY THRESHOLDS

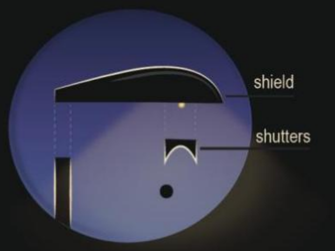
Before planning changes and lighting design strategies, investigate the area to illuminate and consider the areas that should remain in darkness such as floodplains, greeneries, and waterbodies.

Keep in mind the impact of light pollution on flora and fauna and consider their thresholds.

Collaborate with ALAN researchers to identify the natural environments and to identify the aquatic and terrestrial nightscapes to protect.

Recommendations for lighting practitionners

TARGET, SHIELD, AND EQUIP WITH PRECISION



Target the luminaire so its emission is directed towards functional areas.

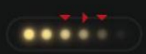
Shielded to reduce light pollution and the emission of light upwards or into floodplains, greeneries, and waterbodies.

Equip the luminaire with shutters to narrow and precise the emission of light downwards.

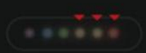
CONTROL

Control the time and dimming of luminaires based on user numbers and with the aid of montion sensors.

Apply curfews to illuminate functional areas only during the hours artificial illumination is needed.



Control the level of light based on user numbers and using the lowest level possible.



Control the spectral composition of light sources limiting short wavelengths to the least amount possible and avoid emitting ultraviolet wavelengths.

ACTIVELY COMMUNICATE

Get informed, collaborate with ecologists, exchange expertise, implement sustainably, share, educate, and repeat.

The active consultation with ecologists can generate new lighting strategies and establish approaches that consider protecting the night.

Recommendations for lighting practitionners

A guideline for night-time illumination near inland waters

WATERBODIES UNDER NATURAL NIGHT-TIME CONDITIONS

Any form of waterbody including streams, ponds, lakes, waterfronts, and river should remain in darkness at night. Therefore consider:

TIME

Control and schedule light with time clocks (e.g. dusk to dawn) to set curfews where illumination remains on during the hours it is needed. Dim light over the course of the night.

NATURAL CONDITIONS AND SEASONALITY

Consider the presence of moonlight near waterbodies and migrating season as the survival of aquatic species might depend on it.

ENVIRONMENTAL LIGHTING ZONES

Reduce unnecessary illumination in areas where it is not needed.

TURN OFF IF NOT NEEDED

IF NEEDED, LET IT BE FUNCTIONAL

SHIELDING

A full-cutoff luminaire to reduce sky brightening up to 90%. Follow the BUG rating system to reduce sky brightening upwards.

Aim for less visibility of the point source at the luminaire's head or the head of the post-top luminaire.

Shield illumination with the aid of shutters to avoid light spilling over the edges towards greeneries or freshwaters.

LIGHT SPATIAL DISTRIBUTION

Illumination is useful when it remains in functional areas of passage.

Waters should remain in darkness at night. Avoid illuminating water surfaces and migratory pathways such as rivers, shores, floodplains, protected landscapes (eg. Natura 2000 landscapes).

LIGHT SPECTRAL CHARACTERISTICS

Reduce short wavelength emissions, including ultraviolet (UV) radiation, green and blue wavelengths.

LIGHT SPATIAL CONDITIONS

Bridge structures near the water should remain in darkness.

Figure 1. An overivew of recommendations for sustainable lighting design. (a,b) Six key recommendations for lighting practitioners to consider night-sky quality, identification of LP and artificial illuminating sources, biodiversity thresholds, luminaire equipment to reduce unnecessary illumination, controllers to regulate the time and spaces in which light emissions take place, and the active communication of protecting nightscapes across disciplines. (c) Guideline on night-time illumination near inland waters considering bridge illumination as lighting scenario that requires careful management.

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Supplementary Material

7.1. Chapter 3

Tables S1-S6 shows an overview of the responses in 6 organism groups when exposed to a type of light source and the physical properties of ALAN. References for Tables S1-S6 correspond to references in Chapter 3.

Table S1. Key findings about the effects of ALAN for the organism group of plants.

#	Light source	Key findings	Ref.
1	FL	An altered foliage was reported in White clover (*Trifolium repens*) and red clover (*Trifolium pratense*) when they were exposed to FL with a PPFD of 0.6 - 1 μmol m^{-2} s^{-1} (at plant height) at night.	[59]
2	ALAN (dir.)	An early flowering, and the growth of longer stems, was reported in Whorled tickseeds (*Coreopsis verticillata*) and large-flowered tickseeds (*Coreopsis grandiflora*) when they were exposed to ALAN with a PPFD of 0.05 - 2.0 μmol m^{-2} s^{-1} (approximately 3.7 – 180 lx HPS, CFL).	[60]
3	Two different LEDs	Complex and cascading effects on grasslands were found when they were exposed to two variations of LED light at night: (a)amber LEDs (near monochromatic, λp = 588 nm), (b) LEDs (CCT 6000 K). For both treatments, legume cover decreased. It decreased by 19% when it was exposed to (a) and by 12% when it was exposed to (b). No significant effect from (a) or (b) was detected on grasses or non-leguminous forbs; 16% of the herbivore community increased and 10% of herbivores and predators increased. No significant effects were reported on the cover of grasses or non-leguminous forbs when they were exposed to a) and b). The production of flower heads and inflorescence decreased with the presence of herbivores in *L. pedunculatus* when exposed to (a,b) at night; No significant effect was reported on inflorescence in the presence of predators; There was a decrease of 29% in carbon to nitrogen ratio when exposed to (a) or(b); There was a decrease of 17% in the abundance of pea aphids *A. pisum* when exposed to (a), while no significant effect was reported when exposed to (b). There was a decreased abundance of 55% of grey field slugs *Deroceras reticulatum* when exposed to (b) in the presence of a visual predator.	[61]

Table S1. Key findings about the effects of ALAN for the organism group of plants.

#	Light source	Key findings	Ref.
4	ALAN (dir.)	The dense cover of epicuticular wax crystals was reported on the leaves of yellow poplars (*L. tulipifera L.*) when they were exposed to ALAN with a varied PAR irradiance (PPFD) that included a) 1 μmol m^{-2} s^{-1}, b) 3 μmol m^{-2} s^{-1}, c) 50 μmol m^{-2} s^{-1}. A gradual reduction of guard cells was observed when plants were exposed to a gradual increase of PPFD. The exposure to (a) reduced guard cells by 22%, by 30% when exposed to (b), and by 44% when exposed to (c); When exposed to ALAN there was a reduction of stomatal in aperture and width; There was a gradual decrease in stomatal aperture by 22% when exposed to (a), by 30% when exposed to (b), and by 44% when exposed to (c); Stomatal width decreased when exposed to (a) by 29%, (b) by 58%, and (c) by 72%; Shrinkage of abaxial leaf surface was demonstrated when exposed to (c); Stomatal density increased by 48% when exposed to (a), by 18% when exposed to (b), and when exposed to (c) by 40%; Stomatal size was reduced by 26% when exposed to (a), by 48% when exposed to (b), and by 63% when exposed to (c); Leaves with abnormal development of chloroplast; When exposed to ALAN at dusk, endogenous abscisic acid was reduced by 63% when exposed to (a), by 78 % when exposed to (b), and by 94% when exposed to (c).	[62]
5	ALAN (dir.)	An early budburst was reported in Sycamore maples (*Acer pseudoplatanus*), European beeches (*Fagus sylvatica*), English oaks (*Quercus robur*), and European ash trees (*Fraxinus excelsior*) when they were exposed to ALAN (using night-time satellite images).	[63]
6	ALAN (dir.)	An increased flowering process was observed in tussock bellflowers (*Campanula carpatica Jacq.*), large-flowered tickseeds (*C. grandiflora*), garden petunias (*Petunia x hybrida*), and black-eyed susans (*Rudbeckia hirta L.*) when they were exposed to ALAN.	[64]
7	ALAN (dir.)	Parts of the plants of Traganum moquinii exposed directly to the artificial light show a significant decrease in the production of flowers, compared to the parts in plants in shade, and to the plants more distant from artificial lights. In consequence, plants exposed more directly to artificial light have a lower potential for seed reproduction. The spectrum of artificial light also affects the plants, and light between 600 and 700 nm primarily affects the reproductive cycle of the Traganum moquinii species.	[65]

Table S1. Key findings about the effects of ALAN for the organism group of plants.

#	Light source	Key findings	Ref.
8	ALAN (dir.)	A delay in the flowering state of short day plants and the promotion of flowering in long day plants were observed when they were exposed to ALAN with ca. 10 lx.	[66]
9	LEDs	Lotus pedunculatus and herbivore pea aphid (*Acyrthosiphon pisum*) were exposed to two variations of LED light: a) cool white LEDs (CCT 6000 K) with an illuminance of 10 lx ; b) amber LEDs (near monochromatic λp = 588 nm) with an illuminance of 10 lx. The presence of aphids suppressed the density of flower heads over the course of the year; both a) and b) light treatments decreased the flower density when compared to flowers kept in darkness.	[67]
10	HPS and LEDs	Exposure to white light with a broad SPD such as cool white LED light (CCT > 5000 K) with a luminous flux of 5000 lm, and HPS (CCT ca. 2000 K) with a luminous flux of 5300 lm, resulted in the disrupted pollen transport of nocturnal pollinators, an increase in pollination, increased seed count in the disrupted pollen transport of nocturnal pollinators, and an increase in pollination of white campion wildflowers (*Silene latifolia*). The following variations were defined as a) HPS with a continuous duration, b) HPS switched off at midnight, c) LEDs with a continuous duration, and d) LEDs switched off at midnight. Illuminances varied between 0.1 lx and 100 lx depending on the distance to the source.	[68]
11	LEDs	LEDs with an illuminance of 180 lx, a broad SPD (400 – 750 nm), and a CCT = 6500 K were observed to increase the leaf litter decomposition in Chinese wingnut (*P. stenoptera*). The increase of leaf litter decomposition led to a decreased lignin content in leaf litter, which changed the fungal community composition and structure, and increased microbial biomass.	[69]
12	LEDs	LEDs with a broad SPD (400 – 750 nm), and a CCT = 6500 K were observed to decrease the lignin content of plant leaf litter by 12% in Chinese wingnut (*P. stenoptera*) involving cadmium (Cd) polluted conditions in aquatic ecosystems; they also altered the fungal community structure.	[70]
13	ALAN (dir.)	ALAN with an illuminance of 7 – 12 lx caused an alteration to the plant's toughness of smooth brom (*Bromus inermis Leyss*).	[71]

Table S1. Key findings about the effects of ALAN for the organism group of plants.

#	Light source	Key findings	Ref.
14	ALAN (dir.)	When exposed to ALAN, there was an alteration and delay of leaf colouring at the tree crown observed in staghorn sumac shrubs (*Rhus typina L.*) and sycamore maples (*A. pseudoplatanus L.*).	[72]
15	LEDs	Velvet grass (*Holcus lanatus*), sweet vernal grass (*Anthoxanthum. odoratum*), and colonial bentgrass (*Aliciella tenuis*) were observed to have varied responses when exposed to LEDs with different illuminance levels, SPD, and durations: cool white LEDs (6000 K) with a) an illuminance of approximately 30 lx from dusk to dawn; b) approximately 14.6 lx from dusk to dawn; c) approximately 14.4 lux between 24h – 04h; and d) amber LEDs (near monochromatic SPD with λp = 588 nm) with an illuminance level of approximately 18.3 lx from dusk to dawn. When velvet grass (*H. lanatus*) and sweet vernal grass (*A. odoratum*) were exposed to amber LED with (d), their constant cover (frequency) increased. When colonial bentgrass (*A. tenuis*) was exposed to amber LED with (d) its cover (frequency) decreased. When colonial bentgrass (*A. tenuis*) was exposed to b), cool white LED, approximately 14.6 lx, its biomass was lowered. Also, a lowered biomass in colonial bentgrass (*A. tenuis*) was reported when it was exposed to amber LEDs with (d). When sweet vernal grass (*A. odoratum*) was exposed to amber LEDs with (d) there was a significant increase in its biomass. When velvet grass (*H. lanatus*) was exposed to cool white LEDs with (a) and amber LEDs with (d), an increase in biomass was observed.	[73]
16	ALAN (dir.)	European horse-chestnut (*Aesculus hippocastanum*) trees exposed to road lighting had bigger leaves and less signs of senescence in autumn; ALAN appeared to extend the larval activity of horse-chestnut leaf miner (*Cameraria ohridella*) in the winter months.	[74]
17	LEDs	There was no direct effects on plant height; however, 34.6% of the leaves of Brassicales (*Brassica nigra Linnaeus*), Fabale pea seedlings (*Pisum sativum Linnaeuss*), and tomato plants (*Solanum lycopersicum*) were reportedly damaged by insects attracted to the illuminated leaves when these plants were exposed to neutral white LEDs (CCT 4200 K) with an illuminance ranging from about 67 – 105 lx at night.	[75]

Table S1. Key findings about the effects of ALAN for the organism group of plants.

#	Light source	Key findings	Ref.
18	ALAN (dir.)	ALAN was reported to alter the end of the vegetative season in the leaves of London planetrees (*Platanus x acerifolia*) during autumn.	[76]
19	LEDs	Cool white LEDs (6500 K) with an illuminance of approximately 180 lx, a broad SPD (400 – 750 nm), and a CCT = 6500 K, increased the decomposition of leaf litter from the Chinese wingnut (*Pterocaya stenoptera*), decreased dry mass, reduced the toxicity of silver nanoparticles (AgNP – commonly contained in commercial products that are used daily, which then end up in freshwater ecosystems), and increased the microbial biodiversity (a significant abundance of fungi was reported compared to the bacterial community).	[77]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
1	HPS	When rustic shoulder-knot moths (*Apamea sordens*) at the larval stage were exposed to HPS with an illuminance of 7 – 12 lx at night, there was a decrease in body mass gain, and altered performance and development. Their larval weight decreased by 43% indicating lower larval fitness.	[71]
2	FL	FL with a broad SPD ranging at about 250 – 3000 nm at night on the top of a railing for a footbridge across a canal, was demonstrated to affect the density of nocturnal orb-web spiders (*Larinioides scloptearius*) at illuminated locations (0.0 – 17.7 individuals/m^2). A higher density of spiders was reported in comparison to unlit locations (0.0 – 4.7 individuals/m^2). Seasonal changes were observed to affect spider density in these locations as there was a significant increase in autumn. The insect density and capture rate of spiders were higher in illuminated locations. Also, the webs in illuminated locations entangled more prey compared to unlit locations.	[78]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
3	ALAN (dir.)	The attraction of camel spiders (*Solifugae*) to light sources was demonstrated when they were exposed to ALAN with a luminous flux of 750 lm at dusk.	[79]
4	ALAN (ind.)	ALAN proximate to littoral zones was shown to attract large-sized buzzer midges (*Chironomus plumosus*), the small-sized Tanypus punctipennis and Procladius spp.	[80]
5	ALAN (ind.)	During the period between 1985 – 2015, a decline in moth population affecting 481 moth species was highly correlated with urban illuminated areas.	[81]
6	HPS	The attraction of moth families was reported when they were exposed to HPS with a luminous flux = 96 lm, CCT = 2000 K. A street lighting matrix (lighting layout) showed varied attractions of moths to mid and corner luminaires in a lighting matrix with HPS (CCT 2000 K) with a luminous flux of 96 lm. Moths were caught at corner luminaires, to a lower amount at wing luminaires and with much lower proportion at luminaires positioned in the middle of the matrix indicating a barrier effect. No sexual differences in the attraction rate nor in the attraction radius of male and female moths was demonstrated.	[82]
7	FL	FL with a broad spectral output and with λp = 405 nm and 617 nm were observed to attract arthropods at night. FL with λp = 617 nm caused the least amount of moth attraction.	[83]
8	ALAN	ALAN was demonstrated to impact the macro-moth population after multiple years of night-time exposure to ALAN with a varied SPD (white, green, and red). A higher decline in population was observed when moths were exposed to ALAN with a broad SPD (white) and green wavelengths. Little to no decline was reported when moths were exposed to ALAN with longer wavelengths (red).	[84]
9	ALAN (dir.)	ALAN with an illuminance of 10 – 12 lx decreased the density and diversity in tetragnathid spider families, decreased the size of emerging aquatic insects (riparian emergent insects) and increased the size of terrestrial arthropods.	[85]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
10	ALAN (dir.)	An attraction and aggregation of arthropods from riparian ecosystems was observed in illuminated areas at night.	[86]
11	ALAN (dir.)	ALAN at illuminated river bridges altered the food chain of insects and insectivorous predators such as birds and peregrine falcons.	[87]
12	HPS and HPM	HPS and HPM light sources rich in ultraviolet (UV) wavelengths were observed to alter insect flight activity. A greater attraction was reported for HPM compared to HPS. A lower attraction was reported in HPM with ultraviolet (UV) absorbing filters. The study suggests the use of filters or UV absorbing glass to reduce the invisible light emission in order to potentially reduce the attraction of insects at night.	[88]
13	LEDs and HPM	Exposure to LEDs and HPM in urban and peri-urban environments was observed to attract insects including *Diptera*, *Hemiptera*, *Hymenoptera*, and *Lepidoptera*.	[89]
14	LEDs and FL	Numbers of flying terrestrial insects were attracted to FL and LED light sources in correlation to the CCT values, which were ranging from (2700 K – 3510 K).	[90]
15	HPS and LEDs	A higher amount of flying insects including *Diptera*, *Trichoptera*, *Coleoptera*, *Hymenoptera*, *Hemiptera*, *Ephemeroptera*, *Psocidae*, *Lepidoptera*, *Neuroptera*, *Thysanoptera*, *Aranae*, *Plecoptera*, *Isoptera*, *Othoptera*, and *Blattodea* were attracted to LEDs compared to HPS. The CCT of LEDs had no significant effect on invertebrate attraction. All lights had a broad SPD: HPS had a CCT of ca. 2000 K and LEDs had varied CCTs (2700 K, 3000 K, 3500 K, 4000 K).	[91]
16	CMH, HPM, LPS, and LEDs	The highest level of attraction occurred when insects were exposed to HPM compared to LPS, CMH, and LEDs. LEDs attracted less individual insects compared to the other light sources. The difference between LPS, CMH was reported as insignificant.	[92]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
17	CMH, HPS, and LEDs	The highest attraction of arthropods including *Diptera*, *Lepidoptera*, *Erebidae*, *Chironomidae*, *Coleoptera*, *Noctuidae*, and *Psychodiodae* occurred when they were exposed to CMH compared to HPS and LEDs.	[93]
18	CMH, HPS, and LEDs	The attraction of aquatic and terrestrial insects to the horizontally polarised light reflected from black and white illuminated surfaces occurred when aquatic and terrestrial insects were exposed to CMH, HPS, and LEDs at night. Phototaxis was measured to be of higher relevance than the degree of polarization for most of the tested insects.	[94]
19	LEDs	The street illumination from LEDs on a bridge, reflected on the road surface attracted terrestrial and aquatic insects. (Mayflies typically lay eggs on the surface of the water. Instead, their eggs were laid on illuminated human-made structures.) A high degree of horizontally polarised light, reflected from illuminated surfaces can resemble the surface of water. This was shown to alter oviposition which may lead to reproductive failure in aquatic and terrestrial arthropods near aquatic habitats including mayflies (*E. virgo*).	[95]
20	LEDs	LEDs with different SPDs (warm/neutral white, green and red) with an illuminance of 10 lx were used to study avoidance in arthropods (*Operophtera brumata*) when they were exposed to ALAN. Green showed the highest avoidance, white the second highest, and red the lowest avoidance of the light treatments. All treatments had higher avoidance than no ALAN. A higher number of mated female arthropods were observed on top of non illuminated tree trunks.	[96]
21	FL	A lower propensity to fly towards light was observed in urban moths commonly accustomed to illuminated locations at night. A relative attraction to FL was reported in moths from darker locations.	[97]
22	LEDs	Cool white LEDs (CCT 5700 K) with a luminous flux of 1000 lm induced the avoidance of illuminated areas as an anti-predator behaviour in the cricket-like insects tree weta (*Hemideina thoracica*) and cave weta (*Rhaphidophoridae*).	[98]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
23	LEDs	Warm white LEDs (CCT 2700 K) with a luminous flux of 55 lm resulted in a reduced light avoidance behaviour in urban spiderlings and an altered web building choice of location for urban and rural populations of spiders (*Steatoda triangulosa*).	[99]
24	ALAN (ind.)	ALAN with an illuminance of 0.1 – 5 lx decreased aphid abundance by 45.5%, increased plant biomass, and altered the parasitism rate; Higher illuminance levels were considered to potentially increase a plant's biomass by increasing the photosynthetic rate of the plant, however, the effect of night-time illumination may vary from one plant species to another. Parasitoids were reported to attack aphids when exposed to ALAN with an illuminance of 1 lx and 20 lx, which may indicate that active parasitoids depend on photoperiods. Parasitism rate of *Aphidius megourae* increased by 10 % with an illuminance of 0.1 – 5 lx, while the parasitism rate of *Aphidius ervi* and *Lysiphlebus fabarum* responded significantly to night-time illumination. The overall parasitism rate declined when aphids were exposed to low or high illuminance levels.	[100]
25	LEDs	When exposed at night to cool white LEDs with an illuminance of 20 lux and a broad SPD, the nocturnal juvenile Australian garden orb-web spider (*Eriophora biapicata*) displayed an altered web site selection, as well as changes in foraging behaviour and prey capture success. An increase in prey availability and changes in the preference of foraging sites were observed in Australian garden orb-web spider (*E. biapicata*). Of 51 spiders, 48 (94%) constructed their web on the illuminated location. The rate of small prey capture was significantly higher in the illuminated location when compared with the dark location. Medium and large prey were only captured in illuminated sites, although only two large prey were caught overall.	[101]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
26	HPS	A set of HPS streetlights (CCT 2000 K), with a max. illuminance of 50 lx, an average illuminance of 10 lx between two post-lamps, and a min. illuminance of 1 lx, were demonstrated to increase the abundance and diversity of insects to terrestrial predators compared to unlit controls. Also, the nutritional flux of aquatic webs to terrestrial food webs were altered at the lit site. An increased catch of insects occurred at the illuminated site (an approximate of 60 insects per hour) compared to the un-illuminated site (0-1 insects were caught per hour). The most abundant orders were sawflies, wasps, bees, and ants (*Coleoptera*, *Hymenoptera*, and *Diptera*). At the illuminated site 539 moths (*Lepidoptera*) were caught while only 2 were caught at the un-illuminated site. At the illuminated site 80 spiders (*Araneae*) were captured, however, they were six times more abundant at the nonilluminated site.	[102]
27	LEDs and HPM	No effect on insect biomass was reported for insects that were exposed to HPM or LED emission. However, an altered biomass was observed which was affected by the percentage of moonlight illuminance.	[103]
28	LEDs	The night-time exposure to LEDs with different SPDs (λp = 361, 450, 500, 600, 626, and 660 nm) was studied in parasitoid wasp *Aphidius erv*i and its host, the pea aphid (*Acyrthosiphon pisum*). The different wavelengths had no observed effect on the parasitoids probability of walking, and activity depended on the sex of individuals. When tested, males parasitoid wasps (*A. ervi*) were more active than females under all monochromatic wavelength spectra.	[104]
29	HPS	Spider Pachygnatha clercki (*Tetragnathidae*) and three long-legged harvestmen species Opiliones (*Rilaena triangularis* in spring, *Nelima sempronii* and *Phalangium opilio* in summer), were some of the species affected by a HPS streetlight setup (CCT 2000 K) with an illuminance of 1 lx (between two rows of luminaires), 10 lx (between two adjacent luminaires), and 50 lx (maximum) compared to un-illuminated controls. Exposure to HPS increased the density of aquatic and terrestrial prey which altered the diet of riparian secondary consumers.	[105]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
30	LEDs	Three different night-time experiments demonstrated altered predator species flashes, a visual signal in fireflies *Photinus pyralis* and *Photuris versicolor*, when they were exposed to night-time illumination. For Experiment 1, an illuminated location with white LED floodlights (CCT not given) mounted at 0.3 m heightreported that 189% of individual fireflies *P. pyralis* and *P. versicolor* were found in illuminated areas at night. The number of found species varies for the prey species, and the number of individuals increased over the course of the evening. For experiment 2, LED floodlights were mounted at 3 m height with an illuminance of about 57.4 lx that operated from 21h30 – 23h30. Unlit locations reached an illuminance of about 0.03 lx. When exposed to LEDs, female fireflies P. pyralis and P. versicolor never flashed, whereas 11 females tethered in unlit areas flashed at least once. For experiment 3, male fireflies did not flash near female fireflies when they were exposed to one LED at the center of a mesocosm, at a height of 2.5 m, and with an illuminance of about 0.01 lx and increasing at about 174 lx. Although there was no significant effect based on the presence of a predator, and no significant interaction between predator presence and light pollution - LEDs significantly decreased the number of predator species flashes in *P. pyralis* and *P. versicolor*.	[106]
31	LEDs	The night-time exposure to cool white LEDs (CCT 5900 K) with varied illuminances levels of 0, 1, 10, and 100 lx resulted in increased mating behaviour and less engaged females, while males reared and mounted females more often under 100 lx in the crepuscular and nocturnal Australian black field cricket (*Teleogryllus commodus*).	[107]
32	LEDs	When Black field crickets (*Teleogryllus commodus*) were exposed to cool white LEDs (CCT 5900 K) with a varied illuminance of 1, 10, and 100 lx at night, there was altered function of their immune system, measured with haemocyte concentration, lytic activity, and phenoloxidase activity. LEDs incited negative effects on haemocytes, while the effects on lytic activity and phenoloxidase activity were more complex or largely unaffected by LEDs.	[108]
33	LEDs	Cool white LEDs (CCT 5900 K) and varied illuminance levels of 0, 1, 10, and 100 lx were shown to affect the fecundity and survival rate in the Black-bellied fruit fly (*Drosophila melanogaste*r). The oviposition rate decreased and female flies were reported to lay less eggs when they were exposed to a gradual increase of illuminance levels (1 – 100 lx).	[109]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
34	LEDs	LED light (CCT not reported) with an illuminance of 20 lx was observed to affect the development of orb-weaving spiders (*Eriophora biapicata*). When they were exposed to ALAN, there was accelerated development with orb spiders maturing significantly earlier, compared to spiders that had no ALAN exposure. Orb-weaving spiders growing under ALAN were smaller in size, with an increase in mortality, and there was a reduced number of eggs produced by females, affecting reproductive success and survival.	[110]
35	LEDs	The night-time exposure to green LEDs (near monochromatic λp = 520 nm) for varied periods of time (2, 4, 6, 8, and 10 hours) resulted in altered development stages for northern armyworm moths (*Mythimna separata*). Long exposure to LEDs prolonged the egg period, decreased the hatch rate when exposed to 6, 8 and 10 h, shortened the developmental period of larvae when exposed to 4 and 10 h, increased the larval survival rate when exposed to 10 h, decreased fecundity per female when exposed to 8 and 10 h, and decreased the oviposition quantity per day when exposed to 6, 8, and 10 h, pre-oviposition periods were also prolonged when exposed to 10 h, and oviposition periods were lengthened when exposed to 2, 6, and 8 h. However, no significant differences in pupae rate were reported.	[111]
36	ALAN (dir.)	A significantly high abundance of spiders and beetles was observed to remain under ALAN. The taxa attracted to ALAN included Lycosidae: *Trochosa ruricola*; Tetragnathidae: *Pachygnatha degeeri*; Linyphiidae: *Dicymbium nigrum*, *Centromerita bicolor*, and Oedothorax spp, - *Oedothorax retuses* and *Oedothorax fuscus* combined and three beetle taxa (Carabidae: *Pterostichus niger*; Pselaphidae: *Rybaxis longicornis*; Ptiliidae: *Acrotrichis spp.*)	[112]
37	HPS	The attraction of non-biting midges (*Chironomidae*), crane-flies (*Tipulidae*), dragonflies and damselflies (*Odonata*), mayflies (*Ephemeroptera*), and mosquitoes and blackflies (*Culicomorpha*) occurred proximate to a river when it was illuminated with warm white HPS (CCT 2000 K) with a luminous flux of 5600 lm.	[113]
38	FL	FL operating at sunset (at 18h30) that emitted light upwards to illuminate higher building levels, resulted in the attraction of nocturnal insects such as *Paederus fuscipes*.	[114]

Table S2. Key findings about the effects of ALAN for the organism group of arthropods: insects, and spiders.

#	Light source	Key findings	Ref.
39	FL	The Wellington tree weta (*Hemideina crassidens*) did not present a changed preference in fruit choice when exposed to cool white FL (CCT 4100 K) and with λp = 350, 450, 530, 570, and 700 nm. When exposed to FL the wetas showed a preference for naturally coloured bright blue fruits over fruits dyed dull red. FL did not affect the selection of fruits at night.	[115]
40	FL and LEDs	A reduced activity pattern was observed in ground beetles (*Pterostichus melanarius*) when they were exposed to FL and LED emission at night. LEDs rich in long wavelengths were reported to have the least disruption to their movement and speed compared to FL with a broad SPD (320 – 780 nm).	[116]
41	LEDs	Cool white LEDs (CCT 6000 K) with a luminous flux of 4000 lm, were placed facing downstream to guide female egg-laying mayflies (*Ephoron virgo*) towards the water (i.e. underneath the bridge) to prevent the mass deaths of mayflies on the road surface of illuminated river bridges. The study demonstrated that the management of artificial lighting can aid the survival of mass swarming mayflies.	[117]
42	LEDs	Garden lamps with cool white LEDs (CCT 7250 K) attracted invertebrates, which included 126 ground beetles, two species *Calathus melanocephalus* and *Pseudoophonus rufipes*, which may alter the nocturnal activity pattern of invertebrates. One single garden lamp attracted 101 invertebrates while four garden lamps attracted 540 invertebrates. The study reported an active nocturnal behaviour in *Chrysopa nigricorni*, 75% of *C. nigricorni* were active at night and 8% of *C. nigricorni* were active in the day, while with Beetle species (*Thamnatophilus sp.*) 48% were observed to be active at night near the garden lamps. Nocturnal carabid species decreased their activity during the night under LEDs.	[118]
43	LEDs	A lower abundance of isopods (*Tylos spinylosus*) was observed in illuminated areas at night when they were exposed to cold white LEDs (CCT 5000 K) with an illuminance of 120 lx, with a gradual decrease to 3 lx towards low tide, compared to the non illuminated locations where the abundance of isopods was higher with a peak of abundance at 02h30. Under illuminated conditions at night, locomotor activity during the day decreased (activity from 06h00 - 08h00 was decreased, and during 09h00 - 20h00 was drastically slowed), which inhibited the circadian rhythm of coastal nocturnal species such as *T. spinylosus*.	[119]

Table S3. Key findings about the effects of ALAN for the organism group of fish.

#	Type of light source	Key findings	Ref.
1	CMH	CMH with an irradiance between of 13.0 – 15.3 Wm^{-2} (5 m distance) and 0.02 - 0.10 Wm^{-2} (50 m distance from the light) resulted in the attraction and aggregation of fish including sand lances (*Ammodyteshexapterus sp.*), three-spined sticklebacks (*Gasterosteus aculeatus*), Pacific herrings (*Clupea pallasi*), great sculpins (*Myoxocephalus polyacanthoscephalus*), and soft sculpins (*Psychrolutes sigalute*s).	[120]
2	ALAN (dir.)	When European eels (*Anguilla anguilla*) were exposed to luminous fluxes of about 60 lm (bright light source) and about 3 lm (dim light source), they exhibited avoidance to ALAN. The avoidance behaviour increased with lights that were directed upstream.	[121]
3	ALAN (ind.)	When European eels (*A. anguilla*) were exposed to ALAN they displayed avoidance to illuminated waters.	[122]
4	LEDs	LEDs with a different SPD (white, blue 480 nm, and yellow 550 nm) (CCT not mentioned for white) and low (1 Hz) and high (30 Hz) flicker frequency, were used to investigate the ALAN response of American eels (A. rostrata). Blue light at a high flicker frequency showed the greatest ALAN avoidance effect. The study proposes the use of artificial light to guide eels into safe waters.	[123]
5	ALAN (dir.)	An avoidance of illuminated waters was reported for vendace fish (*Coregonus albula*) when light sources were submerged at 30 m depth in the water.	[124]
6	ALAN (ind.)	When B. boops were exposed to ALAN, they displayed altered nocturnal emergence, which forced them to drift away from illuminated waters towards shaded locations to avoid predators.	[125]

Table S3. Key findings about the effects of ALAN for the organism group of fish.

#	Type of light source	Key findings	Ref.
7	CMH	Night-time illuminated waters exposed to CMH with an illuminance of 14 lx (upstream) was linked to altered behaviour and migratory timing in Atlantic salmon (*Salmo salar*) smolts that were leaving their natal stream.	[126]
8	CMH	When Atlantic salmon (*S. salar*) were exposed to CMH with fitted filter sheets and a range of illuminance levels (6.1, 11.3, 12.9, 20.0, 22.7, and 49 lx) at night, there was a late initiation of fry dispersal.	[127]
9	CMH	A delayed dispersal timing (by 1.4 – 2.2 days) and disrupted diel pattern behaviours were observed in Atlantic salmon (*S. salar*) when they were exposed at night to CMH with illuminances of 1, 2, 4, and 8 lx.	[128]
10	LEDs	Exposure to warm white LEDs at night with an illuminance of about 13 lx, was observed to alter fish predatory behaviour, their habitat use, and sessile invertebrate prey assemblages. It also decreased fish abundance.	[129]
11	CMH, HPS, TH	An altered predator-prey interaction was reported for predator juvenile rudd (*Scardinius erythropthalmis*) and prey (*Daphnia pulex x pulicaria*) when they were exposed to three different light sources that included: TH, HPS, and CMH. a) An increase in the reaction distance and swimming speed was observed in juvenile rudd under THs at night compared to the night-time exposure of HPS. b) Increased reaction distance and swimming speed was noted in juvenile rudd under CMH at night compared to the night-time exposure of TH and HPS. c) A greater evasiveness was observed in *D. pulex x pulicaria* under THs and HPS compared to CMH and no exposure to ALAN.	[130]
12	FL	When European perch (*Perca fluviatilis*) were exposed to FL with an illuminance of 100 lx and a CCT of 6000 K, the suppression of melatonin levels was observed.	[131]

Table S3. Key findings about the effects of ALAN for the organism group of fish.

#	Type of light source	Key findings	Ref.
13	ALAN (dir.)	When waters were exposed to an illuminance of 1 lx at night there was an observed decrease in melatonin production in the European perch (*P. fluviatilis*). Cortisol levels did not differ between exposure to 0 lx and 1 lx.	[132]
14	LEDs	An altered production of melatonin was reported for perches (*P. fluviatilis*) when they were exposed to blue LEDs with short-narrow-band wavelengths with an illuminance of 0.15 lx. Exposure to blue LEDs at 0.15 lx were the least suppressive compared to red LEDs (long-narrow band wavelengths) with an illuminance of 0.62 lx, and green LEDs (mid-narrow band wavelengths) with an illuminance of 2.2 lx.	[133]
15	FL and LEDs	Low light intensities of FL and LEDs with a broad SPD were observed to disturb the melatonin rhythms in roaches (*Rutilus rutilus*) at very low intensities and at different wavelengths. Therefore, light pollution in urban waters has the potential to impact the biological rhythms in fish. However, the mRNA expression of gonadotropins was not affected by ALAN during the period of the experiments. Thus, the suspected implications of ALAN on the reproduction of roaches could not be substantiated.	[134]
16	ALAN (ind.)	When exposed to ALAN, there was an observed suppression in the secretion of melatonin in golden rabbitfish (*Siganus guttatus*). The moon's brightness was considered to alter melatonin levels at night as well.	[135]
17	ALAN (ind.)	When exposed to ALAN, Zebrafish (*Danio rerio*) were reported to develop ovarian tumour, lose circadian rhythmicity, and have lower concentrations of melatonin in the brain, retina, ovary, and serum. The long term exposure of one year increased the expression of NF-KB, a cellular transformer of tumour genesis which formed thecoma (benign ovarian neoplasms) and granulosa cell tumours (a type of ovarian cancer) when exposed to ALAN.	[136]

#	Light source	Key findings	Ref.
18	CMH	When exposed at night to CMH with an illuminance of 8 lx, there was an observed lowering in the cortisol rate of Atlantic salmon (*S. salar*). This was linked to changes in their dispersal across the water.	[137]
19	HPS	When juvenile bonefish (*Albula vulpes*) were exposed at night to HPS with an illuminance of 48 – 80 lx at the water's surface, their blood glucose concentrations were elevated (a stress indicator).	[138]
20	LEDs	The reduction of thyroid hormone levels and changes in settlement were reported in larvae surgeonfish (*Acanthurus triostegus*) when they were exposed at night to cool white LEDs (CCT 6500 K),with an illuminance of 20 to 25 lx. A preference for darker habitats at night was observed. Researchers also found there was a reduction in thyroid hormone levels during metamorphosis, faster growth, more rapid swimming behaviour, higher susceptibility to predation, and a higher mortality rate. The visual cue response was not considered altered when exposed to LEDs.	[139]
21	FL	When larval fish Nile tilapia (*Oreochromis niloticus*) were exposed to FL with a broad SPD (400 – 750 nm) located at 1m above the water surface for a photoperiod of 8 h at 100 lx or 2500 lx and a photoperiod of 24 h at 100 lx or 2500 lx, they were observed to have low larval growth and feed conversion efficiency. The combined effects of a varied photoperiod and illuminance resulted in altered growth rhythms. The study suggests light intensity can potentially change growth during the larval stage.	[140]
22	CMH and LEDs	When Atlantic salmon (*S. salar*) were exposed to various LEDs there was an increase in their growth and body weight, and an increase in their swimming activity, which may reduce the incidence of sexual maturation. Three LEDs were kept at maximal output (100%, irradiance 38 μmol s^{-1} m^{-2}), and 4 LEDs were dimmed to 75% (irradiance 3.3 μmol s-1 m-2), 50% (irradiance 2.3 μmol s^{-1} m^{-2}), 25% (irradiance 1.13 μmol s^{-1} m^{-2}), and 1% (irradiance 0.06 μmol s^{-1} m^{-2}), and CMH (with an irradiance of 4.5 μmol s^{-1} m^{-2}). These light sources were observed to potentially alter the physiological and behavioural responses in Atlantic salmon (*S. salar*).	[141]

Table S3. Key findings about the effects of ALAN for the organism group of fish.

#	Light source	Key findings	Ref.
23	LEDs	No difference in the amount of fry yields was reported for adult guppies (*Poecilia reticulata*) when they were exposed continuously to LEDs with different SPDs at night. This included three monochromatic LEDs with λp = 645, 525, and 480 nm, and one white LED (CCT not mentioned) with a broad SPD (440 – 660 nm).	[142]
24	CMH and LEDs	The distant presence of CMH in relation to two types of LEDs (an LED characterised by short wavelengths with λp = 450 – 499.5 nm and another LED with a broad SPD with λp = 460 nm and 553 nm) was observed to maintain melatonin levels irrespective of intensities. No significant difference was reported in the mean weight, length, and growth rate of Atlantic salmon (*S. salar*).	[143]
25	ALAN (ind.)	When exposed to ALAN, Atlantic salmon (*S. salar*) were observed to have no significant effect on their growth rate. However, there was an accelerated oocyte reabsorption, which may alter their basic pattern of growth.	[144]
26	HPS	The blood concentration of sex steroids (17β-estradiol; 11-ketotestosterone) as well as the mRNA expression of gonadotropins (luteinizing hormone, and follicle stimulating hormone) were reduced in roaches (*Rutilus rutilus*) and Eurasian perches (*P. fluviatilis*) when they were exposed at night to HPS (CCT 2000 K) with an illuminance of 13 – 16.5 lx at the water's surface and 6.8 – 8.5 lx 50 cm below the water surface.	[145]
27	ALAN (dir.)	*Girella laevifrons* fish exposed to ALAN with an illuminance of 78 lx were observed to have an increase in activity and oxygen consumption.	[146]
28	LEDs	A decreased hatching and reproductive rate was observed in clownfish (*Amphiprion ocellary*) when they were exposed at night to cool white LEDs (CCT 5000 K) with an illuminance of 26 lx (at the water's surface).	[147]

Table S4. Key findings about the effects of ALAN for the organism group of amphibians

#	Light source	Key findings	Ref.
1	ALAN (dir.)	ALAN with an illuminance of 14.7 lx altered the preference of leaf litter in frogs and salamanders. When exposed to ALAN, Jefferson salamanders (*Ambystoma jeffersonianum*) and blue-spotted salamanders (*Ambystoma laterale*) both displayed a preference for coniferous litter over deciduous litter.	[148]
2	ALAN (ind.)	The passage of bullfrogs (*Lithobates catesbeianus*) from their typical habitats to urban areas was reported to be affected by ALAN and spatial and temporal factors.	[149]
3	ALAN (ind.)	ALAN may alter the passage of amphibians in typically visited landscapes and from land to aquatic environments. A decline in amphibian populations was shown to be caused by road-kills. Most anuran road-kills were observed concentrated in locations along the road section. The mortality rate in amphibians was influenced by ALAN, waterbody distance, managed wood, silviculture, and grassland.	[150]
4	LEDs	When northern green frogs (*Rana clamitans melanota*) were exposed to white LEDs with an illuminance of 52 to 120 lx, males were observed to have altered vocalisation calls. There was also a reduced occurrence of male calls and a reduction in the calls detected by females.	[151]
5	HPS	HPS with an illuminance of 60 lx induced an earlier calling behaviour in frogs. Lesser swimming frogs (*Pseudis minuta*) had an altered activity peak when they were proximate to illuminated areas. In settings without illumination, amphibians showed longer varied vocalisations (a sign of calling behaviour in males) with the exception of Sanborn's treefrogs (*Dendropsophus sanborni*) and Hensel's swamp frogs (*Pseudopaludicola falcipes*) which exhibited a longer vocalisation during calling seasons.	[152]
6	ALAN (ind.)	When *Hyla chrysosceli* were exposed to ALAN, this resulted in an altered detection and consumption of prey.	[153]

Table S4. Key findings about the effects of ALAN for the organism group of amphibians

#	Light source	Key findings	Ref.
7	ALAN (dir.)	Very low illuminance has been observed to impact frog behavior. A 5-minute exposure to ALAN was observed to increase the orientation towards prey and attempts to capture prey in *Hyla squirella*. No attempt to capture prey occurred in *H. squirella* when they were exposed to complete darkness, but at the illuminance of 0.001 lx, all squirrel tree frogs oriented towards prey and attempted to capture prey. Orientation towards prey was reported in 50% of squirrel tree frogs when they were exposed to very low illuminance of 0.00006 lx which is less than starlight.	[154]
8	LEDs	Common toads (*Bufo bufo*) displayed increased activity when they were continuously exposed at night to near monochromatic LED light (λp = 590 nm) with an illuminance of 0.01 (dark control), 0.1 lx, 5 lx, and 20 lx.	[155]
9	LEDs	Exposure at night to cool white LED light (CCT 6000 – 6500 K) and varied illuminances of 0.01 (dark control), 0.1 lx, and 5 lx was observed to alter the mate selection and reproductive success of male toads (*B. bufo*).	[156]
10	LEDs	Exposure to neutral white LEDs (CCT ca. 4000 K) with an illuminance of 3 lx and 16 lx resulted in the reduced growth of juvenile toads and a lack of retreat to leaf litter. Post-metamorphic growth was reduced by 15% in juvenile American toads (*Anaxyrus americanus*).	[157]
11	FL	Yungas red-belly male toads (*Melanophryniscus rubiventris*) exposed to FL at an illuminance of 30 lx showed an immune response that caused high production levels of neutrophil proportions and altered ratios between neutrophils to lymphocytes.	[158]
12	ALAN (ind.)	When eastern gray treefrogs (*Hyla versicolor*) were exposed to ALAN, there was an unaltered mate choice behaviour reported in females.	[159]

Table S5. Key findings about the effects of ALAN for the organism group of reptiles.

#	Light source	Key findings	Ref.
1	ALAN (ind.)	Satellite imagery data from 1992 - 2012 reveals the spatial extent of ALAN across Southeast Asia and South Asia, areas that also have a high richness of terrestrial and freshwater mammals, birds, reptiles and amphibians. For the group of reptiles, geckos were shown in areas such as Southeast Asia and South Asia where ALAN has increased in the past years.	[160]
2	ALAN (dir.)	15 reptile species that include Lace monitor (*Varanus varanus*), red bellied black snake (*Pseudechis porphyriacus*), and common blue tongue (*Tiliqua scincoides*) were attracted to ALAN.	[161]
3	ALAN (dir.)	Changes in the predatory behaviour was reported in 34% of Moorish wall geckos (*Tarentola mauritanica*). ALAN is reported as an opportunistic circumstance for geckos to catch easy prey.	[162]
4	ALAN (dir.)	Marine turtles including *Caretta caretta L*., *Chelonia mydas*, *Eretmochelys imbricata*, *Lepidochelys olivacea*, *Natator depressus* and *Dermochelys coriacea* were attracted to ALAN.	[163]
5	ALAN (dir.)	ALAN was shown to deviate the nocturnal trajectories of the marine turtle *Natator depressus*.	[164]
6	LEDs	Deviated nocturnal trajectories were observed in loggerhead sea turtles (*Caretta caretta L.*) when they were exposed at night to LEDs with a broad SPD.	[165]
7	ALAN (dir.)	ALAN with a SPD rich in ultraviolet and short-wavelengths disturbed the hatching behaviour and altered the trajectories in land of green turtles (Chelonia mydas).	[166]

Table S5. Key findings about the effects of ALAN for the organism group of reptiles.

#	Light source	Key findings	Ref.
8	HPS, MH, LPS, and LEDs	Varied organism groups including arachnids, insects, reptiles, birds, and mammals were significantly stimulated by light sources with a broad SPD and short wavelengths, which include HPS, MH, LPS, and LEDs. The highest visual range sensitivities in reptiles were presented when exposed to MH, followed by HPS and LEDs. LPS was reported as the light source that induced the least detectable sensitivities in reptiles.	[167]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
1	ALAN (ind.)	The nest-building behaviour (height choice of the nest) was altered in urban great tits (*P. major*). Nests were built at higher locations, and thinner nests were built in cavities when proximate to night-time illumination, which is probably due to avoidance of predators and light pollution.	[168]
2	ALAN (ind.)	An earlier onset for breeding and offspring fledgings was observed in urban areas with noise, light pollution, temperature, and humidity, compared to great tits (*P. major*) that bred in forests. Although attempts were made to control the temperature, humidity, light, and noise, the differences persisted, which led to inconclusive results. The study results imply that forest and city bird populations may be shaped by other environmental factors that were not considered in the study.	[169]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
3	LEDs	This study reported varied responses in great tits (*P. major*) and pied flycatchers (*Ficedula hypoleuca*) when they were exposed to LED light with an illuminance of 8.2 lx and with varied SPDs (white, green, red). The two year experiment showed an early egg-laying behaviour in great tits (*P. major*) for the first year for white and green light when compared to individuals kept in the dark. However, no such effect was observed in the second year. For pied flycatchers (*F. hypoleuca*), no effect was reported in the laying of eggs for both years when exposed to ALAN. In both great tits and pied flycatchers, ALAN presented no effect on their clutch size. However, in the first year of the study, great tits were observed laying larger clutches away from the location where ALAN was present. ALAN caused no effect on the probability of brood failure, the number of chicks fledged, and the breeding densities of great tits and pied flycatchers.	[170]
4	ALAN (ind.)	When exposed to ALAN, urban tawny owls (*Strix alvoc*) showed an early onset in their breeding behaviour compared to rural birds.	[171]
5	ALAN (dir.)	Urban blackbirds (*T. merula*) were observed to have an advanced reproductive maturity of 19 days earlier compared to rural birds. Urban birds in the business district presented an earlier onset of the day. At an intermediate level of urbanisation, no significant difference in onset of the day was reported for blackbirds (*T. merula*) in rural forests and urban parks.	[172]
6	ALAN (dir.)	Exposure to ALAN was observed to cause an early onset of gonadal development and an early onset of hormonal secretion in urban blackbirds (*T. merula*).	[173]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
7	LEDs	Different stages of gonadal growth were activated for male great tits (*P. major*) when exposed to warm white LED light with varied illuminance of 0.5, 1.5, and 5 lx at night. The study reported an increased development of germ cells at 0.5 lx. Also, males exposed to 0.5 lx and 1.5 lx showed transcript levels related to steroid synthesis, spermatogenesis, and a slight growth of the testes size. Males exposed to 5 lx presented significantly larger testes compared to males exposed to lower illumination. The study suggests that a photoperiodic response was induced in male great tits (P. major) at night when exposed to low levels of LEDs.	[174]
8	LEDs	An altered sexual selection process was noted in wild great tits (*P. major*) mates, which can potentially affect the parentage of great tits offspring when exposed to LED light with an illuminance of 8.2 lx and different SPDs (white, green, red). Few young broods reported an increased extra pair copulation when exposed to white and red LED light with distance from the nearest sources. No effects were reported related to the distance to the nearest light source when exposed to green LED lights.	[175]
9	ALAN (dir.)	Low levels of estradiol were reported in female and male scrub-jays (*Aphelocoma coerulescens*) when they were exposed to ALAN with an illuminance of 3.2 lx.	[176]
10	LEDs	When great tits (*P. major*) were exposed to warm white LED light with varied illuminances of 0.05 lx, 0.15 lx, 0.5 lx and 1.5 lx at night, the onset of their activity was significantly advanced. The activity offset was delayed and melatonin levels were decreased at midnight. Night-time activity increased and melatonin levels measured at midnight decreased with higher intensities.	[177]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
11	FL	Zebra finches (*Taeniopugia guttata*) showed an increased cell proliferation in their ventricular zone, a decrease of neural densities in two distinct areas of the brain significant in areas essential for visual perception, associative learning, audition, and vocal communication in birds, and suppressed melatonin production under FL with a broad SPD and illuminances of 0.5, 1.5, and 5 lx, which is suggested to increase body mass as well (except for the exposure of 5 lx). Melatonin levels were significantly lowered at all illuminances. However it was significantly lowered for illuminances of 0.5 and 5 lx.	[178]
12	FL	Higher locomotor activity was reported in urban birds when they were exposed to FL at night with an illuminance of 0.53 – 8 lx and a broad SPD, compared to rural birds (no ALAN exposure, 0 lx). Urban birds showed an early onset of locomotor activity before luminaires started to operate and stayed active thirty minutes more compared to rural birds, which started their activity after luminaires started operating and remained quiet after the lights went off. Suppressed melatonin levels were observed in urban birds compared to rural birds. Also, ALAN was reported to induce lower species diversity and the species richness of intestinal microbiota in birds, which may result in weight loss, digestive dysfunction, and immuno-deficiency in Eurasian tree sparrows.	[179]
13	ALAN (dir.)	Birds during long nocturnal migration flights may stop-over at illuminated locations, which may increase the density of migrating birds in areas illuminated at night, but may decrease within a few kilometres of the operating source of light at night. The attraction of birds towards illuminated locations may include a potential impact on the selection process of forest stop-over and habitats in migrating birds.	[180]
14	ALAN (ind.)	The attraction of nocturnal migratory birds to light polluted locations may alter the perception of orientation and navigation cues, which can potentially lead to destination shifts and changes in flying routes.	[181]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
15	CMH	Nocturnally migrating birds were observed to have significant attraction and disorientation when exposed to CMH (red, green, blue) and MH with opaque filters. Both exposures were observed during overcast conditions (cloudy with more than 50% cloud cover and clear with at most 50% cloud cover), and moonlight (less than or equal to half moon and more than half moon) at night. The exposure to white and red MH was noted to highly disturb and attract birds. Under blue MH birds followed a seasonally migratory direction. Under green MH birds were less oriented than in blue MH, however, birds were less attracted and disturbed in comparison to red and white light.	[182]
16	ALAN (ind.)	Disorientation has been observed in nocturnally migrating birds,. Birds may be attracted to illuminated locations at night. During these nocturnal flights, disorientation might lead to looped migrations which may have a larger effect in the number of attracted birds and may raise the mortality rate in juvenile birds, as young birds undertake their first migratory flights at night during autumn.	[183]
17	CMH, HPS, and LEDs	When exposed to CMH, HPS, and LEDs at night, approximately 230 migrating birds were grounded, including short-tailed shearwaters (*Ardenna tenuirostris*). Also, the study suggested that the attraction and disorientation occurred during night flights. MH was observed to attract the highest number of birds, as it is a source rich in short-wavelengths. However, the study suggests that the attraction of birds is a wavelength dependent response.	[184]
18	ALAN (dir.)	The upward emission of ALAN has been observed to cause collisions of nocturnally migrating birds against man-made structures which can result in the death of birds, and for those that are injured, potentially put them at risk of predation. Birds, which produced nocturnal flight calls during migration flights, collided more often with buildings as a response to positive phototaxis towards ALAN, compared to birds that did not produce such communication calls. About 69,000 collisions involving 93 species from 15 families of birds were reported.	[185]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
19	ALAN (ind.)	ALAN was reported to cause the death of about 6,000 nocturnally migrating birds for spring, and about 11,800 birds for the fall season. These deaths involved 121 species.	[186]
20	ALAN (indir.) and moonlight	This study investigated the number of birds influenced by ALAN and moonlight. The vast majority of birds were found grounded during low moonlight visibility (with less than 20% of the moon's face illuminated or above the horizon and at sea level during sunset and sunrise). Bird species influenced by ALAN included Flying Leach's storm-petrel (*Oceanodroma leucorhoa*), European storm-petrel (*Hydrobates pelagicus*), and Manx shearwater (*Puffinus puffinus*).	[187]
21	ALAN (ind.)	ALAN was observed to attract and disorientate short-tailed shearwaters (*Ardenna tenuirostris*), with a 39% fatality rate.	[188]
22	ALAN (ind.)	298 species of migratory birds such as Basra reed warbler (*Acrocephalus griseldis*) and the Sakhalin leaf warbler (*Phylloscopus borealoides*) were exposed to light polluted locations except for the golden crowned sparrow (*Zonotrichia atricapilla*). The study observed that birds were exposed to ALAN during migration and in non-breeding ranges.	[189]
23	ALAN (ind.)	Nocturnally migrating birds were observed to be exposed to light polluted locations when flying at higher altitudes. ALAN in urban areas was reported to affect. Flight altitudes in migrating birds were reported higher (vertical distribution of flying/migrating birds) when flying over bright locations when compared to darker areas (non-urban locations) at night. However, the study indicates that the flying ranges depend on site and seasonality.	[190]
24	ALAN (ind.)	Fallout behaviour at night was observed when a large number of birds were grounded during migration. Fallout is a result of weather conditions and light pollution which can induce disorientation during night flights, and/or attract birds towards illuminated areas, leading to potential collisions, and predation, and may prevent birds becoming airborne again. The study observed that a considerable number of fallouts involving grounded Hutton's shearwater fledglings (*Puffinus huttoni*) coincided with the new moon. 0.1 – 0.3 % of annual fledglings was recorded each year for a period of 8 years. However, fallouts were not observed to occur in direct correlation to the extent of light pollution on land.	[191]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
25	ALAN (dir.)	A consistent spatial pattern of fallout was reported in Newell's shearwaters (*Puffins newelli*) when they were exposed to illuminated areas on land at night. However, the study suggests ALAN is not exclusively limited to land, and that it may also adversely impact birds in flight at sea which could affect large populations of fledglings near coastlines.	[192]
26	ALAN (ind.)	Night-time exposure to ALAN has been shown to significantly decrease the overall efficacy of nocturnal insectivorous neotropical migrating birds.	[193]
27	LEDs	Blackbirds (*Turdus merula*), long tailed tits (*Aegithalos caudatus*), gold crests (*Regulus regulus*), willow warblers (*Phylloscopus trochilus*), and great tits (*Parus major*) were exposed to LEDs with an illuminance of 8.2 lx and with different SPDs (white, green, red). There was a significant difference in bird activity in dark locations when compared to the activity of birds in locations exposed to green and red LED light. However, the study suggests that the results remain inconclusive for birds as it is unclear what may have caused the change in the number of active birds at night at illuminated transects.	[194]
28	LEDs	Great tits (*P. major*) were exposed to white LED light with an illuminance of 1.6 lx at the bottom of their nests. An early onset of activity was observed, specifically during the waking up time. Also, birds were observed being active at night, which was observed to reduce their sleep time by 5%. Female great tits spent a significant portion of the night time awake under ALAN.	[195]
29	LEDs	Great tits (*P. major*) were exposed to white LED lights at night with an illuminance of 1.6 lx at the bottom of their nests. Females were observed to fall asleep later and they woke up earlier, which significantly reduced their resting portion. The frequency of their sleep bouts decreased, while the length of their sleep bouts remained the same. Female chicks showed altered sleeping patterns at night, which increased their begging and interrupted the sleeping portion of the night.	[196]
30	LEDs	The total daily activity of male urban great tits (*P. major*) did not differ when the birds were exposed to LED lights with different SPDs (white and green) and an illuminance of 1.5 lx. Both light treatments showed a higher level of daily energy expenditure and a preference for roosting behaviour. However, forest birds were considered more active when they were exposed to white light. No conclusive results were reported on the plasma levels of oxalic acid (a biomarker of sleep deprivation).	[197]

Table S6. Key findings about the effects of ALAN for the organism group of birds.			
#	**Light source**	**Key findings**	**Ref.**
31	LEDs	Great tits (*P. major*) feeding offspring while exposed to LED light with an illuminance of 7.6 lx showed lower daily energy expenditure compared to birds in the dark. However, the study revealed an increase in food availability in the illuminated transects where lower daily energy expenditure was reported which may have mediated this result.	[198]
32	LEDs	An advanced onset of activity during the morning and an advanced activity during the night was reported for captive blue tits (*C. caeruleus*) when they were exposed to LED light with different SPDs (white, green, red) and an illuminance of 5 lx. An advanced onset (more than 2 h and 1 h) was observed with white and green light, respectively, when compared to the birds with no ALAN exposure.	[199]
33	ALAN (ind.)	European robins (*Erthiacus rubecula*), European blackbirds (*T. merula*), European wrens (*Troglodytes troglodytes*), great tits (*P. major*), and blue tits (*C. caeruleus*) were observed to be active at night when exposed to ALAN. European robins (*E. rubecula*) and European wrens (*T. troglodytes*) extended their night-time activity, which led to a premature start of activity before sunrise 03h30 – 04h00. In various occasions, European robins (*E. rubecula*) started earlier at 00h30, and European blackbirds (*T. merula*) started earlier at 04h00 and 05h00, while great tits (*P. major*) and blue tits (*C. caeruleus*) did also to some extent. European robins (*E. rubecula*), also showed an active behaviour at night, but most of their activity occurred during the day.	[200]
34	ALAN (ind.)	This study evaluates the activity rhythms of urban adult male European blackbirds (*T. merula*) during two periods that include earlier in the night (10h00 – 00h30) and later in the night (00h30 – 3h00). The advancement of onset and daily activity was observed in urban birds compared to birds in rural locations. Also, an earlier onset of activity was reported in birds located within the business district that were exposed to high levels of ALAN late at night. However, the night time exposure to ALAN was not considered to influence the end of daily activity.	[201]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
35	ALAN (ind.)	Active nocturnal behaviour was exhibited during the breeding season and after sunset that continued until early in the morning. The active hunting behaviour of Eleonora's falcons (*Falco eleonorae*) was also reported to occur during nights with little moonlight or overcast conditions. ALAN was observed to increase the capture of nocturnal migrant species such as members of the genera *Sylvia* and *Acrocephalus*.	[202]
36	ALAN (dir.)	The night-time behaviour of the common swift (*Apus apus*) was studied in four locations with four different illuminance levels (0.005 lx, 0.83 lx, 3.85 lx, and 120 lx). No activity was observed during sunset at 0.005 lx. The highest level of night-time activity was registered at 120 lx. Morning activity started earlier in colonies exposed to 0.005 lx, 0.83 lx, and 3.85 lx.	[203]
37	LEDs	An advanced onset of activity was observed in great tits (*P. major*) when they were exposed to the light emitted from white LEDs with varied illuminances (0.15, 0.5, 1.5 and 5 lx), rather than a phase shift of their internal circadian clock.	[204]
38	ALAN (ind.)	When exposed to ALAN, an earlier seasonal timing was reported in great tits (*P. major*), blue tits (*C. caenleun*), common chaffinches (*Fringilla coelebs*), and European blackbirds (*Turdus merula*), which may cue changes in behavioural patterns of activity such as dawn and dusk singing, and rest. Birds were seen to wake up earlier and they showed extended activity patterns during the night-time such as foraging, which continued throughout the night. The length of sleep in birds was shortened.	[205]
39	LEDs	A prolonged activity and extended foraging period were observed in great tits (*P. major*) when they were exposed to white LEDs with an illuminance level of 10 lx.	[206]
40	ALAN (ind.)	Altered foraging behaviour was observed in mockingbirds (*Mimus polyglottos*) that were located in areas with high levels of illuminance such as parking lots. With increased illuminance, mocking birds were observed to feed their nestlings later into the night.	[207]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
41	ALAN (ind.)	An altered timing and distribution of foraging opportunities were reported in redshanks (*Tringa totanus*) when they were exposed to ALAN. Their night-time foraging activity was influenced by the moon phase on clear nights. During the new moon, redshanks were seen to spend less time foraging than during the full moon.	[208]
42	ALAN (ind.)	This study investigated the interaction and foraging behaviour of bats and nighthawks (*Chordeiles minor*) attracted by an illuminated obelisk. The illuminated obelisk was considered to attract insects, and as a consequence, also attract potential predators such as bats and nighthawks. Nighthawks were observed foraging at a higher location compared to bats.	[209]
43	ALAN (dir.)	Altered foraging activity was observed in urban blackbirds (*T. merula*) at locations with different illuminance levels: urban centers (0.36 – 44 lx), parks (0.12 – 0.15 lx), and forest (0.07 lx). Longer foraging periods were reported in areas with higher illuminance, such as urban centers, in comparison to darker areas such as parks and forests. An extended foraging behaviour was most pronounced during March, when days were shorter, and decreased considerably by mid-April. The body condition of blackbirds (*T. merula*) did not differ with the presence of ALAN.	[210]
44	ALAN (dir.)	An altered timing of singing was reported in European robins (*Erithacus rubecula*), blackbirds (*T. merula*), great tits (*P. major*), and blue tits (*C. caenleun*), with a significant impact on European robins (*E. rubecula*) when they were exposed to ALAN with an illuminance of 4 lx at the center of each site. The light source had a luminous flux of 8850 lm, a CCT of 2900 K, and a broad SPD.	[211]
45	HPS	The reproductive behaviour and communication of singing birds were hindered in chaffinches (*Fringilla coelebs*), blue tits (*C. caenleun)*, great tits (*P. major*), blackbirds (*T. merula*), and robins (*E. rubecula*) when they were exposed to HPS with an illuminance of 100 lx. For instance, female birds laid their eggs earlier, and males started their dawn songs earlier before morning, which may modify pairing success.	[212]

Table S6. Key findings about the effects of ALAN for the organism group of birds.			
#	**Light source**	**Key findings**	**Ref.**
46	ALAN (ind.)	An earlier dawn singing with no additional effects of ALAN was observed in robins (*E. rubecula*) and blackbirds (*T. merula*). Singing birds that include great tits (P. major), blue tits (*C. caeruleus*), and chaffinches (*F. coelebs*) had similar onsets of dawn song relative to sunrise across the season and similar effects of an earlier dawn singing when they were exposed to ALAN in five peri-urban forest sites with street lighting during their breeding season.	[213]
47	ALAN (ind.)	An onset of dawn chorus behaviour was observed in American robins (*Turdus migratorius*) for two years when they were exposed to ALAN. Whereas, the onset of dawn chorus occurred during true night in breeding.	[214]
48	ALAN (ind.)	An onset of dawn chorus behaviour was observed in American robins (*T. migratorius*) in a two year experiment where American robins were exposed to ALAN. The onset of dawn chorus occurred during true night in breeding.	[215]
49	LEDs	An earlier daily onset of dawn singing was observed in 14 species of birds in eight dark forest edges that were illuminated with LED light with different SPDs (white, green, red) with an illuminance level of 7.4 lx. No other effect was observed, such as an earlier daily onset of dawn singing among the 14 species of birds.	[216]
50	ALAN (dir.)	No impact was reported in the dawn singing behaviour of rufous-collared sparrows (*Zonotrichia capensis*) when they were exposed to ALAN with an illuminance of 0.7 - 9.4 lx.	[217]
51	ALAN (ind.)	The exposure to environmental factors such as noise and light pollution were observed not to affect the timing of dawn songs for male house wrens (*Troglodytes aedon*). However, social factors were seen to influence the timing of dawn songs in male house wrens (*T. aedon*). Earlier singing was noted in male house wrens (*T. aedon*) that were building nests during the nesting stag compared to male house wrens that were in incubation or the nestling stage. Male house wrens sung earlier in the presence of numerous neighboring male birds. During the building stage, unpaired male birds showed a late onset singing compared to paired males.	[218]
52	ALAN (ind.)	No effect on calling activity was observed in wood pigeons (*Columba palumbus*) when they were exposed to ALAN.	[219]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
53	LEDs	Great tits (*P. major*) exposed at night to white LED lights with an illuminance of 1.6 lx and 3 lx (inside of the nesting box) during the month of December (winter) and February (pre-breeding season) had a decreased duration of sleep (~ 40 min) with an early onset of sleep (~24 minutes). Birds were observed leaving their nest 18 minutes earlier. Sleep was delayed at 3 lx compared to birds that were exposed to 1.6 lx.	[220]
54	ALAN (ind.)	Male and female great tits (*P. major*) exposed to ALAN showed increased oxalate levels (a component seen in sleep loss) in male nestlings. However, the study suggests it is difficult to predict the correlation between sleep loss and increased oxalate levels in developing nestlings..	[221]
55	LEDs	Silvereyes (*Zosterops lateralis*) were studied using LED light with different SPDs (white, blue 470 nm, green 510 nm, yellow 580 nm and orange 620 nm). Their sleep onset time was determined by the end of chirping. The results showed that white, orange, and yellow light significantly delayed sleep onset while blue and green light showed only a slight interference. The higher the irradiance level (0.01, 0.02, 0.03 W/m²), the longer the sleep onset was postponed.	[222]
56	ALAN (ind.)	ALAN is considered to alter the patterns of resting behaviour in female great tits (*P. major*) during the night, which varied between females. Female birds spent 93.3% of the night in a resting position. The variation of pattern resting behaviour was not affected or linked to urban environmental factors such as temperature, atmospheric humidity, ALAN, or nocturnal noise.	[223]
57	LEDs	Great tits (*P. major*) and blue tits (*C. caeruleus*) both had their sleep affected by white LED light with an illuminance of 3 lx, with great tits showing more pronounced effects in comparison to blue tits. Great tits showed a loss of 50 mins of sleep, while blue tits only reported an altered evening latency, sleep bout length and frequency. Both great and blue tits presented an increased sleep bout length, decreased bout frequency, and an altered pattern in falling asleep.	[224]
58	LEDs	An active night-time behaviour and a gradual decrease of oxalic acid concentrations (indicating sleep deprivation) were reported in great tits (*P. major*) when they were exposed to white LED light with an illuminance of 8.2 lx.	[225]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
59	LEDs	No effect on the night-time sleep behaviour was observed in free-living great tits (*P. major*) when they were exposed to white LED light with an illuminance of 1.6 lx. However, the birds were living in cavities, which may shield to some extent, the ALAN treatments.	[226]
60	ALAN (dir.)	An altered nest selection was observed in urban black birds (*T. merula*), indicating a preference for illuminated nests at night as predators avoided the nests. The avoided predators included tawny owls (S. aluco), rodents, martens (*Martes spec*), and possibly also racoons (*Procyon lotor*). A correlation was also made between ALAN and advanced laying dates (by almost a week) when birds transitioned from nest sites in darkness to nest sites exposed to an illuminance of 1 lx.	[227]
61	ALAN (dir.)	ALAN and noise pollution was reported to influence the density of birds and their inter-seasonal stability, while food sources available were also considered to impact the species richness and density of birds. About 64 species of birds were observed to be affected by ALAN and noise pollution. The most numerous bird species that were impacted included great tits (*P. major*), magpies (*Pica pica*), blackbirds (*T. merula*), blue tits (*Cyanistes caeruleus*), rooks (*Corvus frugilegus*), fieldfares (*Turdus pilaris*), and house sparrows (*Passer domesticus*).	[228]
62	ALAN (ind.)	In urban birds, the combined 24h exposure to ALAN and noise pollution, specifically noise, decreased the daytime activity of male great tits (*P. major*), while ALAN was considered to have no effect on their daytime activity. The combined exposure to ALAN and noise increased the night-time activity in urban birds, compared to forest birds. No significant interaction of ALAN and noise was observed. ALAN significantly influenced the onset of activity for urban and forest birds.	[229]
63	CMH	Mixed-species flocks of birds that included wood-warblers (*Parulidae*), tyrant fly-catchers (*Tyrannidae*), and mimids (*Mimidae*) were observed to forage on insects attracted to the emission of CMH at night.	[230]

Table S6. Key findings about the effects of ALAN for the organism group of birds.			
#	**Light source**	**Key findings**	**Ref.**
64	ALAN (dir.)	European blackbirds (*T. merula*) exposed to an illuminance of 0.17 lux (range 0.07 – 61.7 lux) were shown to have lower levels of testosterone in female birds. Female blackbirds showed clear seasonally adapted levels of estrone, which increased in February and March, and then declined until May. In females, levels of estrone were reported to decrease with increasing lamp densities, while no effect was reported to influence male estrone concentrations.	[231]
65	LEDs	When nestling great tits (*P. major*) were exposed to white LED light with an illuminance of 3 lx (at the bottom of the nest) there was no increase in body mass. There was also no effect on their oxidative status. Whereas, great tits (*P. major*) from non-illuminated locations were observed to have a gradual body mass gain and no effect on oxidative status.	[232]
66	LEDs	When female great tits (*P. major*) were exposed to LED light with an illuminance of 7.6 lx and with varied a SPD (white, green, red) they laid their eggs earlier when compared to female birds, which were exposed to no ALAN. Female great tits (*P. major*) exposed to green and white light, laid eggs earlier than the female great tits exposed to darkness at night. While birds exposed to red light laid their eggs earlier, this was not as significantly earlier as the female birds exposed to white and green light. During spring, when temperatures were recorded to be low, an advanced egg laying date was seen in females exposed to LED light when compared to those exposed to no ALAN.	[233]
67	LEDs	An elevated corticosterone hormone was reported for great tits (P. major) when the bird's nests were illuminated with cold white LED light (CCT > 6000 K) with an illuminance of 1 lx at the nest height.	[234]
68	LEDs	This study exposed Zebra finches (*Taeniopygia guttata*) to warm and cool white LED lights (CCT 3000 K and 5000 K) with an illuminance of 0.3 lx. Higher rates of night time activity were observed in individuals that were exposed to 5000 K light compared to 3000 K light and no ALAN. Birds in the 5000 K treatment group also had increased corticosterone levels compared to those that were exposed to 3000 K and no ALAN, but there were no changes in their body condition or food intake. Individuals that were active during the night did not consequently decrease daytime activity.	[235]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
69	ALAN (dir.)	Urban and rural tree sparrows (*Passer montanus*) were compared when they were exposed to ALAN with illuminance of 12.5 lx to analyse their levels of luteinizing hormone, testosterone, and estradiol when exposed to night-time illumination. Urban tree sparrows were observed to have an earlier increase of luteinizing hormone, a lower peak in the secretion of luteinizing hormone, and lowered levels of testosterone and estradiol compared to rural birds that were exposed to lower levels of night-time illumination, while rural birds presented a higher peak in luteinizing hormone.	[236]
70	FL	Captive Australian budgerigars (*Melopsittacus undulatus*) were exposed to FL with an illuminance of 200 lx, a CCT of 4000 K, and different durations of exposures at night (30, 60, and 90 minutes). The study showed a gradual increase of body mass over a period of 3 months for all durations of exposures compared to no exposure. Increased duration of exposure to ALAN resulted in decreased egg production (by 85% at 30 min and 92% at 60 min). Birds exposed to 90 min of ALAN did not present an onset of egg production and showed reduced hatchability (from 61 – 41%). Additionally, disease severity increased with a duration of exposure which may increase susceptibility to infections.	[237]
71	LEDs	Great tits (*P. major*) were exposed to white LED light with an illuminance of 1.6 lx and 3 lx (inside their nesting box) during the winter period (Nov. – Feb. 2010 - 2015). This did not alter their exploration behaviour. The exploration behaviour was not associated with the roosting behaviour in nest boxes illuminated at night. However, the percentage of birds that roosted in illuminated nest boxes at night decreased to 71%. No conclusive evidence was found for ALAN as an environmental component that may induce personality dependent effects on the sleep patterns in birds. Sleep behaviour in slow and fast explorers was observed to be equally disrupted by ALAN.	[238]
72	ALAN (ind.)	The arrival of various birds was associated with ALAN, temperature, rainfall, and urban land cover. However, no effect was observed on the timing of their foraging behaviour or their arrival to these locations in winter when the birds were exposed to ALAN.	[239]

Table S6. Key findings about the effects of ALAN for the organism group of birds.

#	Light source	Key findings	Ref.
73	ALAN (dir.)	ALAN and noise pollution were observed to alter the nest attendance and weight gain of Scopoli's shearwaters (*Calonectris diomedea*). The birds gained less weight during nights with higher levels of moonlight regardless of light and noise pollution.	[240]
74	FL	When Australian budegerigars (*Melopsittacus undulatus*) were exposed to FL with an illuminance of 200 lx, a CCT = 4000K for 60 minutes, there was a significant increase in their body mass, and food and water intake, as well as a decrease in their reproductive behaviour, plus an increase in stress responses compared to individuals kept in darkness.	[241]
75	ALAN (dir.)	When wild tree sparrows (*Passer montanus*) were exposed to ALAN with varied illuminances of 0, 85, 150, 300 lx, they were observed to have an accelerated reproductive endocrine activation of the hypothalamic-pituitary-gonadal axis. Key proteins (TSH-b, Dio2, and GnRH-I), which express the reproductive endocrine activation in the hypothalamus, were significantly higher at an illuminance of 85 lx. Meanwhile, tree sparrows (*P. montanus*) exposed to 150 and 300 lx were observed to have a reduction in the peak expression of their pituitary hormone and estradiol levels, but there was no delay in the timing of these peaks compared to birds that were exposed to dark settings.	[242]
76	ALAN (dir.)	When female and male king quails (*Excalfactoria chinensis*) were exposed to ALAN with an illuminance of 0.3 lx, they were observed to have an increase in innate immune activity (increased bacterial activity) at different developmental stages.	[243]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials

#	Light source	Key findings	Ref.
1	HPS	Lesser horseshoe bats (*Rhinolophus hipposideros*) were observed to have a delayed commuting behaviour and altered flying trajectories, which negatively limited the selection of flying routes when they were exposed to HPS at night.	[24]
2	ALAN (indir.)	Mammals are potentially threatened by the expansion of ALAN in North American, European, and East-Asian cities increasing towards South American, South-East Asian, and sub-Saharan African cities. The regions with high mammal species richness showed a 354 % increase in the extent of light pollution. Bats were particularly affected by the increase and extent of ALAN.	[160]
3	ALAN (dir.)	No effect was reported on the nocturnal activity and behaviour of common wombats (*Vombatus ursinus*) when they were exposed to ALAN. The study observed 956 mammals detected at night out of 1086 species, which included wombats (622; 57%) and kangaroos (228; 22%) which made up 79% of the total detected species.	[161]
4	LEDs	This study investigated the activity of bats when they were exposed to LED light with different SPDs (white, green, red) with an illuminance of 8.2 lx. Bat activity was significantly increased when they were exposed to green light in comparison to red lights and no ALAN.	[194]
5	LEDs	Tammar wallabies (*Macropus eugenii*) were exposed to two different LED lights: a) cool white LED (CCT 5000 K) with an irradiance of 2.8 W/m^2, and b) amber LED (CCT 1700 K) with an irradiance of 2.0 W/m^2. A reduction of melatonin production was observed in wallabies exposed to cool white light compared to the amber light.	[244]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials			
#	**Light source**	**Key findings**	**Ref.**
6	ALAN	About 4,000 species of mammals were found exposed to ALAN in less than 10% of their habitat range during the years 1992 – 2012. In addition, North America, Europe, and Japan are geographic areas that are experiencing an increase in ALAN. The study observed about 4,000 mammal species have experienced changes in ALAN within their habitat range.	[245]
7	ALAN	The presence of bat species at night that included *Pipistrellus nathusii* and *Pipistrellus pygmaeus*, was investigated when they were exposed to ALAN with a monochromatic SPD (green λp = 520 nm). The presence of both bat species increased by more than 50% when ALAN was operating, in comparison to no ALAN.	[246]
8	ALAN	A large-scale survey on the calls made by bats at two different locations showed that the type of operating light sources at night and the density of operating luminaires were not associated with an increase in bat activity at night. The study demonstrated that the most abundant active species at night was *Pipistellus spp.* However, bat activity at night and calls made by lesser noctules (*Nyctalus leisleri*) were significantly linked to the density of luminaires and the type of operating light sources.	[247]
9	ALAN	Noctules (*Nyctalus noctula*), an insectivorous bat, were observed foraging close to aquatic and vegetative areas, and illuminated locations at night. They showed no preference or avoidance while commuting in forests at night when they were exposed to ALAN. However, the study suggests that their foraging locations might be influenced by the presence of ALAN.	[248]
10	LEDs	When lesser horseshoe (*Rhinolophus hipposideros*) and *Myotis spp.* bats were exposed to cool white LED light with an illuminance of 3.6 lx, they were observed to display repulsion away from the light during flight and their activity was reduced.	[249]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials			
#	**Light source**	**Key findings**	**Ref.**
11	HPS	When Sowell's short-tailed bats (*Carollia sowelli*) were exposed to HPS with an illuminance of 4.5 lx they had a repulsive response, less explorative flight trajectories, and a reduced harvest action of fruits.	[250]
12	ALAN	Pond bats (*Myotis dasycneme*) showed altered flight paths when they were exposed to ALAN with an illuminance of 30 lx.	[251]
13	HPS, LEDs, induction lamps	A restricted use of flying routes was considered to potentially disrupt the foraging activity of individual lesser horseshoe bats *(Rhinolophus hipposideros*) when exposed to HPS (referred as orange), neutral white LEDs (referred as white), and two induction lamps with narrowband wavelengths rich in mid and long wavelengths (referred as greed and red). All light sources, which were placed on hedgerows, were reported to reduce the activity of lesser horseshoe bats (*R. hipposideros*) during night flights. Also, lesser horseshoe bats (*R. hipposideros*) changed their flight paths to the dark side of the hedgerows, as a rapid adaptation, that allowed them to reach their foraging sites. Other species concisdered in the experiment were Myotis spp., which were observed avoiding HPS, LEDs, and the induction lamps rich in mid wavelengths. While *Pipistrellus spp.* was observed more active under PS, LEDs, and the induction lamps rich in mid wavelengths in comparison to nights exposed to no ALAN. *Nyctalus* or *Eptesicus spp.* presented no effect under ALAN. The study suggests the preservation of dark corridors as responses may vary among bat species.	[252]
14	ALAN	When Kuhl's pipistrelles (*Pipistrellus kuhlii*) and Botta's serotine bats (*Eptesicus bottae*) were exposed to ALAN with an illuminance of 12 lx they were both observed to have faster flight behaviour and a lower flying altitude.	[253]
15	FL	Suppressed melatonin levels were observed in female Japanese monkeys (*Macaca fuscata fuscata*) when they were exposed to FLs with illuminances of 10 – 30 lx. Whereas, the lower exposure of 2 – 5 lx did not suppress melatonin levels.	[254]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials			
#	**Light source**	**Key findings**	**Ref.**
16	HPS	When gray mouse lemurs (*Microcebus murinus*) were exposed to HPS their nocturnal emergence, which is an anti-predator response, was delayed. Less time was spent outside of the lemur's refuge. Also, exposure to ALAN was observed to cause a delayed return to their refuge. Moreover, their core temperature was also elevated, which suggests an increase in locomotive activity when the lemur's were exposed to HPS.	[255]
17	ALAN and moonlight	No significant differences were reported in the body mass and daily caloric food intake of female grey mouse lemurs (*M. murinus*) transitioning from short day to long day photoperiods when they were exposed to moonlight and ALAN. However, females that were exposed to ALAN had a higher core temperature and shorter locomotor activity compared to those that were exposed to moonlight. The higher core temperature was present for both photoperiodic exposures that included short days and long days. While the duration of nocturnal active behaviour was on average 66 min shorter in individuals that were exposed to ALAN compared to those lemurs that were exposed to moonlight.	[256]
18	ALAN (dir.)	Djungarian hamsters (*Phodopus sungarus*) exposed to pulses of ALAN with an SPD that was rich in long wavelengths were observed to have an earlier stop of locomotor activity, which eventually led to the suppression of their locomotor activity with a significant decrease in body temperature.	[257]
19	FL and LEDs	Light sources with a broad SPD such as LEDs and FL significantly influenced the period, the strength, and the duration of the active behaviour in mice (*C57BL/6J*). LEDs and FL both reduced the period at which activities occurred.	[258]
20	LEDs	Striped field mice (*Apodemus agrarius*) and bank moles (*Myodes glareolus*) were exposed to warm white LED light (CCT 3000 K) from street lights with an average illuminance of 5.8 lx. Striped field mice showed decreased activity during the daytime when they were exposed to LED light at night. When both species were exposed to white LED light there was a reduced home range overlap, proximity, and activity synchrony of conspecifics (members of the same species).	[259]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials

#	Light source	Key findings	Ref.
21	LEDs	Rodent bank voles (*Myodes glareolus*) exposed to cool white LED light (CCT 7250 K) with an illuminance of 0.8 lx showed an increased activity and an altered use of space during the quarter moon and new moon. No significant effect of ALAN was seen to impact their body mass, or their fecal glucocorticoid metabolites (a metric hormone for circadian disruption and lowered body mass). Male bank voles (*M. glareolus*) showed a greater body mass compared to females. During both the new moon and visible quarter moon, a higher activity was observed for voles that were exposed to ALAN, compared to voles in the dark.	[260]
22	ALAN (dir.)	Male *C57BL/6* mice showed varied responses when they were exposed to ALAN with monochromatic SPD (blue λp = 470 nm and green λp = 530 nm). The blue light was observed to alter their sleep and arousal. Night-time exposure to ALAN caused delayed sleep, increased glucocorticoid (an indicator of induced stress), and behavioural arousal. Mice exposed to the green light brought about rapid sleep. Altered sleep and arousal was seen in mice lacking melanopsin.	[261]
23	ALAN and moonlight	An altered core temperature, the timing and occurrence of estrus, and no significant difference in locomotor activity and urinary 17-ß estradiol (E2) concentration were reported in female grey mouse lemurs (*M. murinus*) that were exposed at night to two types of night-time illumination that included moonlight and ALAN, during the transition of a short day to a long day photoperiod. An early occurrence of estrus (a cycle in female mammals that presents physiological changes induced by reproductive hormones) while in a short day photoperiod was observed in female grey mouse lemurs (*M. murinus*) exposed to LEDs, compared to female grey mouse lemurs (*M. murinus*) that were exposed to moonlight exposure. No significant difference was present in urinary E2 values observed in female grey mouse lemurs that were exposed to moonlight and LEDs.	[262]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials			
#	**Light source**	**Key findings**	**Ref.**
24	LEDs	When Wistar rats were exposed to cool white LED light (CCT > 6000K) with an illuminance of 200, they showed a remodeled retina and no sign of death of the outer nuclear layer in the retina, but a noticeable reduction of the outer nuclear layer in the retina. No differences in the number of nucleus, no retinal ganglion cell death, and no damage to the inner structure were detected. However, light sensitive photopigments melanopsin and neuropsin were observed to have a modified location and expression. The study suggests that ALAN does not affect cell survival at this layer, but may induce deep retinal remodelling, which can potentially lead to blindness and circadian rhythm desynchrony.	[263]
25	LEDs	An impaired and delayed healing process was observed in female mice (*C57Bl/6*) that were exposed to white LED light (CCT 5000 K) with an illuminance of 5 lx. The study showed that the night-time period is an essential part of rhythmic cycles necessary for the recovery of wounds in mice.	[264]
26	ALAN and moonlight	Tammar wallabies (*Macropus eugenii*) were exposed to ALAN with a long wavelength SPD (red), broad SPD (white), and no ALAN; as well as three different moon phases (full moon, quarter moon, and new moon) at night. ALAN increased foraging activity and decreased the time allocated to predator avoidance. Predation risk at night can be potentially increased due to the time spent foraging, which reduces the vigilance behaviour necessary to avoid predators. Moon phases had no significant variation in time allocation to behaviour. However, foraging activity increased when the wallabies were exposed to all moon phases under both exposures to ALAN (red, white) in comparison to moon phases with no ALAN. The wallabies were observed to be less vigilant under red ALAN in comparison to no ALAN exposure.	[265]
27	ALAN	Suppressed melatonin levels and a delay of birth were observed in Tammar wallabies (*Macropus eugenii*) that were exposed to ALAN. Individuals living in habitats located within a naval base with ALAN presented lower levels of melatonin when compared to those exposed to no ALAN. Tammar wallabies exposed to ALAN gave birth with a one month delay.	[266]
28	LEDs	Mares (*Equus callabus*) were exposed to monochromatic blue LED light (λp = 468 nm) at different illuminance levels ranging from 0.1, 3, 10, 50, and 100 lx to study their melatonin levels. No significant difference in melatonin was reported when the mares were exposed to 3 lx and below.	[267]

Table S7. Key findings about the effects of ALAN for the organism group of non-human mammals: bats, primates, rodents, marsupials			
#	**Light source**	**Key findings**	**Ref**
29	ALAN	Siberian hamsters (*Phodopus sungorus*) were exposed to ALAN with illuminance levels = 5 lx to determine if ALAN might alter their circadian clock functions and the molecular mechanisms of their photoperiodic responses. A disrupted short day response in testes mass regression was observed. Also, significantly large testes were seen in Siberian hamsters that were exposed to ALAN compared those that were exposed to 0 lx. The photoperiod and duration of exposure to ALAN was observed to have a significant effect on spermatid nuclei counts in the testes and sperm count in epididymis. The photoperiod had a notable impact on the body mass of Siberian hamsters which was reduced in a short day photoperiod compared to a long day photoperiod. Siberian hamsters exposed to a short day photoperiod and ALAN, were observed to have larger bodies and darker pelage compared to those that were exposed to a short day photoperiod and darkness at night. The photoperiod and duration of ALAN was seen to affect pelage colouration and density. However, no difference in pelage was reported for Siberian hamsters that were exposed to a short day followed by ALAN and a long day exposure. Siberian hamsters exposed to a short day were observed to have a greater pelage density than Siberian hamsters exposed to a long day. However, the pelage density of Siberian hamsters exposed to a short day and ALAN were not significantly different from those that were exposed to a short or long day without ALAN. Siberian hamsters that were exposed to a short day were seen to be less active than those that were exposed to a long day or short day with ALAN. Non-reproductive Siberian hamsters that were exposed to ALAN were observed to have an increase in activity compared to hamsters exposed to a short day. Between light and the dark phase, the locomotor activity of Siberian hamsters was significantly different. Siberian hamsters The photoperiod and exposure to ALAN were considered closely linked with the expression of the circadian clock gene Period1 Per1 and the gene expressions required for photoperiodic responses that include the melatonin receptor Mel-1a, eyes absent 3 Eya3, the thyroid stimulating hormone receptor Tshr, the gonadotropin-releasing hormone GnRH, and the gonadotropin-inhibitory hormone GnIH. An increased in the levels of of Per1 (the circadian clock gene Period1), Mel-1a (melatonin receptor), Eya3 (eyes absent 3), Tshr (the thyroid stimulating hormone receptor), GnRH (the gonadotropin-releasing hormone), and GnIH (the gonadotropin-inhibitory hormone)	[268]

		were detected in Siberian hamsters that were exposed to ALAN compared to those that were exposed to short days.	
30	FL	One male and female potto (*Perodicticus potto*), one female pygmy slow loris (*Nycticebus pygmaeus*), one female aye aye (*Daubentonia madagascarieusis*), a breeding pair of Mohol bushbabies (*Galago moholi*), and one male Mohol bushbaby with a black and rufous elephant shrew (*Rhynchocyn petersi*) were exposed to FL with a SPD rich in long wavelengths and FL with a SPD rich in short wavelengths to demonstrate if active behaviours in Strepsirrhinies primates are affected by FL at night. The active behaviours of Strepsirrhinies primates including social skills, movement, feeding behaviour, self directed, and object examination were significantly reduced when they were exposed to FL with a SPD rich in short wavelengths compared to FL with a SPD rich in long wavelengths. The breeding pair of Mohol bushbabies), the male and female potto, and female pygmy slow loris were observed to be active when exposed to FL with a SPD rich in long wavelengths. The male and female potto, and female pygmy slow loris were seen to spend less time moving when exposed to FL with a SPD rich in short wavelengths compared to the nighttime exposure to FL with a SPD rich in long wavelengths. All mentioned species in this study spent more time examining objects at night when they were exposed to FL with a SPD rich in long wavelengths. Additionally, the female aye aye was observed to have a lowered salivary melatonin concentration when it was exposed to FL rich in short wavelengths compared to when it was exposed to FL with a SPD rich in long wavelengths. The study suggests that the activity increased in all species involved in this study when they were exposed to a SPD rich in long wavelengths.	[269]

Statement of academic integrity

I hereby certify that the submitted thesis "The environmental impact of artificial lighting in urban settings: gaps, challenges, and sustainable urban lighting design" is my own work and that all published or other sources of material consulted in its preparation have been indicated. I have clearly pointed out any collaboration that has taken place with other researchers and stated my own personal share in the investigations in the Thesis Outline. I confirm that this work has not been submitted to any other university or examining body for a comparable academic award.

Berlin, Germany
Date: 30.01.2024