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Light or flight?

The impact of artificial light at night on insect predation risk

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General discussion

Insects dominate life on Earth, comprising about 80 % of all animal species (Stork, 2018). They sustain countless ecosystem processes: they regulate plant communities through pollination, herbivory and detrivory, and they form a major food source for higher trophic levels (Chowdhury et al., 2023). Yet insects are currently undergoing severe declines in mass, abundance and species richness (Hallmann et al., 2017; Seibold et al., 2019). They are suffering "a death by a thousand cuts", as multiple stressors act simultaneously upon them (Wagner et al., 2021).

Given their central role in ecosystems, there is an urgent need for effective mitigation strategies to halt further insect losses. Artificial light at night (ALAN) is recognised as one of the threats to insect biodiversity (Owens et al., 2020), and ecologically responsible lighting should therefore be part of conservation planning.

Therefore, in this thesis, I explored the impact of ALAN on insects by investigating changes in predator-prey interactions. I assessed how ALAN influences predation pressures, which directly affect insect populations. By relating predation pressure to the spatial and temporal activity patterns of both predators and prey, as well as the prey's anti-predator colouration and behaviour, I aimed to clarify how changes in predation pressure arise.

In the following paragraphs, I summarise our findings by connecting the results from different chapters and I discuss them in the broader context of how ALAN can affect food web interactions. I formulate answers to the research questions brought forward in the introduction and highlight important findings that emerged during the research. I propose directions for insect conservation efforts and end with recommendations for future ALAN research.

Does ALAN affect the activity patterns of predators and prey?

ALAN blurs the line between day and night, reshaping how animals behave after sunset. In Chapters 2–5, we explored how ALAN changes the activity patterns of both diurnal and nocturnal species. We expected clear, opposing responses: extended or increased activity in diurnal species (Frank, 2009; Gomes et al., 2021, 2024; Henke et al., 2022; Maurer et al., 2019; Spoelstra et al., 2018) and delayed or inhibited activity in nocturnal species (Jiang et al., 2023; Rotics et al., 2011; Secondi et al., 2021; Stone et al., 2009; van Geffen et al., 2015). What we found was more nuanced, with responses shaped by species' ecology.

For diurnal predators, ALAN effectively stretches the day into the night. Great tits (*Parus major*) and jumping spiders (*Marpissa muscosa*) both became more active at night when exposed to ALAN (Chapter 3 & 4). However, the conditions under which they responded strongly differed. Great tits already altered their activity patterns at very low

light levels (1.5 lux, 2700 K; Chapter 3), whereas the jumping spiders only responded under much more extreme illumination (100 lux, 5500 K; Chapter 4). This highlights that the threshold for responding to ALAN can differ across taxa.

For diurnal, active hunting spiders there is limited research on the effects of ALAN on activity patterns. Some observational studies report ALAN-aided nocturnal foraging for four jumping spider species: *Menemerus bivittatus, Plexippus paykulli, Platycryptus undatus* and *Sitticus fasciger* (Edwards, 1969; Frank, 2009; Wolff, 1982). However, the specific light levels and spectral compositions in these reports remain unknown, making it difficult to directly compare their responses to our controlled experiments with *M. muscosa*. Our results suggest that the jumping spiders only show altered activity patterns under high levels of ALAN (Chapter 4).

For birds, the literature on ALAN effects is comparatively rich and largely consistent with the patterns seen in our study. Many species start their day earlier or end it later under ALAN (Da Silva et al., 2014; de Jong et al., 2016, 2017). While we did not see an increase in nighttime foraging in our experiment (Chapter 3), nocturnal foraging has been documented for several predominantly diurnal birds, including both insectivores and wader species (Da Silva et al., 2017; Lebbin et al., 2007; Leopold et al., 2010; Leveau, 2020; Russ et al., 2015; Santos et al., 2010). ALAN-induced nocturnal foraging can become especially beneficial when it leads to an increased availability of light-attracted prey (Leopold et al., 2010). In contrast, our laboratory study described in Chapter 3 represented a closed system where the prey availability remained constant, so that we only measured a direct behavioural effect of light.

As expected for nocturnal species, ALAN reduced activity in both cryptic *Mamestra brassicae* caterpillars (Chapter 2) and *Pipistrellus* bats (Chapter 5), though each responded in different ways. The pipistrelle bats redirected their foraging efforts towards darker areas, so that the ALAN effect was spatial rather than temporal. The *M. brassicae* caterpillars became more inactive overall when exposed to ALAN. However, unlike the bats, the caterpillars were confined to the illuminated environment and could not escape to genuinely darker habitats, only to partially sheltered areas beneath leaves. It is possible that caterpillars also show spatial avoidance of lit areas under more natural conditions.

Bat emergence times are strongly influenced by predator risk and prey availability, both of which vary with ambient light conditions (Jones & Rydell, 1994; Thomas & Jacobs, 2013). ALAN has been shown to delay bat emergence time (Stone et al., 2009). However, in our study (Chapter 5), the bats had already emerged and commuted to their foraging grounds. During foraging, bats likely mainly track the temporal patterns of available insects. Under ALAN conditions, pipistrelle bats were found to shift from a

bimodal pattern to all-night foraging, correlated with increased insect presence throughout the night (Hermans et al. (2024). Intriguingly, this was not what we observed. In our study, night-flying insects shifted their temporal patterns under ALAN, but bats did not follow these shifts (Chapter 5).

In this field experiment, flying insects showed an earlier median activity in the second half of the night under lit conditions, meaning they were more active towards the middle of the night (Chapter 5). Generally, insects are most attracted to light when there is a strong contrast between the light source and the surrounding natural light. This contrast is greatest during the darkest part of the night, between the twilight periods. As a result, with the introduction of ALAN, insect activity may become even more concentrated in these darkest hours. Alternatively, this shift in timing could be explained by ALAN altering when insects perceive twilight. By increasing ambient light levels, ALAN may temporarily shift the light-intensity threshold that (de)activates insects (Gomes et al., 2024). If insects in ALAN-impacted areas perceived dawn to occur earlier, they might shift their second activity peak to earlier hours. If so, we would also expect dusk to be perceived later, delaying the first activity peak. This pattern was not evident in our data, although our ability to detect it may have been limited by the low number of insects caught under dark conditions.

While some of our results aligned with predictions for how diurnal and nocturnal species respond to ALAN, not all species were affected as anticipated. In particular, caterpillars exhibited unexpected responses. The predominantly diurnal, aposematic *Pieris brassicae* caterpillars showed no detectable change in activity in response to ALAN, whereas cryptic, nocturnal *Pieris napi* caterpillars increased their nocturnal movement and daytime feeding under ALAN (Chapter 2). Caterpillar activity patterns are not well documented, especially in relation to ALAN (Niepoth et al., 2018). While some species show clear diurnal or nocturnal rhythms, many are active both during the day and at night (Haynes et al., 2023; Heinrich, 1979; Niepoth et al., 2018). In our study, all caterpillar species were significantly more active in either the day or night, but their activity never ceased completely in either phase. This lack of strict separation in circadian activity may help explain why caterpillar responses to ALAN did not always match our expected responses. Furthermore, caterpillar behaviours are not only determined by light, but are also mediated by plant volatiles, which respond to light as well (Shiojiri et al., 2006). This thus adds an extra layer of complexity. In our experiments where we used living plants (Chapter 2), such plant responses are likely included. However, we did not measure plant volatiles, so we can only speculate as to what factors changed caterpillar behaviour under ALAN.

ALAN can have several fitness effects in nocturnal as well as in diurnal species. In nocturnal species, ALAN may reduce the time available for feeding and mating,

because ALAN can restrict their activity (van Geffen et al., 2015; van Langevelde et al., 2017). In contrast, in diurnal species, ALAN may give a larger time window to feed and perform other essential behaviours, which may thus increase their fitness. However, increased activity can have negative consequences, as such activities can also increase exposure to predators (Henke et al., 2022). Moreover, deleterious physiological effects may arise from ALAN-induced sleep disruption (Cirelli & Tononi, 2008) or from the chronic exposure to ALAN itself (Petrović et al., 2025; Schumann et al., 2025). Consistent with this idea, species that prolong their foraging activity under ALAN often show no improvement in body condition, suggesting that extended activity may come with trade-offs (Haynes et al., 2023; Russ et al., 2015; Taylor et al., 2022). Thus, ALAN-induced changes in activity patterns of predators and prey can change food web interactions, whereby winners and losers in the predatory arms race are unpredictable.

Does ALAN affect the spatial distributions of prey and predators?

In general, the way prey and predator species responded spatially to ALAN appeared to depend largely on perceived predation risk, which in turn is shaped by species traits such as escape skills and anti-predator colouration (Chapter 2,4,5). While cryptic species benefit from minimal movement and hiding, aposematic species can benefit from increased exposure (Ioannou & Krause, 2009; Nielsen & Mappes, 2020). In contrast, in many flying insects the attractive force of light seems to be an innate response that overrules the detrimental predation risk (Chapter 5).

In our laboratory experiments, caterpillars and spiders could not escape the light but could only seek shelter from it (Chapter 2 & 4). Under these conditions, ALAN increased hiding behaviour in cryptic species, including nocturnal *M. brassicae* caterpillars and diurnal *M. muscosa* jumping spiders (Chapters 2 & 4). Although we examined *M. muscosa* primarily as a predator, this spider is itself also prey for other species. As light makes cryptic species more conspicuous, hiding is likely their safest strategy. Increased sheltering under lit conditions has also been found in other palatable species (Dissegna & Chiandetti, 2025; Kenyon et al., 1995; indirect light response: Shiojiri et al., 2006). The only exception to these patterns was the cryptic, nocturnal *P. napi*. This species did not exhibit any spatial response, it only increased its movement under ALAN conditions (Chapter 2). For aposematic prey species, responses to ALAN were expected to be different, because exposure brings out their conspicuous warning signals that reduce predation risk (Nielsen & Mappes, 2020). In our laboratory experiment, diurnal *P. brassicae* caterpillars were indeed found more often on top of leaves under ALAN (Chapter 2).

In our urban field experiment, bats and flying insects were free to move and could either approach or avoid illuminated areas (Chapter 5). In this field experiment, pipistrelle bats preferred dark foraging grounds within urban environments, regardless of light dimming. These fast-flying, agile bats are known to exploit light-attracted insects around streetlights (Hermans et al., 2024; Spoelstra et al., 2017). However, pipistrelles do avoid illuminated areas during other activities, such as drinking and flying, suggesting that illumination carries costs (Hale et al., 2015; Russo et al., 2017). Although increased prey availability at lit sites can outweigh these costs during foraging, our results suggest that in extensively illuminated urban environments, this benefit–risk balance is less favourable. When lights are widespread, escaping visually hunting predators becomes more difficult because dark refuges are scarce. At the same time, prey aggregation around individual light sources may be reduced: urban insect populations show diminished flight-to-light behaviour (Altermatt & Ebert, 2016), and the insects that remain light-attracted are spread across many different light sources. Thus, even light-opportunistic species appear to reduce foraging in illuminated areas, suggesting that the benefit–risk ratio of feeding in the light is increasingly skewed towards risk in highly lit urban environments.

In our urban field experiment, we also found that insects remained attracted to light, especially at undimmed streetlights in urban environments, in contrast to the bats (Chapter 5). This persistent flight-to-light behaviour in insects is associated with negative fitness costs and negative insect population trends (Storms et al., 2025; van Langevelde et al., 2018; Wakefield et al., 2015). The detrimental impact of flight-to-light behaviour is further supported by evidence of evolutionary changes in urban moth populations, which show reduced flight-to-light responses compared to rural populations (Altermatt & Ebert, 2016; Van de Schoot et al., 2024). Thus, the attraction of insects to ALAN is a response to a misleading cue, which inadvertently traps them within an unfavourable light sphere (Fabian et al., 2024; Truxa & Fiedler, 2012).

Does the impact of ALAN depend on the visual ecology of species?

Visual acuity and colour sensitivity can vary significantly between species (Caves et al., 2024; Veilleux & Kirk, 2014), so that different light intensities or spectra can have varying impacts across taxa. Moreover, prey conspicuousness influences how effective light is for predator foraging (Medina et al., 2025). Cryptic species benefit from reduced conspicuousness to predators (Heinrich, 1979; Ioannou & Krause, 2009), whereas aposematic species gain from clearly displaying their warning signals (Nielsen & Mappes, 2020) and are generally less vulnerable to visually hunting predators (Aslam et al., 2020). However, if light levels are too dim for visual predators to distinguish warning colouration, the increased exposure of aposematic species may become

maladaptive. Similarly, the predation risk for cryptic species may increase if they fail to hide, as ALAN can make them more conspicuous.

Predator visual acuity is central to how ALAN affects predation. Great tits began their activity earlier in the day under ALAN, but did not spend their time foraging on caterpillars (Chapter 3). This suggests that these birds may be visually limited and unable to hunt effectively under low light conditions (1.5 lux, 2700 K). Visual limitations could impair the birds' ability to distinguish cryptic caterpillars from their background, thereby keeping foraging opportunities low under dim ALAN. Indeed, Kacelnik (1979) reported that light intensities below roughly 7 lux were too dim for great tits to efficiently forage on cryptic dummy caterpillars.

For the jumping spiders (*M. muscosa*), activity did not increase at 10 lux (Chapter 4), suggesting that this light level is already insufficient for effective hunting, although we cannot rule out that this response is driven by their internal clock rather than visual constraints. For two other jumping spiders of the genus *Cyrba,* 1.35 lux was found to be enough to discriminate dummy prey (Cerveira et al., 2019). Nevertheless, prey detection does not necessarily imply that the predators can successfully attack prey (Forster, 1982).

In addition to predator visual acuity, prey conspicuousness is also critical in determining the effects of ALAN. To investigate how predators respond to cryptic and aposematic prey under ALAN conditions, we conducted field experiments with clay caterpillars (Chapter 3). By using differently coloured clay models, we found no evidence of differential predation rates on aposematic or cryptic caterpillar models under ALAN conditions. We had expected that cryptic caterpillars would be more vulnerable to predation under increased illumination (Medina et al., 2025). However, a dummy predation experiment cannot account for potential behavioural changes in real caterpillars of both anti-predator colour types (Chapter 2). This is an important factor, caterpillar behaviour can directly influence the effectiveness of their colouration.

Taken together, these findings show that the impact of ALAN on predator–prey interactions cannot be predicted from the light regime alone. Instead, predation outcomes emerge from the interplay between the lighting conditions, predator visual constraints, and prey colouration and behaviour.

Does ALAN alter predation pressures?

ALAN can alter predation dynamics by enabling diurnal predators to extend or intensify their foraging into nighttime hours (Frank, 2009; Maurer et al., 2019; Russ et al., 2015), At the same time, nocturnal predators may be constrained in their ability to forage under ALAN (Secondi et al., 2021; Stone et al., 2009). In Chapters 3–5, I examined how

ALAN shapes predation by a diurnal songbird, a diurnal hunting spider, nocturnal bats, and a mixed community of diurnal and nocturnal predators. I found that predators responded differently, and that their responses were often more complex than a simple nocturnal–diurnal distinction.

When looking at the diurnal species, we indeed found that diurnal *M. muscosa* jumping spiders clearly increased their predation under ALAN (Chapter 4). Previous work on passive and active hunting spiders have shown similar foraging opportunities under ALAN (Frank, 2009; Willmott et al., 2019). These increased foraging opportunities are likely due to a combination of factors such as increased activity, enhanced visual capacity, and greater prey availability (Cerveira et al., 2019; Frank, 2009; Perkin et al., 2014). However, not all diurnal predators increased their nocturnal foraging. I found that diurnal great tits advanced the onset of their general activity pattern under ALAN conditions, while their foraging behaviour on cryptic caterpillars did not change (Chapter 3). One plausible explanation is that the birds are constrained by their visual performance, as I explain above.

When focusing on nocturnal species, we found that urban pipistrelle bats reduced their foraging under streetlights, irrespective of whether lights were dimmed or not (Chapter 5). Like many nocturnal species, bats are often light-averse, likely because light makes them more visible to their own predators (Rydell, 1992; Spoelstra et al., 2017). Still, some bat species are light-opportunistic (Rydell, 1992; Spoelstra et al., 2017). How bats respond to light is largely dependent on their traits and foraging strategies, as these determine predation risk (Voigt et al., 2021). For example, fast-flying pipistrelles are light-opportunistic and often found to exploit insects underneath streetlights (Blake et al., 1994; Hermans et al., 2024). The fact that we found reduced foraging activity of these bats may be due to the omnipresence of light in urban environments, which may have simultaneously increased risk and decreased the benefit of foraging under streetlights. Our contrasting finding thus underlines that ALAN's effects are not only species-specific, but also context dependent.

Our outdoor dummy predation experiment involving a community of both diurnal and nocturnal predators also revealed no effect of ALAN on predation (Chapter 3). Since these experiments were conducted at the Light on Nature sites, which are forest plots that have experienced more than a decade of light exposure (Light on Nature; Spoelstra et al., 2015), our results could possibly be explained by long-term effects of ALAN on predator community assemblages, as the loss of light-sensitive species may have knock-on effects on predation. Alternatively, the contrasting foraging responses of diurnal and nocturnal predators may have balanced each other out in the area.

Taken together, our variable outcomes on the effects of ALAN on predation pressures in Chapters 3–5 mirror the variable results reported in the literature (Amoroso, 2024; Eckhartt & Ruxton, 2022; Grenis et al., 2015; Jackson et al., 2025; Mcmunn et al., 2019; Miller et al., 2017; Nuñez et al., 2021). Rather than exerting a uniform directional effect, ALAN interacts with the sensory limits of predators, the traits and behavioural strategies of predators and prey, and the surrounding lightscape. The result is a mosaic of increased, decreased, or unchanged predation pressures, all of which together can highly reshape existing food webs.

ALAN affects urban and rural ecosystems differently

Urban habitats can be viewed as novel ecosystems, exposing organisms to distinct and often extreme pressures, with omnipresent artificial light likely being one of the most pervasive. Only a few common-garden experiments have compared the responses between urban and rural populations to ALAN. These studies suggest that urban populations can evolve distinct behaviours to cope with extreme urban lightscapes. For example, urban populations of the common moth *Yponomeuta cagnagella* (Yponomeutidae) show reduced flight-to-light behaviour compared to rural populations (Altermatt & Ebert, 2016), likely linked to their smaller wings and therefore reduced mobility (Van de Schoot et al., 2024). In contrast, urban populations of the spider *Steatoda triangulosa* (Theridiidae) exhibit reduced light avoidance compared to rural spider populations (Czaczkes et al., 2018).

One of our most unexpected findings was that the urban pipistrelle bats in our study behaved differently from what we know of pipistrelles studied in less urbanised areas (Chapter 5). Although pipistrelles are typically considered light-opportunistic species (Hermans et al., 2024; Spoelstra et al., 2017), we found that our urban populations preferred to forage in darkness.

As behavioural and genetic responses can differ markedly between rural and urban environments, it is important to compare rural and urban populations in the context of ALAN. Traditionally, ALAN research has focused more on natural than urban settings, partly because it is challenging to disentangle the effects of artificial light from other co-occurring stressors in cities (Halfwerk & Jerem, 2021; Liu et al., 2024). However, with the emergence of adjustable, smart lighting systems, we can now experimentally manipulate light intensity and spectrum within urban areas while keeping other factors constant, as demonstrated in Chapter 5. This opens new possibilities for understanding how urban populations respond to ALAN.

Automated monitoring holds great opportunities, but should be used with caution

Monitoring species in nature is generally labour-intensive and time-consuming, especially when data needs to be collected across large spatial and temporal scales. We experienced these human limitations first hand in Chapter 5 and started adopting machine learning methods to speed up the process. Machine learning is an advancing field within ecological research (Cipriano et al., 2025). Incorporating these methods into our research is highly valuable, especially given current ecological crises that demand faster processing and analysis of biological data. At the same time, it remains essential to be aware of their limitations, to validate automated outputs, and to continue improving these methods as the technology advances.

In Chapter 6, we trained an openly available object detection model, YOLOv8 (Jocher et al., 2023), on picture data from sticky sheets that trap insects and validated its performance against the manually collected dataset from Chapter 5. In this way, we showed that automated monitoring can greatly accelerate data collection, while also being user-friendly and cost-effective. In Chapter 4, we used the same YOLOv8 framework, but in a different context, i.e. to measure spider activity which underscores the flexibility and adaptability of this method.

Machine learning methods also have limitations. For automated object detection and tracking, it is important to carefully consider light conditions during study design; model performance was lower under dark conditions than under (un)dimmed light (Chapter 6). In addition, it is important to determine the desired temporal resolution before the start of the experiment. When higher temporal resolution is required, it is important to note that model performance may decrease, as objects are not always detected immediately and lighting effects become more pronounced.

Recommendations for insect conservation

To counteract current insect declines, it is important to mitigate the threats insects face, including ALAN. This requires a critical reassessment of our current lighting infrastructure (Owens et al., 2020).

To date, much of the research and mitigation efforts on the impact of ALAN has focused on street lighting (see also Chapter 3, 5 and 6). In this thesis, I show that dimming streetlights can help mitigate negative impacts, but also that even relatively low light levels can still alter the behaviour of insects and their predators. Since streetlights are widespread and publicly regulated, they present great opportunities to reduce the ecological impact of artificial lighting. However, our efforts must extend beyond streetlights, as many other light sources contribute to overall light pollution (Walczak

et al., 2023). In particular, private and commercial lighting is less regulated and can reach more extreme values in both intensity and colour spectrum.

Broad-spectrum lights with cool colour temperatures, such as the 5500 K used in two of our laboratory studies (Chapters 2 and 4), are more typically employed for applications such as sports field lighting, terrain lighting, garden lights, and monument illumination. Our experiments show that both caterpillars and spiders alter their behaviours under such cold white lighting. The increased herbivory and predation that we observed illustrate the direct impact of these ALAN conditions on the food web.

My recommendation is therefore to regulate lighting in public, private and commercial areas towards warmer light colours and dim lights to the lowest feasible levels. In addition, I advocate phasing out the most extreme lighting setups found in non-streetlight outdoor applications, unless their necessity can be convincingly demonstrated. However, these measures alone are not enough. Since our results show that disturbances of both predator and prey behaviours occurred even under dim conditions and warmer light colour temperatures, the primary goal should be to preserve and restore darkness, both inside and outside urban areas.

My recommendations are not new, but build further upon previous research and align with existing guidelines, such as "The Five Principles for Responsible Outdoor Lighting" (International Dark-Sky Association, 2024). These principles promote using light only when necessary, employing dim and warm-coloured lighting, limiting light spill to non-target areas, and restricting lighting to periods of actual use. Although more research is needed to evaluate novel lighting technologies in this rapidly changing field, there is already ample consensus within ALAN research to justify implementing these major guidelines now.

A key advantage of measures such as dimming lights and reducing unnecessary lighting is that they not only benefit the environment, but also save money by lowering energy use. The main barrier of turning to darkness is the strong perceived link between light and safety (Boomsma & Steg, 2014; Peña-García et al., 2015). However, evidence that light improves safety is weak (Gaston et al., 2015; Steinbach et al., 2015). Nevertheless, the feeling of safety is socially and politically important. Therefore, I advocate for efforts to disconnect safety perception from light presence. This challenging task requires translating scientific findings into compelling storytelling, implementing factual safety improvements, and fostering societal transformation.

Suggestions for future research

This thesis was primarily designed to investigate how ALAN could impact insect populations through altered predation pressures, while providing first insights into

potential patterns and pathways underlying these effects. To further disentangle the underlying mechanisms of how ALAN impacts predator-prey interactions, I recommend a more detailed examination of predators' visual capacities under different ALAN conditions. In addition, incorporating long-term studies that consider life-history traits and population dynamics within the predator–prey framework will provide a more comprehensive understanding of the ecological consequences of ALAN. Moreover, distinguishing between plastic and genetic responses to ALAN, particularly when comparing urban and rural populations, will yield important insights into the evolutionary dimensions of species' responses to ALAN.

As we move rapidly toward what has been termed the Sixth Mass Extinction (Cowie et al., 2022; Kolbert, 2014; Wake & Vredenburg, 2008), we unfortunately lack the luxury of unlimited time for exhaustive research. Identifying key traits that determine species' responses to ALAN will help us predict impacts across broader taxonomic groups rather than focusing solely on individual species (Spoelstra et al., 2017; van Langevelde et al., 2018; Chapter 2). Integration of machine-learning methods can accelerate this research by enabling the efficient processing of substantially larger datasets (Chapter 6). Evolving technologies also offer new opportunities; for example, tracking caterpillar feeding activity on live plants (Chapter 2) can now be done more efficiently using acoustic monitoring with the Insect Eavesdropper™ (Bick Lab, University of Wisconsin-Madison). These tools greatly enhance temporal resolution and allow us to address more detailed ecological questions.

Technological innovations within the lighting industry are essential to ensure that new light sources have minimal ecological impacts. Close collaboration with lighting designers and municipalities can place ecologists at the foundation of new developments, guiding innovation toward biodiversity-friendly solutions. Early-stage engagement is also essential to prevent the widespread adoption of lighting systems that could subsequently be found environmentally harmful.

Societal support is maybe even more important to develop more ecologically friendly lighting solutions in public spaces. I therefore advocate for an interdisciplinary approach that integrates ecological and social assessments. Such an approach would evaluate not only how well lighting technologies mitigate ecological impacts, but also how they are perceived in terms of safety, comfort, and suitability by residents and other stakeholders. This dual perspective is essential to ensure that ecologically responsible lighting solutions are both effective and publicly accepted.

Conclusion

The chapters in this thesis collectively show that species responses to ALAN are highly diverse. There is no single, definitive answer to whether ALAN increases or decreases

predation pressure on insects. Instead, outcomes emerge from a complex interplay of temporal, spatial, behavioural, and visual changes. These interactions generate strongly context-dependent and species-specific responses. Crucially, our variable results do not indicate a lack of impact. On the contrary, it is precisely these heterogeneous responses among species that have the potential to profoundly reshuffle food webs. Future research should distinguish more explicitly between urban and rural contexts and identify key functional traits within and between species that help predict responses to ALAN.

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