Title: Anthropogenic lighting affects moth abundance and diversity differently across ecosystems

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Highlights

- Light traps with known lighting properties were used in two different ecosystems.

- Abundance and diversity of captured moths were higher in forests than grasslands.

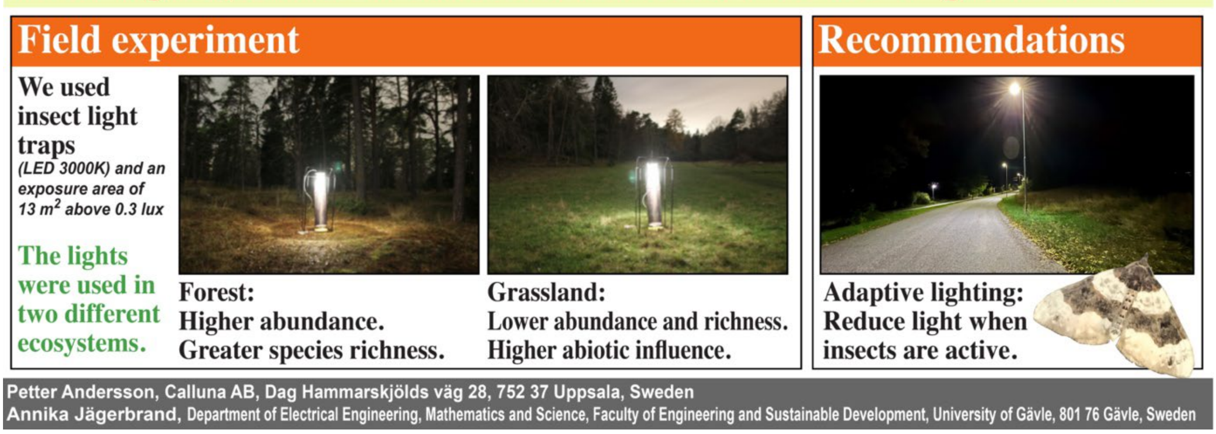
- Environmental factors had greater effects on attraction to light in grasslands.

- Different moth families showed varying attraction to light traps across ecosystems.

- The findings suggest the need for ecosystem-specific mitigation strategies.

Keywords: light pollution; nocturnal; insects; Crambidae; Geometridae; Noctuidae; artificial lighting

Graphical abstract



How light pollution affects moths in forests & grasslands

Field experiment

We used insect light traps *(LED 3000K) and an exposure area of 13 m² above 0.3 lux*

The lights were used in two different ecosystems.

Forest: Higher abundance. Greater species richness.

Grassland: Lower abundance and richness. Higher abiotic influence.

Recommendations

Adaptive lighting: Reduce light when insects are active.

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Abstract

Light pollution poses a significant threat to nocturnal insects, yet our understanding of how insects are affected by lighting across ecosystems is limited. The purpose of this study was to investigate differences in light-induced attraction in abundance and diversity of moths in forest and grassland ecosystems. This study presents a novel comparison of moth attraction between these ecosystems using identical light traps with known lighting properties across 32 sites. We found significantly higher moth abundance and diversity (species richness) in forests compared to open grasslands, where environmental factors such as temperature and cloudiness had stronger effects on moth attraction in grasslands. Notably, moth families showed varying responses across ecosystems, suggesting potential sampling biases in light attraction studies. Our findings point to the need for ecosystem-specific approaches in light pollution mitigation strategies and provide a methodological approach for future research on the impacts of anthropogenic light on biodiversity. The results have important implications for conservation planning and the management of anthropogenic lighting in diverse landscapes.

1. Introduction

The human need for illumination and the desired benefits of lighting our surroundings has led to an increased use of light at night (Boyce, 2019). This has resulted in light pollution, which refers to the adverse effects of anthropogenic light (CIE, 2020). Light pollution is recognised as a pervasive environmental problem with serious consequences worldwide, including reduced ability for astronomical observations of celestial objects (Kocifaj et al., 2023) and far-reaching implications for most species and their ecosystems (Jägerbrand and Spoelstra, 2023). Light pollution is a serious environmental problem impacting the majority of economically developed regions across the globe (Falchi et al., 2016a). The problem of anthropogenic nighttime lighting is escalating in almost all countries worldwide, with an annual rise of 2.2% in upward light emissions in already lit areas (Kyba et al., 2017).

A group of organisms significantly affected by nocturnal light are insects, whose responses to anthropogenic lighting have been extensively reviewed (Bruce-White and Shardlow, 2011; Boyes et al. 2020; Owens and Lewis, 2018; van Langevelde et al., 2018). Insects, the most species-rich animal group on Earth, play essential roles in ecosystems by providing services such as pollination, decomposition, soil formation, and pest control (Schowalter et al., 2018). Numerous studies have documented substantial declines in insect diversity and biomass (Hallman et al., 2017; Sánchez-Bayo and Wyckhuys, 2019; van Klink et al., 2020; Wagner et al., 2021; van Langevelde et al., 2018). These declines are linked to various factors, including habitat destruction and degradation, climate change, land use changes and habitat fragmentation (e.g., Sánchez-Bayo and Wyckhuys, 2019), as well as the potential impacts of anthropogenic light at night (Boyes et al., 2020; van Grunsven et al., 2020).

Many nocturnal insects are often attracted to light, a phenomenon known as phototaxis (Jekely, 2009; Gorostiza et al., 2016). Such attraction to light may cause mortality through circling, exhaustion, injury and increased predation risk when exposed in the light (Eisenbeis, 2006). Thus, anthropogenic light may potentially affect ecosystem services such as pollination and biodiversity (e.g., Macgregor and Scott-Brown, 2020). Insect attraction to light sources is influenced by several factors, including light intensity (Jägerbrand et al., 2023), spectral power distribution (e.g. Longcore et al., 2015; Niermann and Brehm, 2022), flickering (Barroso et al., 2017), light distribution and optics of the luminaire (Bolliger et al., 2022). However, very little is known about how the attraction of nocturnal insects to light sources is affected by the spatial context, such as the surrounding ecosystems. For instance, studies of moth attraction to anthropogenic light has been conducted in different types of ecosystems such as grasslands (Wakefield et al., 2016; Degen et al., 2016), urban environments (Straka et al., 2021), prairies (Grenis et al., 2023), woodland edges (Wakefield et al., 2018) and aquatic ecosystems (Meyer and Sullivan, 2013). However, as single studies in most cases are confined within the same ecosystem, test different light sources and are conducted at different times of the year, comparisons between results from different ecosystems are hard to make. Still, understanding differences in responses to light between different ecosystems is important to predict differences in responses in biodiversity and ecosystem services.

Grasslands, covering up to 40% of Earth's terrestrial surface, and forests, covering 30% and accounting for most of the terrestrial primary production and biomass, are both crucial biomes providing essential ecosystem goods and services globally (Blair et al., 2014; Pan et al., 2013). Due to differences in topography and elevation of physical features, these ecosystems exhibit varying light distributions and exposures for organisms. Forest ecosystems typically experience dim light conditions as vegetation filters and absorbs light, allowing limited light to reach the forest floor (Veilleux and Cummings, 2012). In contrast, open grasslands lack these filtering effects, allowing unobstructed light to dominate the landscape. These differences between closed forests and open grasslands may also result in varied exposure of insects to environmental factors such as weather conditions and moonlight. For instance, lower temperatures may significantly reduce moth catches in light traps, while increased cloud cover can increase them (Yela and Holyoak, 1997). It has also been shown that trap catches of moths can be considerably higher near the period of the new moon compared to full moon (Williams and Sing, 1951). Consequently, environmental factors can affect insect activity differently across ecosystems with potential interactive effects from anthropogenic light. Therefore, it is essential to consider confounding factors like weather conditions and moonlight exposure in studies of the effects of anthropogenic light attraction in different ecosystems.

In this study, we compare insect attraction to light in two different ecosystems, open grasslands and forests. Our objective was to investigate differences in light-induced attraction regarding abundance, richness, and diversity of moths between these ecosystems. For this purpose, we sampled moths in grassland and forest ecosystems with light traps using identical light exposure (same light sources, intensities and distributions). We used “spot” lamps and shielding to limit vertical light spread, creating a light cone confined to the nearby ground. This setup allowed us to implement identical attraction radii, enabling a comparison of abundance, richness and diversity per square meter of exposed area (above a threshold value for full moon/insects, see Jägerbrand et al., 2023). This approach is novel in studying insect attraction to light at night and facilitates comparisons between ecosystems.

2. Methods

2.1 Study area

The study area is situated south of Stockholm, in Huddinge, Haninge, and Botkyrka municipalities. The study area consists of boreo-nemoral mixed heterogeneous landscape types, such as forests with mixed evergreen and deciduous species, lakes, agricultural areas and open field grasslands. The forest ecosystem was dominated by for example *Picea abies*, *Populus tremula*, *Betula* spp. and *Corylus avellana*. The grassland ecosystem consisted of more or less managed meadows with dominance of various grasses, such as *Phleum pratense*, *Festuca* spp., *Hypericum* spp. *Trifolium* spp. and *Achillea millefolium*.

The brightest field site experience sky brightness of 2.64 mcd/m^2 (Vårby), medium bright sites had a mean value of 1.10 mcd/m^2 (five sites) and the darkest situated sites had 0.60 mcd/m^2 according to the New World Atlas of Artificial Night Sky Brightness (Falchi et al., 2016a, b). In the three municipalities, more than 1500 species of Lepidoptera have been recorded in accordance with the Species Observation System (SLU Swedish Information Center, 2024a) out of approximately 2700 resident species in Sweden (Eliasson et al., 2005).

2.2 Experimental set-up

We performed a field experiment on nocturnal moths using light traps. We used funnel traps with an attached net bag originally designed for the LepiLed light source (Brehm, 2017) (Fig. 1). However, we used a LED lamp (3000K 3.8W 350 lm Osram Germany) as the light source in the experiment (to simulate road lighting which does not have as much UV and blue light as LepiLed have) which was attached to the top lid of the funnel trap. To avoid vertical spread of light from the lamp, the upper surface on the lid of the funnel trap was covered with duct tape. The trap was mounted on a stand consisting of metal frames usually used for portable greenhouses (Fig. 1). We used portable power banks as the power supply for the LED lights. We documented luminance of the light trap and its surroundings (Fig. 1B), and detailed measurements of the illuminance at various distances and heights from the trap is presented in Appendix A.

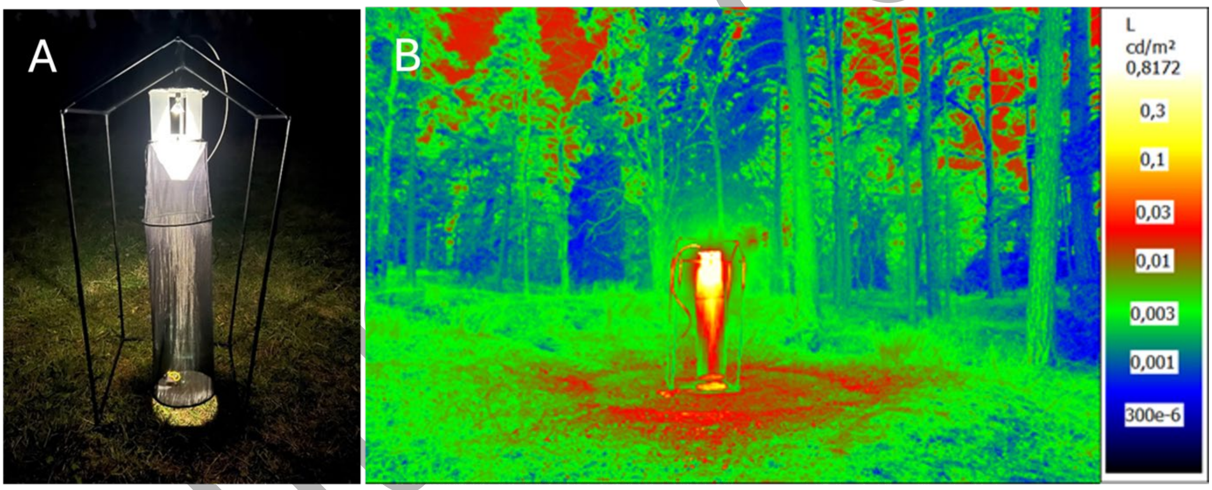

Figure 1. A) Close-up photo of insect trap with light that was used. B) Luminance photo of the insect light trap in the forest. Luminance photos were taken using LMK Mobile Advanced imaging luminance photometer (based on a Canon EOS 550D) and the associated computer software LMK labsoft ver. 12.7.23 (Techno Team Bildverarbeitung GmbH, Ilmenau, Germany). Note that the luminance photo (2B) uses false color to represent luminance values for clearer visualization of the distribution.

The experimental procedures were as follows. Light traps were mounted in late afternoons-early evenings (1-2 hours before sunset) at each site. We sampled two sites per night, one site situated in an open grassland and one site situated inside a forest. The mean distance between traps in open grassland and the nearest forest was 41 m (range 15-160 m). Potential sites had been identified beforehand from studies of aerial photographs. For each site we also used a control trap mounted identical to the light trap but with no light source. These control traps were placed in the vicinity of the light traps at each site, but never closer than 25 m. In the following morning, the traps were revisited and all moth individuals captured were photographed. All moths were released after documentation. This procedure was performed for a total of 16 nights between 26 July and 5 September 2022, resulting in sampling of moths at a total of 32 sites. All moths captured in the traps were identified to species using adequate literature and online databases (Sterling et al., 2012, Elmquist et al., 2011, SLU Swedish Species Information Center, 2024b).

At each sampling location, alongside with the installation of the light traps, we took notes on the prevailing weather conditions using the weather app provided by the Swedish Meteorological and Hydrological Institute (SMHI). We recorded the temperature (in Celsius) and wind speed (in meters/second) from the weather app. In addition, we also noted if the sky was cloudy or clear (as a binary variable) and also obtained information about the lunar phase (moon visibility, in %) during the night from the app Moon Phases and Lunar Calender (Kinetic stars).

2.3 Data and statistical analysis

All statistical analyses were conducted using R 4.1.0. (R Development Core Team, 2021). We analyzed the response variables moth abundance and moth richness at the sites with generalized linear mixed effects models (in the package lme4 (Bates et al., 2015)). In addition, we analyzed species diversity using linear mixed effects models . For all response variables, we included the fixed effects of the ecosystem (forest vs. grassland), temperature, cloudiness (cloudy vs. not cloudy), lunar phase (in %), and wind velocity (m/s). The sampling date was included as a random variable in all analyses. Since there is a possibility that environmental variables may affect trap catches differently in the ecosystems, we included the two-way interactions between the ecosystem and the environmental variables (i.e., temperature, cloudiness, wind velocity, and lunar phase). We used a backward stepwise selection procedure, removing non-significant variables from the full models. The resulting models were then compared using Akaike's Information Criterion (AIC) to determine the best-fitting model, continuing until no further improvement in AIC was possible. Species diversity (Hill's effective number of species) of insects in forest and open ecosystems was assessed using Hill's diversity index (e.g., Chao et al., 2014). We calculated q = 0 (species richness), q = 1 (the exponential of Shannon's diversity) and q = 2 (the inverse of Simpson's concentration index). All taxa are listed in Appendix C.

3. Results

The field experiment yielded 172 moth individuals from 54 species. Species richness at the investigated sites ranged from 1 to 8 species, with abundance ranging from 1 to 21 individuals. Of the 32 sampled sites, six sites captured no moths. Geometridae was the most species-rich family with 13 species (43 individuals), followed by Noctuidae with 11 species (46 individuals) and Crambidae with 10 species (47 individuals). None of the control traps (with no light source) captured any moths.

The total abundance and species richness of the captured moths was significantly higher in the forest compared to the open grassland (Table 1, Fig. 2). Abundance and species richness increased with increased cloudiness whereas abundance also increased with higher temperatures (Table 1, Fig. 3). Furthermore, trap catches in the open grassland increased at nights with higher temperatures and slow wind, as indicated by significant ecosystem by temperature and ecosystem by wind interactions (Table 1).

In Crambidae, abundance was significantly higher in the forest (Table 1, Fig. 4a) and increased with temperature and cloudiness, and there were significant two-way interactions between ecosystem and temperature and wind, where trap catches in open grasslands increased with temperature and decreased with wind (Table 1). However, species richness of Crambidae were only affected by increased cloudiness (Table 1, Fig. 4b).

In Geometridae, we found no significant main effect of the ecosystem for abundance or species richness (Table 1, Fig. 4), but abundance increased significantly with an increased cloudiness. Furthermore, there was a significant ecosystem by cloudiness interaction effect, where species richness of Geometridae decreased in open grasslands with increased cloudiness (Table 1, Fig. 4).

In Noctuidae, we found no main significant effect of the ecosystem on abundance or species richness (Table 1, Fig. 4). However, for abundance we found significant interaction effects between ecosystem and temperature, cloudiness and moon phase, where abundance increased in open grasslands with temperature and cloudiness and decreased with moon phase (Table 1). Species richness of Noctuidae was only significantly affected by temperature (Table 1).

In species diversity, q=1 (exponential of Shannon diversity, effective number of species) increased significantly with cloudiness and a negative interaction effect by ecosystem and wind (Table 2, Fig. 5). However, in species diversity q=2 (reciprocal of Simpson index) we found no significant effects (Table 2, Fig. 5).

Table 1. Results from the generalized linear mixed effects models on abundance and number of species on moths (total), Crambidae, Geometridae and Noctuidae.

Total abundance	**Estimate (standard error)**	**z**	**P**
Intercept	-1.84 (1.20)	-1.53	0.13
Ecosystem (open)	-3.51 (1.47)	-2.38	0.017
Temperature	0.13 (0.06)	2.10	0.035
Cloudiness	1.18 (0.49)	2.42	0.015
Wind speed	0.11 (0.21)	0.51	0.61
Ecosystem (open) x Temperature	0.24 (0.09)	2.82	<0.01
Ecosystem (open) x Wind speed	-0.66 (0.30)	-2.21	0.027
Total number of species	**Estimate (standard error)**	**z**	**P**
Intercept	-0.76 (0.78)	-0.98	0.33
Ecosystem (open)	-3.00 (1.27)	-2.36	0.018
Temperature	0.05 (0.04)	1.33	0.18
Cloudiness	1.04 (0.31)	3.33	<0.001

Wind speed	0.11 (0.13)	0.80	0.43
Ecosystem (open) x Temperature	0.21 (0.08)	2.80	<0.01
Ecosystem (open) x Wind speed	-0.59 (0.24)	-2.42	0.016
Crambidae abundance	**Estimate (standard error)**	**z**	**P**
Intercept	-6.44 (1.48)	-4.34	<0.001
Ecosystem (open)	-8.98 (1.66)	-5.41	<0.001
Temperature	0.20 (0.09)	2.14	0.032
Cloudiness	2.10 (0.92)	2.27	0.023
Wind speed	0.22 (0.47)	0.46	0.65
Ecosystem open x Temperature	0.66 (0.12)	5.36	<0.001
Ecosystem (open) x Wind speed	-1.77 (0.62)	-2.85	<0.01
Crambidae number of species	**Estimate (standard error)**	**z**	**P**
Intercept	-5.27 (2.30)	-2.29	0.022
Ecosystem (open)	-0.56 (0.44)	-1.26	0.21
Temperature	0.17 (0.10)	1.82	0.07
Cloudiness	2.03 (1.00)	2.04	0.042
Geometridae abundance	**Estimate (standard error)**	**z**	**P**
Intercept	-2.77 (1.68)	-1.65	0.1
Ecosystem (open)	0.02 (0.99)	0.02	0.98
Temperature	0.13 (0.08)	1.65	0.01
Cloudiness	1.98 (0.90)	2.20	0.028
Moon phase	-0.03 (0.01)	-2.09	0.037
Ecosystem (open) x Cloudiness	-1.94 (1.00)	-1.95	0.051

Ecosystem (open) x Moon phase	0.02 (0.01)	1.60	0.11
Geometridae number of species	**Estimate (standard error)**	**z**	**P**
Intercept	-2.05 (1.31)	-1.57	0.12
Ecosystem (open)	0.69 (0.87)	0.80	0.42
Temperature	0.09 (0.06)	1.51	0.13
Cloudiness	1.28 (0.76)	1.69	0.091
Moon phase	-0.02 (0.01)	-1.87	0.061
Ecosystem (open) x Cloudiness	-2.08 (1.03)	-2.02	0.044
Noctuidae abundance	**Estimate (standard error)**	**z**	**P**
Intercept	-1.88 (2.55)	-0.74	0.46
Ecosystem (open)	-7.67 (4.09)	-1.87	0.061
Temperature	-0.006 (0.13)	-0.05	0.96
Cloudiness	-0.50 (1.22)	-0.41	0.68
Moon phase	0.03 (0.02)	1.42	0.15
Ecosystem (open) x Temperature	0.46 (0.22)	2.04	0.042
Ecosystem (open) x Cloudiness	2.29 (1.12)	2.04	0.041
Ecosystem (open) x Moon phase	-0.04 (0.02)	-2.01	0.045
Noctuidae number of species	**Estimate (standard error)**	**z**	**P**
Intercept	-3.28 (1.31)	-2.50	0.012
Ecosystem (open)	0.85 (0.49)	1.74	0.08
Temperature	0.20 (0.08)	2.41	0.016
Wind speed	-0.55 (0.29)	-1.91	0.06

Table 2. Results from the linear mixed effects models on species diversity (Hill's effective number of species) of moths (total), Crambidae, Geometridae and Noctuidae. q =1 (exponential of Shannon diversity, effective number of species) and q = 2 (inverse of Simpson's concentration index).

Diversity q=1	**Value (standar error)**	**d.f.**	**t**	**P**
Intercept	-1.33 (1.61)	12	-0.83	0.43
Ecosystem (open)	-0.94 (1.86)	12	-0.50	0.62
Temperature	0.10 (0.09)	12	1.05	0.31
Cloudiness	2.90 (0.76)	12	3,81	0.0025
Wind speed	0.34 (0.34)	12	1.02	0.33
Ecosystem (open) x Temperature	0.20 (0.11)	12	1.92	0.079
Ecosystem (open) x Cloudiness	-1.47 (0.88)	12	-1.67	0.12
Ecosystem (open) x Wind speed	-0.99 (0.39)	12	-2.56	0.025
Diversity q=2	**Value (standar error)**	**d.f.**	**t**	**P**
Intercept	5.19 (1.78)	8	2.91	0.02
Ecosystem open	-3.76 (2.53)	5	-1.49	0.20
Temperature	-0.11 (0.09)	8	-1.13	0.29
Wind speed	0.29 (0.32)	8	0.93	0.38
Ecosystem (open) x Temperature	0.29 (0.13)	5	2.23	0.076
Ecosystem (open) x Wind speed	-1.13 (0.47)	5	-2.38	0.063

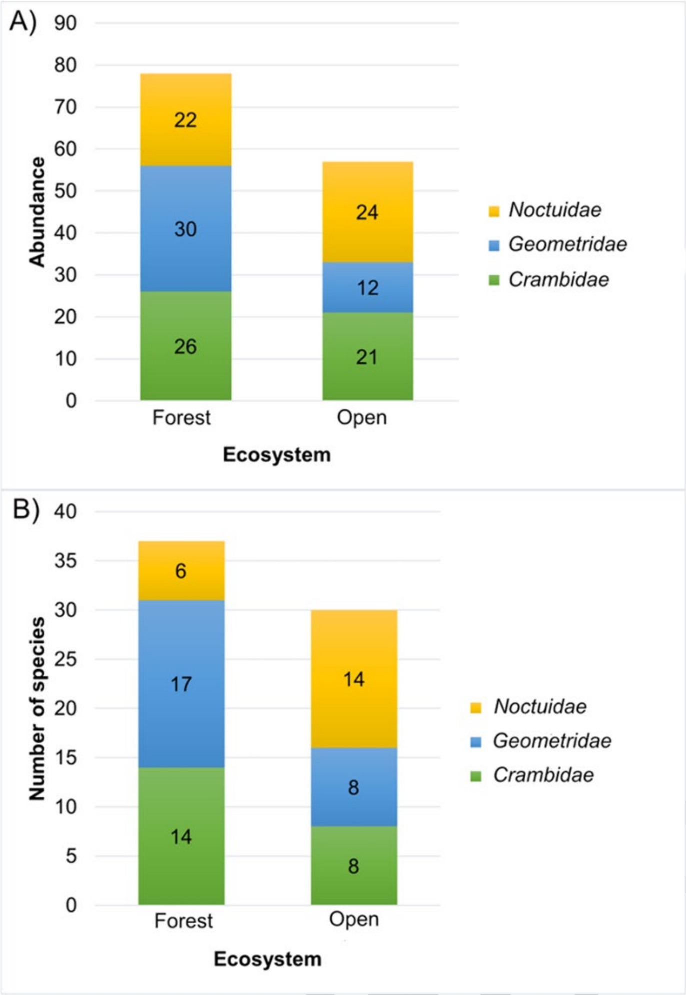

Figure 2. Abundance (A) and species richness (B) of the three most dominant families (Crambidae, Geometridae, and Noctuidae), divided between forest and open grassland ecosystems. The numbers shown in bars represent the abundance and number of species per family.

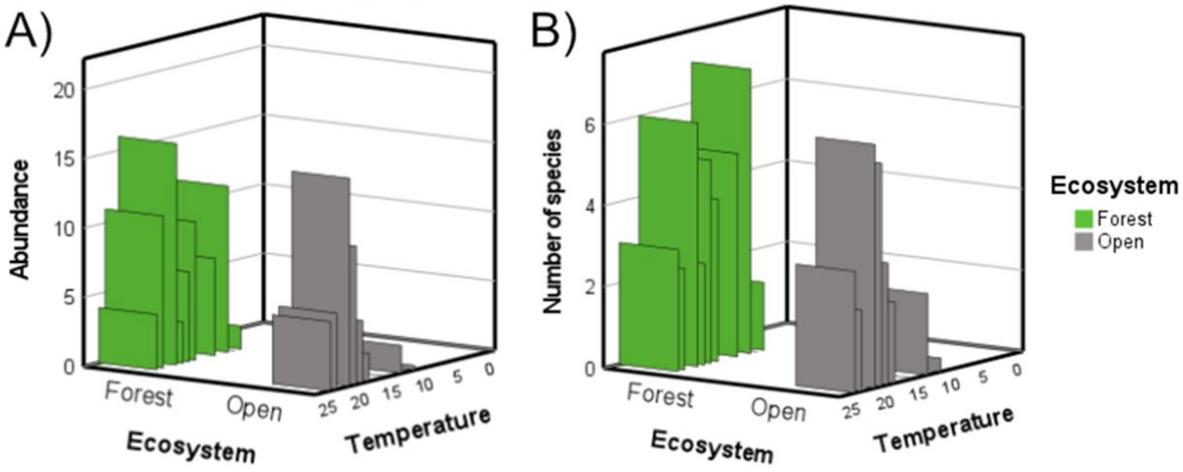

Figure 3. 3D graphs of abundance (A) and number of species (B) for all moths in forest and open grassland ecosystems with temperature (°C).

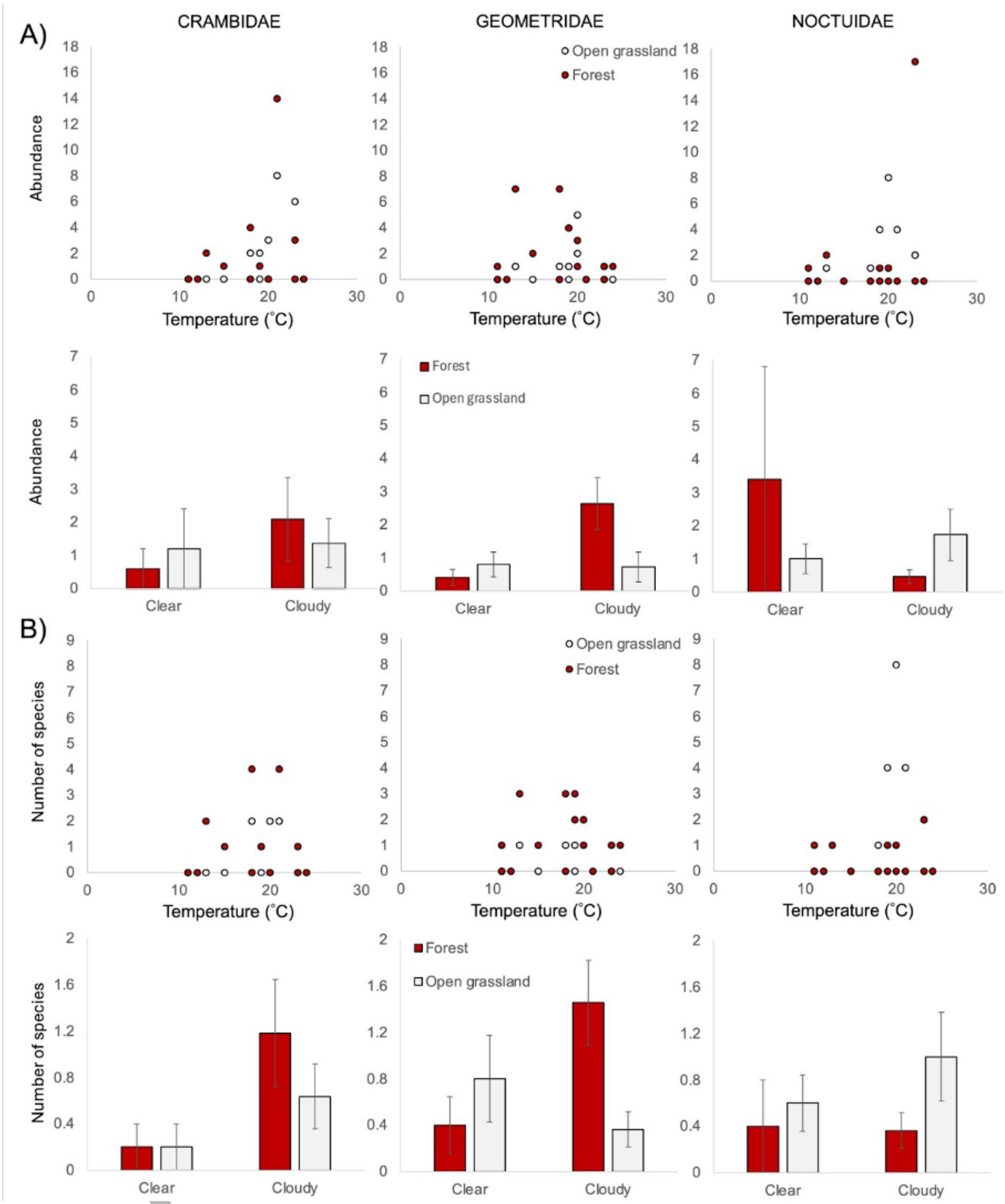

Figure 4. A) Abundance of Crambidae, Geometridae and Noctuidae in relation to temperature and cloudiness. B) Species richness of Crambidae, Geometridae and Noctuidae in relation to temperature and cloudiness. Error bars represent standard error.

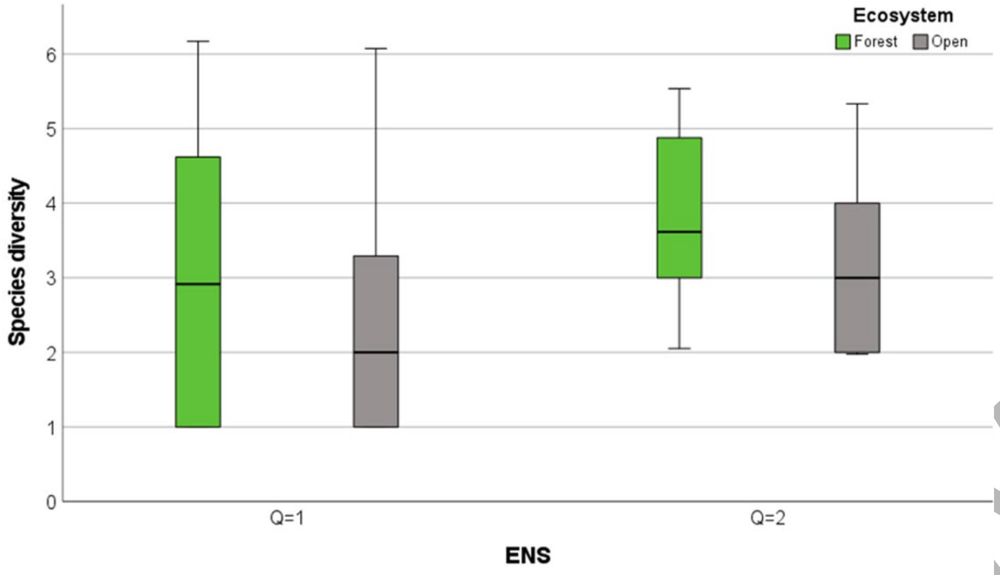

Figure 5. Species diversity (Hill's effective number of species) of insects in forest and open grassland ecosystems. q =1 (exponential of Shannon diversity, effective number of species) and q = 2 (inverse of Simpson's concentration index). For q=0 (species richness) see figure 4b. ENS represents the effective number of species. Error bars indicate 95% confidence intervals.

4. Discussion

Our study offers novel insights into moth attraction to anthropogenic light across different ecosystems, revealing significant ecological implications. We observed marked differences in moth abundance and species richness between traps placed in grassland and forest ecosystems, with forest ecosystems generally yielding higher catch rates. Forests act as thermal buffers, moderating temperatures (De Frenne et al., 2019) and providing shelter from winds, thus creating a more stable and favorable microclimate for insects. This stable environment facilitates extended periods of insect activity, which may explain our findings.
Moth abundance and species richness in open grasslands increased with higher temperatures and increased cloudiness, approaching levels comparable to those observed in forest ecosystems. Our findings align with previous studies demonstrating reduced catches at lower temperatures and decreased cloudiness (Yela and Holyoak, 1997). Importantly, our study further reveals that forest environments exhibit less variation in catch rates across different weather conditions.

To the best of our knowledge, our comparison of light attraction across different ecosystems is the first of its kind. Previous studies on the effects of anthropogenic light at night on moths have primarily focused on behavior and attraction (e.g., Truxa and Fiedler, 2012; van Geffen et al., 2015; Degen et al., 2016; Altermatt and Ebert, 2016; van Langevelde et al., 2017; Boyes et al., 2020, Gaydecki, 2019, Fabian et al., 2024; Longcore et al., 2015). However, these studies have not focused on investigating variations in ecosystem responses using standardized insect traps and lighting setups. While no studies have directly compared different ecosystems, some research has examined smaller-scale effects and explored the impact of trees on insect catches. A field study by Niermann and Brehm (2022) demonstrated differences in microhabitats, with higher abundance and species richness in catch traps at moderately sheltered sites (closer to bushes) compared to exposed sites (i.e. more than 10 m from bushes). Similarly, Straka et al. (2021) used UV-light traps to catch moths in dry grassland ecosystems with differing tree cover and impervious surface amounts along an urbanization gradient with presence of outdoor lighting. They found a positive effect of tree cover density on species abundance and richness, although this effect was primarily driven by results from a single site.

These findings, along with our results, underscore the importance of considering ecosystem variability when studying the impacts of light pollution on moth populations.

In our study, we observed distinct differences in catches among various taxonomic groups across forest and open grassland ecosystems. In forests, we caught higher numbers of Geometridae (30) and Crambidae (26) compared to open grasslands (12 and 21, respectively), while Noctuidae showed similar abundance in both ecosystems (22 in forest, 24 in open). Species richness also varied, with forests hosting more Geometridae (17) and Crambidae (14) species than open grasslands (8 for both), while Noctuidae showed higher species richness in open grasslands (14) compared to forests (6). These findings align with the findings of Merckx and Slade (2014), who demonstrated family-specific sampling areas (attraction radii) and efficiencies for light traps. They found that erebids were attracted from up to 27 m, geometrids from up to 23 m, and noctuids from up to 10 m, with varying capture rates among families. While the specific mechanisms for the family-specific differences in attraction to light traps in different ecosystems in our study cannot simply be explained, it may depend on various ecological traits among taxonomic groups. The varied responses across families and ecosystems could potentially bias results if not accounted for in light attraction studies. Therefore, it is important to evaluate trap efficiency differences among families when interpreting results (Merckx and Slade, 2014).

Our study found fewer moths captured compared to previous studies, likely due to the lower intensity, less attractive wavelengths, and smaller exposure area of our light sources, since we aimed to simulate the attraction of modern electric lighting in natural ecosystems, for example road lighting. We caught five individual moths per trap per night, whereas Niermann and Brehm (2022), using UV light traps, caught approximately 63 individuals per trap per night in open grasslands and orchards in Germany. This underscores the importance of considering lighting design (intensity, spectra, distribution, direction, height, luminaire) when comparing results across studies. It is also important to use lighting designs which simulate currently used electric lighting when aiming to study attraction of anthropogenic lighting rather than using light sources designed for maximal attraction of insects.

In our study, we measured light distribution at different heights and distances from the light trap, providing detailed knowledge about light exposure around it and ensuring repeatability. This aspect is rarely addressed in other studies investigating insect attraction to light. It has been suggested from a controlled lab experiment that a threshold for impacts of light at night in the Greater wax moth (*Galleria mellonella*) is approximately 0.3 lux (Jägerbrand et al., 2023). We used a light trap that emitted light that exceeded that of bright full moonlight (0.3 lux. The illumination was measured vertically at different heights, with the light meter pointing toward the light trap. The light intensity exceeded 0.3 lux over an circular area with a 2 meter radius at different heights from the ground (see also Appendix B), resulting in an estimated insect attraction area of approximately 12.56 m^2. This approach allows for a more precise quantification of the affected area and the relationship between light intensity and insect attraction, addressing a significant gap in the existing literature. By establishing a defined area of influence, we can better estimate the attraction radius and also quantify light attraction through dose-effect responses, with the potential to extrapolate these findings to larger-scale lighting scenarios. Our methodological approach, using light traps with known lighting properties offers a reproducible framework for future research on the impacts of anthropogenic light on biodiversity, enabling other researchers to compare their results across ecosystems.

Our results suggest that anthropogenic lighting may potentially have a greater negative impact on moth populations in open ecosystems, such as grasslands. Adult moths are active for short periods, and unfavourable weather conditions further limit their time for mating and reproduction (Persson, 1972). The added disruption caused by outdoor lighting in open ecosystems further shortens this critical activity window, reducing opportunities for foraging and reproduction. This highlights the need for tailored light pollution management, particularly during periods of insect activity. For example, adaptive lighting systems could be programmed to dim during key periods of insect activity, helping to mitigate the impact on foraging and reproduction. Forest ecosystems buffer weather conditions, promoting insect activity through natural light filtering and protection, making consistent and long-term mitigation strategies the most effective approach to reduce the impact of outdoor lighting. Our findings emphasize the importance of ecosystem-specific approaches to enhance the effectiveness of light pollution mitigation strategies. Using general approaches for light pollution reductions may not be sufficient to protect photo-sensitive species such as nocturnal moths from negative impacts on reproduction in all ecosystems. Further research across ecosystems with varied microclimates could reveal greater differences and lead to more effective mitigation strategies.

5. Conclusions

This study provides the first direct comparison of moth attraction to identical light traps in forest and grassland ecosystems, revealing significant ecological differences. Our findings demonstrate higher catch rates in forests compared to grasslands, with environmental factors such as temperature and cloudiness exerting a stronger influence on moth attraction in open grassland ecosystems. We also observed family-specific variations in light trap catches between ecosystems, highlighting potential sampling biases that should be considered in future research. Our method, with precise measurements of lighting around traps, enables reliable comparisons across ecosystems and provides a clear framework for studies on the impact of light pollution on biodiversity and informing conservation planning and lighting management. These results have important implications for developing tailored light pollution mitigation strategies, emphasizing the need to consider specific ecosystem characteristics. We suggest that future research should explore the mechanisms underlying such ecosystem-dependent differences in moth responses to light.

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Author contribution statement

PA and AJ contributed equally to this study, collaborating on the conception and design, data collection, analysis and interpretation of results, and preparation of the first draft manuscript. PA took a leading role in the fieldwork component of the research. Both authors were involved in reviewing the results and approving the final version of the manuscript.

Declaration of competing interests

The authors declare no competing interests.

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Appendix

Appendix A.

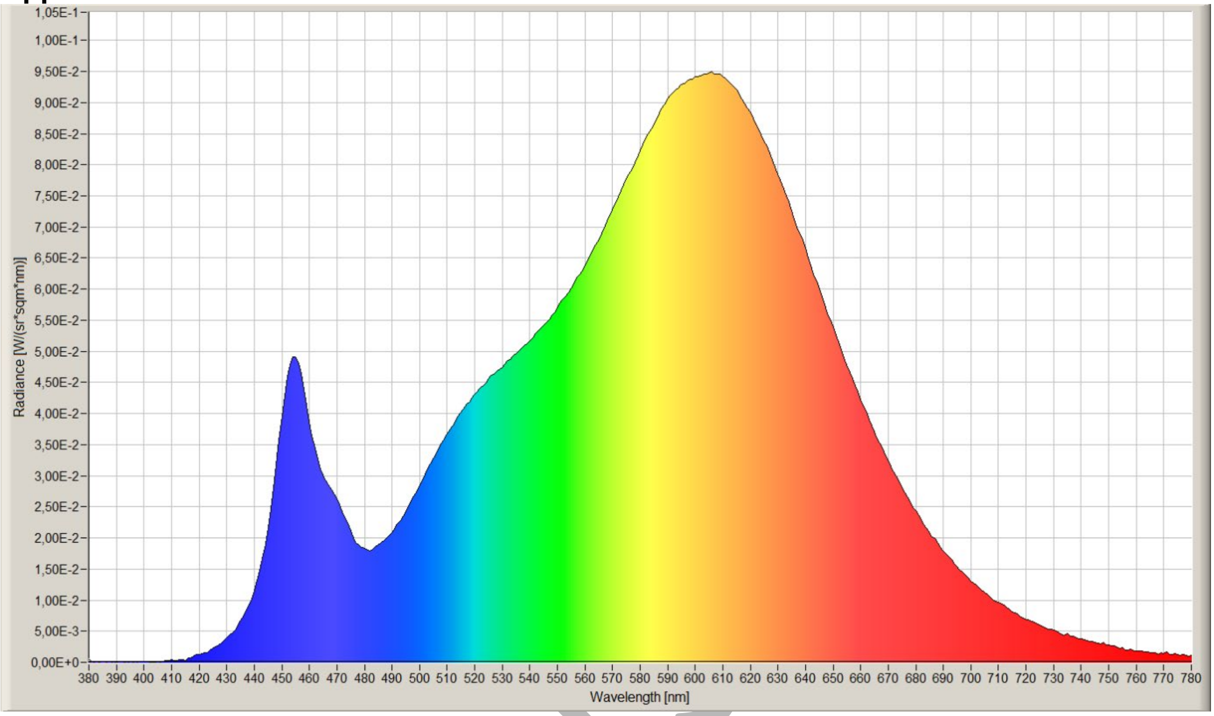

Figure A1. Spectral power distribution of the LED light source used in the insect light trap. The correlated colour temperature (CCT) was 2961K. Measurements were performed using a JeTi Spectro-Radiometer (specbos 1201).

Appendix B. Field measurements of the insect light trap

Light measurements were taken under field conditions on 14-15 November 2022 in a mixed forest and a relatively open meadow in Gustavsberg, Sweden, with overcast and ca 5—10°C, and moon in waning gibbous (57—68%). According to the New World Atlas of light pollution the site has an artificial sky brightness of 1380 µcd/m^2 (Falchi et al., 2016b, Falchi et al., 2016a).

Detailed measurements were conducted for the forest and control measurements were done in the meadow. For the forest ecosystem, illuminance measurements were performed in all four directions (north, south, west, east) from the light trap, to investigate light distribution in the vicinity of the light trap. Vertical illuminances were taken at heights of 0.5 m, 1.0 m, 1.5 m, 2.0 m and at distances of 0.5—5.0 m from the light source at 0.5 m intervals.

Measurements show that at a distance of 1.5 m the vertical illuminance for heights of 1.5 m and 2.0 m is equal to or below 0.3 lux, and at a distance of 2.0 m, it is equal to or below 0.3 lux at heights of 0.5 m and 1.0 m (Table 1). Horizontal illuminances were measured on the ground (5.5 cm above the ground) and at 2 m height, at the same distances from the light trap as vertical measurements were taken (0.5—5.0 m). Again, illuminance was below 0.30 lux at a 2 m distance (Table 2). However, the horizontal illuminance at 2 m did not seem to be influenced by the light from the insect trap and therefore, only a few control points were measured, and the illuminance was found to be 0.04 lux. In the meadow, the vertical illuminance at 1.0 m height and 2.0 m distance from the insect trap was found to be on average 0.29 lux and the horizontal illuminance at 2 m height was 0.11 lux (not shown).

Table B1. Vertical illuminance (lux) at different heights and distances from the insect light trap in the forest ecosystem. Mean values from four different directions (north, south, west, east). Mean values ± standard deviation (SD). Bold indicates illuminance values equal to or below 0.30 lux.

	Height (m)							
	0.5		1		1.5		2	
Distance (m)	mean	SD	mean	SD	mean	SD	mean	SD
0.5	0.96	0.168	3.86	0.579	1.96	0.359	0.31	0.062
1	1.25	0.187	1.12	0.067	0.68	0.072	0.36	0.091
1.5	0.52	0.049	0.48	0.069	**0.30**	0.041	**0.27**	0.018
2	**0.30**	0.026	**0.27**	0.035	0.20	0.014	0.17	0.019
2.5	0.19	0.029	0.17	0.025	0.14	0.014	0.13	0.026
3	0.14	0.021	0.12	0.017	0.10	0.013	0.09	0.015
3.5	0.10	0.017	0.09	0.013	0.08	0.013	0.08	0.014
4	0.08	0.017	0.07	0.013	0.07	0.010	0.06	0.017
4.5	0.06	0.013	0.06	0.010	0.05	0.013	0.06	0.014

5	0.05	0.013	0.05	0.008	0.05	0.014	0.05	0.012

Table B2. Horizontal illuminance (lux) on the ground at distances from the insect light trap. Mean values from four different directions (north, south, west, east). Mean values ± standard deviation (SD). Bold indicates illuminance values equal to or below 0.30 lux.

Distance from light source	Mean	SD
0.5	0.64	0.126
1.0	0.41	0.054
1.5	0.40	0.019
2.0	**0.18**	0.010
2.5	0.06	0.054
3.0	0.07	0.022
3.5	0.06	0.014
4.0	0.05	0.006
4.5	0.05	0.010
5.0	0.05	0.010

Photos taken with a commercial triple-lens camera with LiDAR sensor for light detection and ranging, shows the forest and open meadow sites where measurements were performed under natural conditions with low light (Figure B1 a-b). Photos in figure B1 c-d shows the luminance distribution for the insect light trap in the field under natural low light conditions.

Figure B1. a) Photo of the insect light trap in forest. B). Photo of the insect light trap in the open meadow. c) Luminance photo of the insect light trap in forest, d) luminance photo of the insect light trap in the open meadow.

Illuminance and luminance were measured with Hagner^{TM}s Universal Photometer S5. with Measurement function of illuminance and luminance (1°) of Hagner S5 are 0.01—199.900 lux and cd/m^2 and have an accuracy better than ±3%. The lowest detectable value of measurements is 0.01 cd/m^2 or lux. Operating temperature range is -5°C —+50°C. Luminance photos were taken using LMK Mobile Advanced imaging luminance photometer (based on a Canon EOS 550D) and the associated computer software LMK labsoft ver. 12.7.23 (Techno Team Bildverarbeitung GmbH, Ilmenau, Germany). Canon EOS 550D is a digital singlelens reflex camera with a CMOS sensor with 18.0 effective megapixels resolution and has a working temperature range of 0–40°C and working humidity of 85% or less. The LMK Mobile Advance is designed to convert images directly into luminance values with assistance of a software programme and calibration file.

Appendix C

Table C1. Taxon list from the field experiment.

Species	Family	Number
Acleris emargana	Tortricidae	1
Acrocercops brongniardellus	Gracillariidae	1
Aethes smeathmanniana	Tortricidae	1
Agriphila inquinatella	Crambidae	19
Agriphila selasella	Crambidae	1
Agriphila straminella	Crambidae	2
Agriphila tristella	Crambidae	11
Apamea crenata	Noctuidae	1
Catoptria falsella	Crambidae	4
Cerapteryx graminis	Noctuidae	6
Chiasmia clathrata	Geometridae	1
Clostera pigra	Notodontidae	3
Cosmorhoe ocellata	Geometridae	1
Crambus perlellus	Crambidae	2
Crocallis elinguaria	Geometridae	1
Eana osseana	Tortricidae	1
Eilema depressum	Erebidae	1
Epinotia trigonella	Tortricidae	1
Eudonia truncicolella	Crambidae	4
Eulithis testata	Geometridae	5
Eupithecia centaureata	Geometridae	1
Eupithecia pusillata	Geometridae	7
Eupithecia vulgata	Geometridae	1
Geometra papilionaria	Geometridae	4
Helcystogramma rufescens	Gelechiidae	3
Hydraecia micacea	Noctuidae	1
Hydriomena furcata	Geometridae	1
Idaea straminata	Geometridae	2
Lathronympha strigana	Tortricidae	1
Lithosia quadra	Erebidae	1
Lymantria monacha	Erebidae	1
Mniotype satura	Noctuidae	1
Mythimna impura	Noctuidae	1
Nematopogon robertellus	Adelidae	1

Species	**Family**	**Number**
Noctua pronuba	Noctuidae	1
Notocelia roborana	Tortricidae	2
Notocelia sp.	Tortricidae	1
Nymphula nitidulata	Crambidae	1
Oncocera semirubella	Pyralidae	1
Parapoynx stratiotata	Crambidae	2
Patanis ruralis	Crambidae	1
Pennithera firmata	Geometridae	4
Phragmatobia fuliginosa	Erebidae	1
Rivula sericealis	Erebidae	5
Schrankia costaestrigalis	Erebidae	2
Scotopteryx chenopodiata	Geometridae	11
Thalpophila matura	Noctuidae	5
Tholera decimalis	Noctuidae	2
Xanthia togata	Noctuidae	3
Xanthorhoe ferrugata	Geometridae	4
Xestia sexstrigata	Noctuidae	1
Xestia xanthographa	Noctuidae	24
Yponomeuta evonymellus	Yponomeutidae	8
Ypsolopha nemorella	Ypsolophidae	2

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