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Original Research

Impact of Excessive Artificial Light at Night (ALAN) on Species Diversity of Plants and Epigeic Insects

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Abstract

This study examined the impact of artificial light at night (ALAN) emitted by a lit greenhouse complex in Poland on plant communities and surface-dwelling arthropods. The effects of ALAN were investigated at three different distances from the light source within agricultural ecosystems. Insect populations were sampled using Barber traps, while plant communities were assessed using the Braun-Blanquet method. The findings showed that ALAN did not cause significant overall changes in plant community composition. However, ordination analysis suggested species-specific shifts in response to light pollution, indicating that some plants may adapt differently depending on their proximity to the light source. ALAN caused a notable decrease in arthropod diversity, as measured by the Margalef index; however, not in taxa abundance. These results, based on a single growing season, highlight the potential ecological risks of nighttime lighting for insect biodiversity and emphasise the need for long-term studies to understand its effects fully.

Keywords: light pollution, terrestrial insects, plant communities, nighttime light exposure

Introduction

Unwanted light at night has become a hallmark of our modern world. Light pollution (ALAN) is observed not only in metropolises that are active 24 hours a day, or along highways and expressways, but also in areas far away from these urban centres [1, 2]. One of the sources of artificial light at night in rural areas with prolonged exposure is, for example, horticultural complexes that conduct greenhouse farming. Light plays a crucial role in plant life, as it is the source of energy for photosynthesis. It is also a source of environmental information that regulates vital processes in plants. The range of radiation that plants perceive and utilise is broad

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(300-700 nm) [3], and each light spectrum induces specific reactions, regulating plant growth and development, from movement, germination, to flowering and seed production. Due to photoperiodism, plants also require periods of darkness, during which light receptors (such as phytochromes) undergo changes, and coordinated gene expression regulating metabolism takes place. Artificial light sources that disrupt the natural light/dark rhythm or alter the colour of light reaching plants disturb their circadian rhythms and metabolism. This negatively affects plant growth, development, flowering, and maturation [4].

Significant effects of light pollution include phenological changes in plants, such as the sequence of growth and development phases. Early bud opening in trees and shrubs has been observed in areas subjected to intense light pollution [5, 6], as well as delayed dormancy onset and autumn leaf shedding [7]. Another negative impact of artificial light on plants is the disruption of the darkness period, during which repair processes occur in response to environmental stressors. Plants have developed many defence mechanisms, including the production of protective proteins. Their synthesis often occurs at night, in the absence of light. Excess light is a stress factor for plants. Kwak et al. [8] demonstrated that plants of American tulip tree (*Liriodendron tulipifera* L.) exposed to low-intensity light at night showed reduced pigment content and increased leakage of electrolytes, a common stress marker. In corn crops along a highway in Accra (Ghana), after installing strong sodium lamps, the plants exhibited strong growth but did not produce flowers [9]. Bennie et al. [1] reviewed numerous studies on the impact of ALAN on vegetation, both in crops and in natural plant communities, and found that few studies have been published on the unintended ecological impact of artificial nighttime light on wild plants and natural vegetation. According to these authors, several issues remain unexplained, including direct effects on wild plants, the influence on plant-animal interactions, and the ecological extent of changes caused by this factor. They argue that understanding the ecological consequences of artificial light at night is crucial to assessing the full impact of human activity on ecosystems.

ALAN also disrupts the natural light-dark cycles, which are crucial for the behaviour, physiology, and survival of many nocturnal organisms [10]. Among the most vulnerable to this disruption are invertebrates, particularly nocturnal insects such as moths, beetles, and other epigeic species [11]. Although the impacts of artificial light have been widely studied in various taxa, its effects on epigeic arthropods, organisms that inhabit the soil surface, remain relatively underexplored [12]. These arthropods, including insects such as beetles, moths, and springtails (Collembola), as well as spiders, are vital components of terrestrial ecosystems, contributing to nutrient cycling, soil aeration, and pest control [13]. Attraction of insects to ALAN creates ecological and evolutionary traps that compromise their fitness. Ecological traps occur when organisms are drawn to environments where their survival or reproduction is negatively impacted. For example, insects attracted to light sources often become more susceptible to predators, exhaustion, or harmful environmental conditions [14]. Ground beetles (Carabidae), which are often attracted to artificial lights, can accumulate near these sources, leading to increased mortality due to predation or environmental stressors [15]. This phenomenon significantly disrupts their natural behaviours, such as navigation, foraging, and reproduction [12]. For example, male moths are often diverted from locating mates due to their attraction to artificial lights, resulting in reduced mating success [16]. Similarly, light pollution can alter the activity patterns of spiders, making them more diurnal and interfering with their predatory roles within ecosystems [17]. Therefore, the increasing prevalence of artificial lighting, even in rural areas, disrupts not only the behaviour of individual species but also the ecological balance, leading to cascading effects on biodiversity and ecosystem health [18]. Furthermore, ALAN alters the predatory and foraging behaviour of epigeic arthropods, often making them more visible to both predators and prey. For example, in illuminated environments, ground beetles (Carabidae) experience reduced predation rates as prey become more difficult to detect [19]. However, increased artificial light can also increase predator abundance and activity, further complicating predator-prey dynamics [12].

Artificial lighting also modifies habitat suitability for epigeic arthropods by altering microhabitat conditions, favouring species that are attracted to light while disadvantaging those that avoid it. This can lead to changes in the community's composition, with light-attracted species becoming dominant while others decline, potentially disrupting ecosystem processes [12]. For example, studies have observed changes in Collembola communities in light-polluted habitats, indicating that even small soil-dwelling arthropods are affected by ALAN [20]. Furthermore, artificial lighting can have indirect effects on epigeic arthropods through plant-arthropod interactions. ALAN has been found to influence plant growth and flowering times [21], which in turn affects herbivorous arthropods that depend on these plants for food [22]. Such disruptions can cascade through ecosystems, affecting multiple trophic levels and ecosystem functions. Beyond behavioural and ecological impacts, artificial light can indirectly influence the growth, reproduction, and overall fitness of epigeic arthropods, further threatening their populations [23]. Increased exposure to artificial light can cause physiological stress, reducing reproductive success and increasing vulnerability to other environmental stressors. These combined effects of behavioural changes, altered predation dynamics, habitat modification, and physiological stress underscore the significant threat that light pollution poses to epigeic arthropod communities [12].

Given the essential roles that epigeic insects play in maintaining ecosystem health, such as decomposition, nutrient cycling, and pest control, understanding the effects of ALAN on these communities is critical. In response to these growing concerns, we experimented with varying distances from a light-emitting source (a greenhouse) to investigate how different levels of artificial light exposure influence plant and epigeic arthropod communities. We hypothesised that areas closer to the light source (and higher light intensity) would exhibit altered community compositions and behaviour, with light-attracted species becoming more dominant and others showing reduced activity or declining populations. Furthermore, we hypothesised that light contamination would influence plant communities, shaping them toward species that thrive under increased illumination.

Materials and Methods

Study Area

The effects of ALAN were studied at a large greenhouse complex in Poland (51°01'06.4"N 17°09'20.7"E) of 24 ha. The lights are used (for supplementary lighting) mainly from October to March for 12 hours, starting from 6 am. For the remaining 12 hours, the lights are turned off. Evening supplementary lighting during the autumn and winter period causes the appearance of a light glow, which is a typical example of artificial, excessive nighttime sky lighting leading to light pollution.

The research was conducted on agricultural areas belonging to the Institute of Soil Science and Plant Cultivation – State Research Institute, Department of Weed Science, on plots which were placed at different distances (150, 500, and 900 m) from the light source emitted by the horticultural complex "Siechnice" (Siechnice, Wrocław, Poland). The soil was classified as medium-sandy clay and was slightly acidic, with moderate levels of available potassium and phosphorus, and a high magnesium content. It also had a relatively high organic carbon content.

Plant and Insect Analyses

A total of six relevés were recorded using the Braun-Blanquet method, with plot sizes ranging from 5 to 20 m² (Table S1, Fig. S1). The botanical nomenclature was adopted on the WFO Plant List database [24]. The syntaxonomic classification of species was determined based on Matuszkiewicz [25], and the classification into geographical-historical groups was given according to Zając and Zając [26] – apophytes, Tokarska-Guzik et al. [27] – kenophytes and archaeophytes, and Rutkowski [28] – non-synanthropic spontaneous species and crop species, which are ephemeral plants. The light and thermal requirements of the species occurring in the studied areas were determined based on the work of Ellenberg et al. [29]. The life forms of the species were also defined in accordance with the work of Zarzycki et al. [30].

The study on epigeic insects was conducted on the corn fields. At each site, three Barber traps were installed in a linear arrangement, spaced 15 m apart (Fig. S1). The traps consisted of 500-ml plastic cups filled with glycol, buried flush with the ground surface to capture ground-dwelling arthropods. Small roofs were placed above the traps to prevent rainwater from entering and flooding the cups. The insects were collected during two 2-week sampling periods in the summer of 2022. The captured epigeic arthropods were identified at various taxonomic levels, primarily at the order and family levels, including the following groups: Collembola, Carabidae, Dermaptera, Formicidae, Araneae, Hymenoptera, Coccinellidae, Cantharidae, Symphyla, Staphylinidae, Acari, Opiliones, Orthoptera, Heteroptera, Chilopoda, Myriapoda, and Porcellionidae.

Data Analysis

All the plant analyses were conducted based on the relative contribution expressed in percentage. For each group of sites, based on the species composition of plants and their ecological characteristics, the Shannon-Wiener index (1) and the averaged Ellenberg index in relation to temperature and sunlight (2) were calculated.

(1) Shannon-Wiener index (H'):

$$H' = -\sum p_i ln p_i$$

where:
H' = Shannon-Wiener diversity index
p_i = the proportion (share) of the i-th species in the total number of individuals
ln = natural logarithm.

The weighted mean formula:

$$Weighted\ Index = \frac{\sum(Li \times Ai)}{\sum Ai}$$

where:
Li = Light or Temperature index of species iii
Ai = Abundance of species iii

The calculated indices were compared using the nonparametric Kruskal-Wallis test. Additionally, a Principal Component Analysis (PCA) was performed for the plant communities, which allows for the reduction of dimensionality of the data and identification of the main patterns of variability in the studied data set. The PCA results are presented in a plot, where the individual axes represent the principal components and their eigenvalues indicate the degree of explained variance. Furthermore, the cumulative variance for the ordination axes was calculated to assess what proportion of total variability is captured by the first components of the analysis.

The PCA analysis was performed in Canoco, version 5.0.

To assess insect biodiversity in each locality, the Margalef index of species richness was calculated using the following formula:

$$Margalef\ index = (S-1)/(ln\,(N))$$

where:
S = number of taxa
N = total number of individuals

This index is suited for categorical data, where observations are classified into a finite number of distinct categories [31].

The abundance of dominant taxonomic groups, such as Carabidae and Collembola, along with Margalef index values, was compared across localities using a General Linear Model (GLM) in SAS University Edition software. Since the data did not meet normality assumptions, a negative binomial distribution was used for the analysis. The explanatory variables included the distance from the light source (three levels) and the sampling period (two levels). Statistically significant results are presented in graphical form.

Results

In total, 71 plant species were found (Table S1). The PCA analysis (Fig. 1) revealed that some species exhibited significant shifts along the environmental gradients. The first axis (57.58% of variance) was strongly associated with the distance from the light source, while the second axis (14.74%) explained additional variation (Table S2). *Lolium perenne* shifted strongly towards the positive side of Axis 1, indicating a positive response to greater distance from the light source. In contrast, *Bromus sterilis* and *Anagallis henrieti* were positioned on the negative side of Axis 1, suggesting that these species responded positively to closer proximity to light pollution. Along Axis 2, species such as *Artemisia vulgaris* and *Agrostis stolonifera* occupied distinct positions, while species clustered near the origin, including *Poa annua* and *Poa pratensis,* showed more intermediate responses. No significant differences were observed in the Shannon-Wiener index between locations at different distances from the light source (Table 1, Table S3), suggesting that the structure of species diversity is stable regardless of location and light conditions. No significant differences were found in Ellenberg light and temperature indices at different distances from the light source (Table 1, Table S3). Among life forms, hemicryptophytes (31 species) and therophytes (13 species) were the most common, while other growth forms were less numerous. Apophytes were dominant (41 species). Archaeophytes were represented by 17 species, including vulnerable taxa (Ar VU) and invasive weeds (Ar i ch). Kenophytes consisted of 6 species (Table S1).

Insects

For the most abundant taxonomic groups (Acari, Collembola, Carabidae, Formicidae, Araneae, Coccinellidae, and Staphylinidae), the effect of distance from the light source on abundance was not statistically

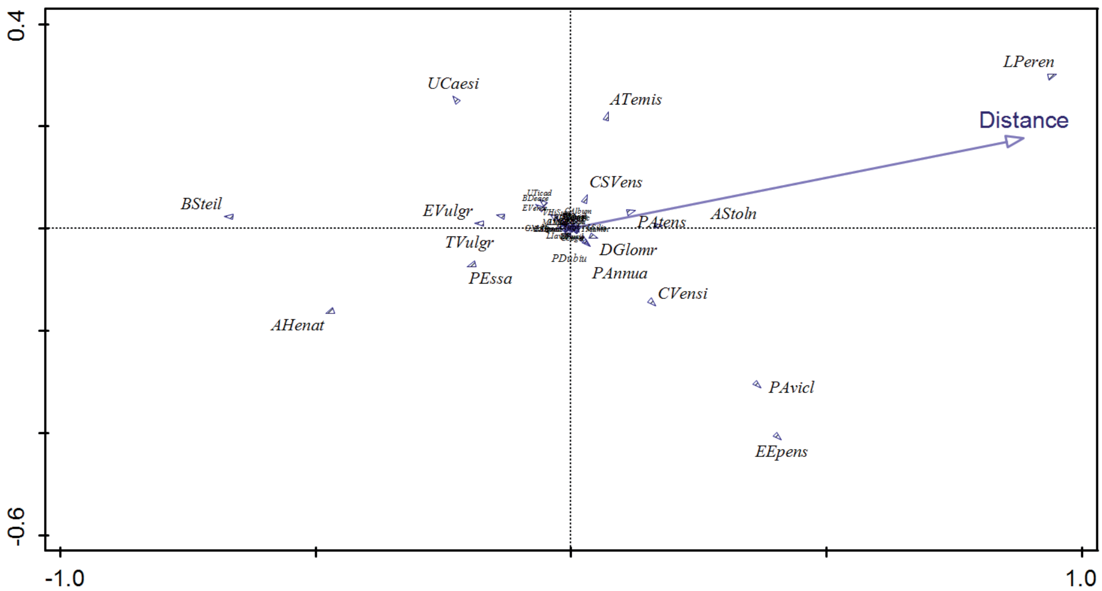

Fig. 1. Species composition of plants based on PCA analysis.
Note: AHenat – *Anagallis arvensis*, ATemis – *Artemisia* vulgaris, AStoln – *Agrostis stolonifera*, BSteil – *Bromus sterilis*, CVensti – *Convolvulus arvensi*s, DGlomr – *Dactylis glomerata*, EVulgr – *Echium vulgare*, LPeren – *Lolium perenne*, PAnnua – *Poa annua*, PEssa – *Poa compressa*, PAtens – *Poa pratensis*, TVulg – *Tanacetum vulgare*, UCaesi – *Rubus caesius* c. Distance - distance from the light source: 150, 500, 900 m in a straight line.

Table 1. Average values and standard deviations of plant community indices at sites at different distances from light sources (50, 150, 500 m). For temperature indices (T) and light indices (L), the weighted means are presented, which result from the Ellenberg index values of the species and abundance of particular species.

Shannon-Wiener index		
Distance from the light source (m)	Mean	SD
150	2.07	0.54
500	2.01	0.021
900	1.86	0.086
Species number		
150	26.50	9.19
500	26.00	1.41
900	21.00	8.48
Temperature index (T)		
150	6.00	0.04
500	6.00	0.12
900	6.50	0.71
Light index (L)		
150	7.50	0.71
500	6.50	0.72
900	5.50	0.71

significant (Table S4). However, biodiversity responded differently: the Margalef index varied significantly with distance ($F = 6.40$, $p = 0.01$), whereas the term effect was not significant ($p = 0.70$). Sites located 900 m from the light source exhibited the highest species diversity, significantly exceeding the values recorded at 150 m, while 500 m showed intermediate diversity (Fig. 2).

Discussion

Plants

Rapid urbanisation and related infrastructure development, including the construction of roads and housing, have significantly deteriorated the growing conditions of plants. This decline is due to various factors such as disturbances in water availability, a lack of essential nutrients, extremely high air and soil temperatures, anthropogenic pollution, and insufficient space for growth [32]. Another emerging issue is light pollution, which disrupts crucial natural periods of darkness for plants. This phenomenon is caused by street lighting, car headlights, billboards, advertising, and store displays. The intense urban lighting has led to the phenomenon of "urban glow", visible from distances of up to several dozen km [33]. Light pollution, primarily in heavily urbanised areas, also impacts plants in suburban zones (meadows, pastures, forests, and fields) due to the nature of light (wavelength) and its ability to travel long

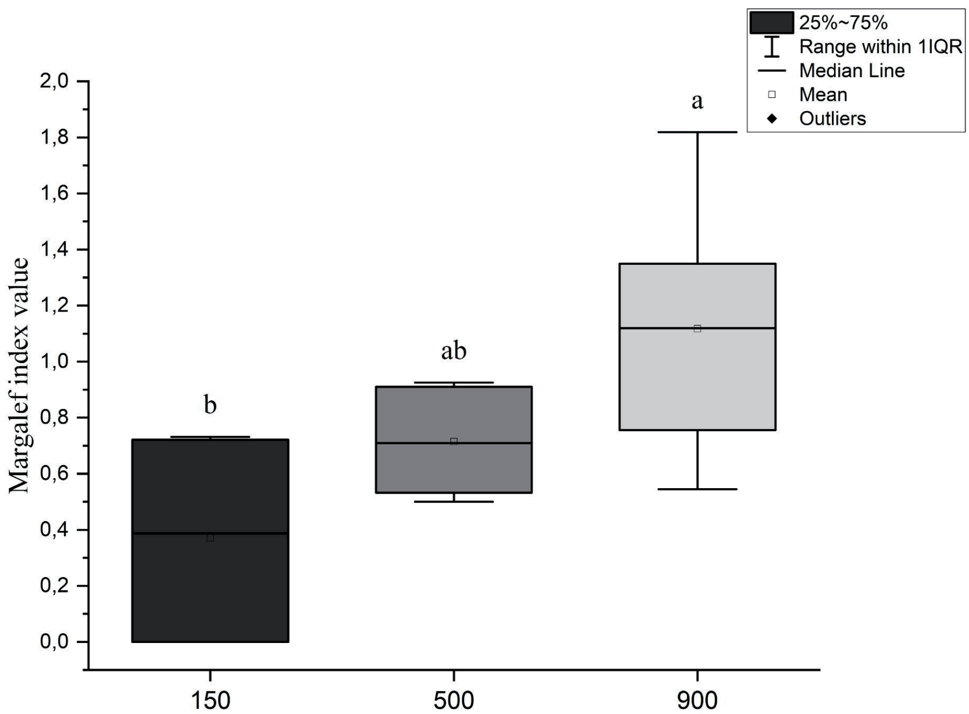

Fig. 2. The effect of the distance from the light source (150, 500, 900 m) on the value of the Margalef biodiversity index based on arthropod occurrence.
Note: Different lowercase letters above the bars indicate the significant changes between the treatments.

distances. Additionally, light pollution in suburban areas is exacerbated by horticultural activities, which involve intense artificial lighting for plant cultivation, especially during short daylight periods [33].

An analysis of plant communities in areas exposed to artificial light at night (ALAN) in the corn crops revealed that these communities are not typical of agricultural land. Segetal communities are poorly developed, showing impoverishment in both species composition and structure. Other community types, mainly meadow and ruderal (in various stages of succession), are somewhat better developed, but still exhibit significant disturbances in species composition, including the intrusion of invasive and expansive species. Many of the communities present are difficult to classify phytosociologically. The occurrence of individual species and the phytocoenoses they form appear to be independent of light and thermal conditions, but strongly correlated with soil properties and applied agrotechnical practices. There is also a significant element of randomness in the presence of species not associated with open areas. Our research did not confirm a clear overall impact of ALAN on the studied vegetation. However, PCA analysis indicated that some plant species were sensitive to light pollution. *Lolium perenne* appeared to be negatively affected by light, while *Bromus sterilis* and *Anagallis arvensis* seemed to benefit from closer proximity to the light source. Nevertheless, no significant differences were observed in overall plant community biodiversity along the distance gradient from the light source, nor in ecological characteristics as measured by the Ellenberg index. However, supporting observations from other studies indicate that the effect of ALAN on light-loving species (which predominate in our study) is less pronounced than on shade-preferring plants [34]. While community-level changes were not evident, species-level shifts may reflect physiological processes disrupted by artificial illumination. ALAN is known to alter photoperiod perception, leading to changes in plant metabolism, antioxidant systems, and hormone regulation [35-37]. Such disruptions can reduce tolerance to abiotic and biotic stress, including frost resistance and pathogen defence [38, 39]. Although our study did not reveal broad vegetation shifts, the observed responses of individual species suggest that prolonged nighttime lighting could gradually influence plant performance and community dynamics. Given the complexity of plant responses to ALAN, long-term research is needed to determine whether subtle species-level effects accumulate into measurable changes in agroecosystems. Understanding these dynamics is crucial, as artificial night lighting is currently not recognised as a form of pollution under Polish law, despite its potential ecological consequences.

Insects

The main finding of this study is that a higher intensity of artificial light significantly decreased the diversity of epigeic arthropods, as measured by the Margalef index. This reduction in diversity suggests that ALAN can negatively impact species richness and community structure in ground-dwelling arthropod populations. This is partially consistent with previous studies indicating that the introduction of ALAN has been shown to attract more predatory species, intensifying the pressure of predation in certain arthropod communities [12].

Despite the observed decrease in diversity, no significant changes were found in the abundances of specific arthropod groups between the different study localities. This indicates that while overall biodiversity is reduced under higher light intensities, certain arthropod groups may not be directly affected in terms of population size, or some species may be more tolerant of or resilient to light pollution. This could lead to a form of "homogenisation" of communities, where the remaining species dominate the habitat, potentially reducing the ecological roles that the more sensitive species play. Over time, this reduction in species richness could destabilise food webs and ecosystem functions, as fewer species are available to perform essential ecological roles such as predation, decomposition, and nutrient cycling [40]. Therefore, studies should focus more on species or functional-group diversity.

Although abundance remains unchanged, the reduction in diversity may still have profound effects on the ecosystem. Biodiversity is critical to maintaining ecosystem stability and resilience, and loss of species reduces the capacity of the ecosystem to respond to further environmental changes or stressors [41]. With fewer species contributing to ecosystem processes, key functions such as soil aeration, organic matter breakdown, and pest control could be compromised.

These findings underscore the urgent need for conservation efforts aimed at mitigating the effects of ALAN on biodiversity. The loss of diversity due to light pollution could have cascading effects on the health and functioning of ecosystems. Furthermore, additional research is needed to explore how species-specific responses to artificial light influence community dynamics and ecosystem processes.

Conclusions

Experimental studies on the impact of excessive artificial light at night (ALAN), emitted by a horticultural complex, did not reveal distinct differences in the response of vegetation accompanying corn crops when comparing areas close to the light source with more distant locations. Research conducted on a selected group of entomofauna showed that artificial light significantly decreased the diversity of epigeic arthropods, as measured by the Margalef index. It is important to note that the results refer to only one growing season and serve as a starting point for further studies, which should be carried out over several years to confirm the long-term effects of artificial light on specific groups of organisms at the study sites.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author, IG, upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

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Supplementary Materials

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