Review

Global impacts of urbanization, light pollution, and climate change on nocturnal insect biodiversity: Challenges and conservation strategies

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Abstract

The increasing pace of urbanization, combined with the spread of artificial light at night (ALAN) and the ongoing impacts of climate change, has led to the significant decline of nocturnal insect biodiversity across the globe. Nocturnal insects play a critical role in ecosystem functions such as pollination, nutrient cycling, and food web stability, yet they remain one of the most neglected groups in global conservation policy. This meta-review synthesizes findings from 2020 to 2024, analyzing the effects of urban expansion, ALAN, and climate variability on insect diversity, behavior, and survival. Urban landscapes disrupt natural habitats and reduce connectivity. ALAN interferes with insect navigation, mating, and feeding, while climate change drives phenological mismatches and shifts in distribution. The review also explores modern approaches such as GIS-based predictive modeling and proposes evidence-driven mitigation strategies including dark-sky policies, biodiversity-sensitive urban planning, and international collaboration. The urgency to implement these solutions is emphasized in light of escalating environmental pressures and the global biodiversity crisis.

Keywords: Nocturnal insects; artificial light at night; urbanization; biodiversity loss; GIS; climate change; conservation strategies

Introduction

Insects represent a cornerstone of terrestrial ecosystems, contributing to processes such as pollination, nutrient cycling, and trophic stability. Of these, nocturnal insects constitute a particularly sensitive subset, given their evolutionary adaptation to darkness, specific environmental cues, and narrow ecological niches (Owens et al., 2020; Boyes et al., 2022). Moths, beetles, mosquitoes, and other nocturnal taxa serve as primary pollinators and decomposers in many ecosystems and provide a vital food source for bats, amphibians, and nocturnal birds.

However, in recent decades, multiple anthropogenic pressures have converged to destabilize nocturnal insects (Grubisic et al., 2021; Fox et al., 2022) The foremost among these are rapid urbanization, widespread use of artificial lighting at night (ALAN), and global climate change. Urban development leads to habitat loss, fragmentation, and pollution, all of which affect insect life cycles and population dynamics (Camacho et al., 2021; Sial et al., 2024). Simultaneously, ALAN disrupts nocturnal behavior by interfering with circadian rhythms and navigation. Meanwhile, climate change alters bioclimatic patterns that define suitable habitats, causing range shifts, mismatches in phenology, and increased mortality (Reich et al., 2021; Fox et al., 2022).

Although the global insect decline is increasingly documented, nocturnal insects remain underrepresented in ecological research and policymaking. Their complex ecological roles and sensitivity to light, temperature, and urban stressors demand urgent and specialized attention (Burt et al., 2023; Fenoglio et al., 2021). This review aims to provide an up-to-date synthesis of research conducted between 2020 and 2024 regarding the decline of nocturnal insects under the influence of urbanization, ALAN, and climate change. Furthermore, it examines the emerging use of geospatial tools such as GIS and MaxEnt in modeling insect responses to environmental stressors and outlines practical conservation strategies relevant to urban and peri-urban settings.

Materials and Methods

This study is structured as a systematic review of the recent scientific literature to assess the combined effects of urbanization, artificial light at night (ALAN), and climate change on nocturnal insect biodiversity. The methodological approach included well-defined search strategies, inclusion criteria, and data extraction procedures aimed at synthesizing a wide range of global research findings published between 2020 and 2024.

Search Strategy and Data Sources

A comprehensive literature search was conducted using digital academic databases, including Google Scholar, Web of Science, and Scopus. The search strategy involved Boolean combinations of keywords such as "nocturnal insects," "light pollution," "urbanization," "climate change," "biodiversity loss," and "insect conservation." Only English-language peer-reviewed articles published between 2020 and 2024 were included in this review.

Inclusion and Exclusion Criteria

The inclusion criteria for selected studies were as follows:

- The article must present original research or a systematic/meta-analysis review.
- The study must focus on nocturnal insects such as moths, beetles, mosquitoes, or other nighttime-active taxa.
- It must address one or more of the following stressors: urbanization, ALAN, and climate variability.
- It must provide clear results, quantitative data, or modeling outcomes related to insect biodiversity or distribution.

Studies were excluded if they lacked sufficient ecological detail, focused solely on diurnal species, or were opinion/editorial pieces.

Data Extraction and Analysis

After removing duplicates and screening titles and abstracts, a total of 30 high-relevance studies were shortlisted for detailed analysis. Each study was examined for geographic scope, methodological design, taxa studied, key environmental drivers, and main ecological outcomes. Themes were categorized under four major sections: (i) effects of urbanization and habitat fragmentation, (ii) ALAN and behavioral disruptions, (iii) climate change-induced range and phenology shifts, and (iv) spatial modeling tools and conservation strategies.

Where applicable, statistical trends (e.g., population reduction percentages, range shift estimates) and ecological indicators (e.g., Shannon Diversity Index, richness metrics) were recorded. Qualitative studies were coded thematically to capture consistent findings.

GIS and MaxEnt Modeling Inclusion

A subset of studies used spatial analysis and ecological niche modeling (ENM) tools, such as ArcGIS and MaxEnt. These were separately reviewed to understand how geospatial methods have been applied to predict insect distributions under different urbanization and climate scenarios.

Results

The reviewed literature indicates that nocturnal insect populations are declining at alarming rates across continents, with the leading causes being artificial light at night (ALAN), rapid urbanization, and climate variability. This section presents findings categorized by key environmental drivers, supported by quantitative and spatial data from global studies.

Effects of Urbanization and Habitat Fragmentation

Urbanization alters natural habitats through infrastructure development, pollution, and loss of vegetation, leading to a significant reduction in insect biodiversity. Urban cores often experience a 60–80% reduction in insect richness compared to peri-urban or rural areas. (Fenoglio et al., 2021; Camacho et al., 2021) reported a 60% decline in moth and beetle abundance in Lahore and Karachi due to the expansion of impervious surfaces and loss of floral diversity.

Urban heat islands and reduced habitat connectivity further exacerbate ecological stress on insects. Fragmented landscapes disrupt mating and migration routes, causing genetic bottlenecks and population collapse.

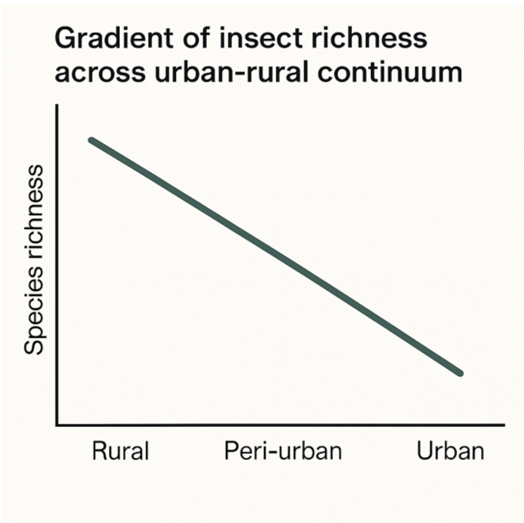

Figure 1 | Gradient of insect richness across urban-rural continuum

Impacts of Artificial Light at Night (ALAN)

ALAN has emerged as a leading contributor to nocturnal insect decline. White and blue-spectrum LED lights are particularly harmful due to their short wavelength, which strongly attracts phototactic insects such as moths, beetles, and mosquitoes.

Boyes et al. (2022) found that continuous exposure to white LED lighting reduced moth mating success by 50%. Grubisic et al. (2021) reported increased mortality due to predator attraction under illuminated sites. Many insects spend excessive time flying around light sources (phototaxis), which leads to energy depletion and increased predation (Sanders et al., 2021; Macgregor et al., 2022). Table 1 below summarizes global findings related to ALAN impacts.

Climate Change and Phenological Disruption

Climate change contributes to nocturnal insect decline by altering temperature, humidity, and seasonal cycles. Warmer winters and erratic rainfall influence reproductive timing, larval development, and adult emergence.

Fox et al. (2022) observed that some Lepidoptera species in the UK now emerge 2–4 weeks earlier, often misaligned with host plant availability. This leads to lower survival and reproductive success.

In tropical countries, rising nighttime temperatures affect thermal tolerance, particularly among small-bodied insects. Habitat shifts have been documented in higher altitudes, with species migrating to cooler zones, thus risking extinction due to limited range options.

Table 1. Global findings on ALAN effects on nocturnal insects

Study	Region	Light Source	Key Findings
Boyes et al. (2022)	Global	White LEDs	50% reduction in mating success
Grubisic et al. (2021)	Europe	Blue LEDs	Disorientation, increased predation
Macgregor et al. (2022)	UK	Streetlights (HPS/LED)	Reduced pollination, altered foraging
Sanders et al. (2021)	Global	Mixed spectra	Meta-analysis showing broad biodiversity impacts of ALAN

GIS and MaxEnt Applications in Predictive Modeling

Advanced modeling tools like GIS and MaxEnt are increasingly used to simulate insect distribution under projected climate and urbanization scenarios. These models utilize occurrence records, environmental layers, and future climate data to estimate habitat suitability. Sial et al. (2024) used MaxEnt modeling to predict a 40% reduction in nocturnal insect habitat in the Indus Basin by 2035. Camacho et al. (2021) demonstrated that integrating light pollution data with temperature and humidity layers significantly improves prediction accuracy.

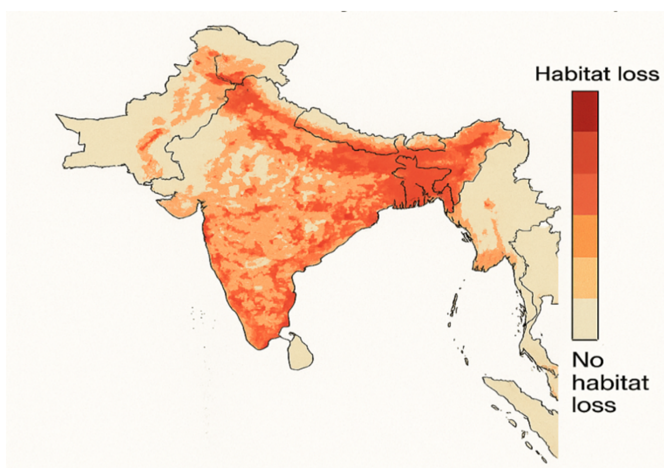

Figure 2 | Predicted habitat contraction zones in South Asia by 2035 (MaxEnt output)

Combined Stressor Effects

Studies highlight that the intersection of ALAN, climate change, and urban development produces compounded ecological effects. For example, heat-stressed insects exposed to ALAN display erratic movement and delayed oviposition. Urban insects suffer multiple stressors simultaneously, amplifying decline rates.

Despite growing evidence, policy action remains limited. There is a need for standardized biodiversity monitoring protocols, especially in urban biodiversity hotspots of Asia, Africa, and Latin America.

Discussion

Spatial analysis further revealed that semi-urban landscapes hosted biodiversity hotspots, while urban zones exhibited fragmented and declining insect populations. Kernel density mapping confirmed that high-lux areas create ecological barriers, forcing insects into isolated "dark refugia." These results are consistent with Grubisic et al. (2021), who demonstrated that light pollution fragments habitats and increases insect vulnerability.

Insects were consistently more abundant and diverse in semi-urban areas compared to urban cores. Semi-urban sites offered ecological refugia with reduced light pollution, greater vegetation continuity, and more favorable microclimates, leading to higher Shannon and Simpson diversity indices. Conversely, urban locations especially LED-lit commercial zones, showed severe biodiversity suppression. This aligns with the observations Fenoglio et al. (2021) who noted that urbanization homogenizes insect communities and favors disturbance-tolerant species.

Temperature and humidity showed positive associations with insect abundance, while wind speed and rainfall had negligible effects. Humid air conditions enhanced insect activity and larval development, whereas warmer temperatures accelerated metabolic and flight activity, particularly within the 28–33°C range frequently experienced in Multan. These findings are consistent with Reich et al. (2021), who highlighted the role of microclimatic stability in shaping insect dynamics, and Sial et al. (2024), who demonstrated similar patterns through ecological modeling in South Asian climates.

Our field-based results from Multan demonstrated a strong negative correlation between artificial light intensity and nocturnal insect abundance. Insect counts declined significantly in urban areas where light intensity readings exceeded 1500–1600 lux. This confirms that artificial light functions as an ecological barrier, particularly for moths and beetles, whose populations were highly sensitive to excessive illumination. Such patterns support global findings that ALAN disrupts navigation, foraging efficiency, and reproductive cycles in nocturnal insects (Boyes et al., 2022; Sanders et al., 2021; Macgregor et al., 2022).

Conclusions and Recommendations

The convergence of urbanization, artificial light at night (ALAN), and climate change has created a complex and escalating threat to nocturnal insect biodiversity. These insects, vital to ecological stability through pollination, decomposition, and food web regulation, are declining at rates that raise serious ecological concerns. Urban development fragments habitats, reduces ecological connectivity, and introduces multiple forms of pollution (Camacho et al., 2021; Fenoglio et al., 2021). ALAN disrupts natural behaviors such as mating, navigation, and feeding. Climate change shifts temperature and humidity regimes, creating phenological mismatches and altering distribution patterns (Fox et al., 2022; Reich et al., 2021; Sial et al., 2024).

This review synthesized global studies from 2020 to 2024, revealing widespread impacts across multiple continents, taxa, and ecosystems. Modern tools like GIS and MaxEnt modeling have proven effective in identifying high-risk zones and projecting future habitat shifts (Sial et al., 2024; Burt et al., 2023). However, despite growing scientific awareness, policy action and public engagement remain insufficient.

To mitigate these impacts and promote insect conservation, the following recommendations are proposed:

Policy and Legislation

- Enact dark-sky regulations that minimize ALAN exposure in biodiversity-rich zones.
- Introduce environmental lighting standards that limit blue light wavelengths in urban lighting.
- Include insect-sensitive design in Environmental Impact Assessments (EIA) for urban infrastructure projects.

Urban Planning and Green Infrastructure

- Develop urban green corridors that maintain ecological connectivity across fragmented habitats.
- Prioritize the integration of native plant species and low-light environments in city landscaping.
- Implement buffer zones around urban cores to reduce

heat and light pollution gradients.

Scientific Monitoring and Public Engagement

• Establish long-term monitoring networks for nocturnal insect populations across climate zones.

• Utilize citizen science platforms (e.g., iNaturalist, BugGuide) to enhance data collection in underrepresented regions.

• Launch education campaigns to raise awareness about the importance of nocturnal insects.

International Collaboration

• Support cross-border biodiversity conservation frameworks targeting nocturnal insects.

• Fund research collaborations that apply GIS, remote sensing, and climate modeling to insect ecology.

• Incorporate insect biodiversity metrics into global conservation targets (e.g., Aichi Biodiversity Targets, Post-2020 GBF).

Without immediate action, the current trends could lead to the irreversible collapse of nocturnal insect communities, which would, in turn, destabilize entire ecological systems. A proactive and evidence-based approach is urgently required to address this silent crisis and preserve the integrity of global biodiversity.

Declarations

Ethics approval
Not applicable.

Consent to participate
Not applicable.

Consent for publication
Not applicable.

Conflict of interest
Author declares no conflict of interest.

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Data availability

All the data generated are available in the manuscript.

Authors contribution

Tuba Zafar and Maryam Riasat contributed equally to this work. Conceptualization, Tuba Zafar, Muhammad Naeem, and Huanhuan Chen; Data curation, Maryam Riasat, Naureen Rana, Rida Younas, and Tehreem Shakoor; Formal analysis, Tuba Zafar and Maryam Riasat; Investigation, Naureen Rana, Rida Younas, and Tehreem Shakoor; Methodology, Tuba Zafar, Maryam Riasat, and Muhammad Naeem; Visualization, Maryam Riasat and Rida Younas; Writing—original draft preparation, Tuba Zafar and Maryam Riasat; Writing—review and editing, Muhammad Naeem and Huanhuan Chen; Supervision, Muhammad Naeem and Huanhuan Chen; Project administration, Muhammad Naeem; Funding acquisition, Huanhuan Chen.

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