



Research article

Vehicular light at night amplifies insect mortality: Implications for ecosystem disruption

Narendra K^{a,*}, Vijay Varadi^{b,2}, Raajasubramanian D^{a,b,**},³

^a Faculty of Science, Department of Botany, Annamalai University, Annamalai Nagar, Tamil Nadu 608002, India

^b Department of Business Development, Golden Gate University, San Francisco, CA 94105-2968, United States



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ABSTRACT

Insect populations are declining globally, threatening pollination systems, food security, and ecosystem stability. While habitat loss, pesticides, and climate change are widely recognized drivers, the ecological consequences of transport-associated artificial light remain poorly understood. Artificial light at night (ALAN) from fixed sources is an established ecological stressor, yet vehicle-emitted illumination represents a mobile and rapidly expanding form of nocturnal disturbance whose biological impacts remain largely unquantified. Here, we quantify the contribution of vehicular light at night (VLAN) to insect mortality along a major highway in southern India using three years (2021–2023) of fortnightly field surveys across 25 fixed transects (5 km total). Across the study period, 25,296 insect carcasses were recorded, with nocturnal mortality associated with vehicular illumination nearly five times higher than daytime traffic-related mortality. Pollinators accounted for approximately 43% of total deaths, with nocturnally active Hymenoptera and Lepidoptera disproportionately affected. Mean mortality per transect increased from 36.6 individuals during daytime surveys to 171.7 at night. Night-time mortality showed a strong positive association with traffic intensity and exhibited a compound annual growth rate more than fourfold higher than daytime mortality, indicating a distinct and amplified mortality regime rather than a simple extension of daytime traffic effects. These findings suggest that vehicular illumination fundamentally alters the ecological profile of road networks, transforming transport corridors into active sensory traps that intensify insect attrition far beyond the baselines of mechanical collision alone. This phenomenon, characterized here as Vehicular Light at Night (VLAN), emerges as a pervasive yet previously under recognized ecological pressure that links infrastructure expansion directly to global biodiversity decline. While direct quantification of ecosystem-service flux remains a critical frontier, the sheer magnitude and functional composition of the observed mortality specifically among functionally vital pollinator taxa signal a profound disruption of insect mediated ecological stability. We therefore propose vehicular light pollution as a pivotal sustainability challenge that bridges the gap between linear infrastructure growth and the subsequent erosion of essential ecosystem services. These results underscore an urgent mandate to integrate mobile artificial illumination into the foundational frameworks of sustainable transport and conservation planning. Addressing this 'moving' pollutant is not merely a matter of mitigation, but a necessary pathway to decouple anthropogenic infrastructure from the drivers of ecological collapse in the Anthropocene.

1. Introduction

Insects form the structural and functional foundation of terrestrial and aquatic ecosystems, where they contribute to pollination, nutrient

cycling, soil formation, and food-web stability, while also serving as a primary food source for many vertebrates [27,28,31]. Growing evidence indicates that insect populations are undergoing widespread declines in abundance and biomass, with serious implications for ecosystem

* Corresponding author.

** Corresponding author at: Faculty of Science, Department of Botany, Annamalai University, Annamalai Nagar, Tamil Nadu 608002, India.

E-mail addresses: narendrakuppan@gmail.com (N. K.), vvaradi@ggu.edu, varadivk@gmail.com (V. Varadi), dr14491@annamalaiuniversity.ac.in (R. D).

¹ Orcid ID - 0000-0001-5637-4106

² Orcid ID - 0009-001-9115-8588

³ orcid.org/0000-0001-6295-7770

functioning, agricultural productivity, and global food security [6,14, 23,26]. Despite increasing recognition of this crisis, the full range of anthropogenic drivers contributing to insect decline remains incompletely understood.

Habitat loss, intensive land use, agrochemical application, invasive species, and climate change are widely recognized as major stressors influencing insect populations [23,24,30,31]. However, additional anthropogenic pressures associated with expanding infrastructure and technological developments have received comparatively limited empirical attention. Among these, artificial light at night (ALAN) has emerged as a rapidly increasing global pollutant that disrupts biological rhythms, alters behavior, and influences population dynamics across a broad range of taxa [9,10]. The expansion of nocturnal illumination is particularly pronounced in developing regions, where rapid urbanization and infrastructure growth are transforming previously dark pristine landscapes [11,17].

Most studies examining the ecological impacts of ALAN have focused on fixed lighting sources such as streetlights, industrial installations, and illuminated buildings. These stationary light sources are known to attract nocturnal insects, interfere with navigation and foraging behavior, increase exposure to predators, and ultimately elevate mortality rates [3,8,32]. At larger spatial scales, increasing illumination around protected areas and biodiversity hotspots has been associated with altered species distributions and community composition [13]. While these effects are increasingly well documented, the ecological consequences of mobile light sources associated with road traffic remain poorly quantified.

Road networks are a pervasive feature of modern landscapes and represent a major source of ecological disturbance. Roads directly cause mortality through vehicle collisions and indirectly affect organisms by fragmenting habitats, modifying microclimates, facilitating the spread of invasive species, and altering species interactions [20]. For insects, roads represent both a physical barrier and a source of chronic mortality. Although road ecology has expanded rapidly in recent decades, insect-focused studies remain scarce relative to those on vertebrates [19, 20]. Importantly, very few studies have explicitly separated the effects of mechanical traffic mortality from those associated with artificial illumination along roads.

Vehicle-emitted lighting, including headlights, auxiliary lamps, and high-intensity beams, differs fundamentally from fixed ALAN sources. Vehicular lighting is mobile, highly directional, temporally concentrated, and spatially extensive, projecting illumination far beyond road surfaces into adjacent agricultural and semi-natural habitats [10]. As global vehicle numbers and road networks continue to expand, exposure of insects to vehicle associated illumination is increasing rapidly. Despite this, empirical studies quantifying insect mortality attributable specifically to vehicular light emissions are virtually absent, representing a critical knowledge gap in both road ecology and sustainability science [20].

Artificial illumination can disrupt insect orientation through multiple mechanisms. Light sources may interfere with celestial navigation cues, polarized-light perception, and chromatic discrimination, leading insects to approach artificial lights under the mistaken perception of floral resources or open sky [12,15]. In addition, localized warming around light sources and aggregation effects mediated by pheromonal cues can further intensify attraction [16,25]. When such attraction occurs along roadways, insects are drawn into zones of high collision risk, transforming illuminated road corridors into ecological traps.

Here, we present a three-year field study quantifying insect mortality associated with road traffic and vehicular light at night along a major highway in southern India. Using repeated, standardized transect surveys, we compare insect mortality during daylight hours, when traffic is present without artificial illumination, with mortality during night-time hours, when traffic operates in conjunction with vehicle-emitted light. Our objectives were to (i) quantify the magnitude and taxonomic composition of insect mortality along highways, (ii) test whether

vehicular light at night significantly amplifies mortality beyond daytime traffic effects, and (iii) evaluate the implications of nocturnal mortality for pollinators and other functionally important insect groups. By identifying vehicular light as an emerging and under-recognized driver of insect decline, this study contributes to a more comprehensive understanding of how transport infrastructure intersects with biodiversity loss and ecosystem service degradation (Fig. 1).

2. Materials and methods

2.1. Study area

The study was conducted along a 5-km stretch of the Bengaluru–Mysuru National Highway (NH-275) in southern India, with surveys conducted on the main highway and, where necessary, on adjacent service roads. The study area represents a high-traffic transport corridor traversing a mosaic of agricultural land, semi-natural vegetation, and peri-urban settlements. The region experiences year-round vehicular movement, with traffic volumes fluctuating seasonally and diurnally. Vehicles typically operate at high speeds, and night-time traffic is characterized by continuous headlight illumination, creating persistent artificial light exposure along the roadway.

This corridor was selected because it is representative of rapidly expanding transport infrastructure in tropical regions, where roads increasingly intersect biologically productive landscapes. The surrounding matrix includes croplands, remnant vegetation patches, and scattered human settlements, providing suitable habitat for a diverse assemblage of insects (Fig. 2 and Fig. S2).

2.2. Field equipment and materials

Field surveys employed standard entomological and observational equipment to ensure accurate sampling and documentation. A Garmin GPS navigator was used for precise geo-referencing of sampling locations along the study transect. Light intensity conditions were assessed using an HTC lux (luminescence) meter to characterize nocturnal illumination associated with vehicular activity. Insect specimens were collected using forceps and soft brushes of varying sizes and stored in labeled collection jars and polythene zip-lock covers while wearing latex gloves to minimize handling contamination. Permanent markers were used for accurate specimen labeling and sample tracking during field collection.

2.3. Measurement of vehicular light exposure

Vehicular light exposure was characterized to distinguish transient illumination generated by moving vehicles from baseline nocturnal ambient conditions. The study roadway was largely devoid of permanent artificial lighting, with streetlights absent or extremely sparse along the sampling stretch. Consequently, ambient nighttime illumination remained minimal under non-traffic conditions.

Light intensity was measured using an HTC lux (luminescence) meter as the primary instrument to quantify variations in illumination associated with vehicular movement. Measurements were recorded periodically under ambient conditions prior to vehicle arrival and during vehicle transit to capture changes in light exposure experienced by insects. Background illumination levels in the absence of vehicles typically ranged between approximately 0–1 lux, indicating near-dark environmental conditions.

Passing vehicles constituted the dominant artificial light source during nocturnal sampling. Headlights produced short-duration but high-intensity illumination pulses, with light exposure varying according to vehicle proximity, traffic density, and angle of incidence relative to the measurement location. Periods of increased traffic resulted in overlapping illumination from multiple vehicles, temporarily elevating local light conditions compared to baseline darkness.

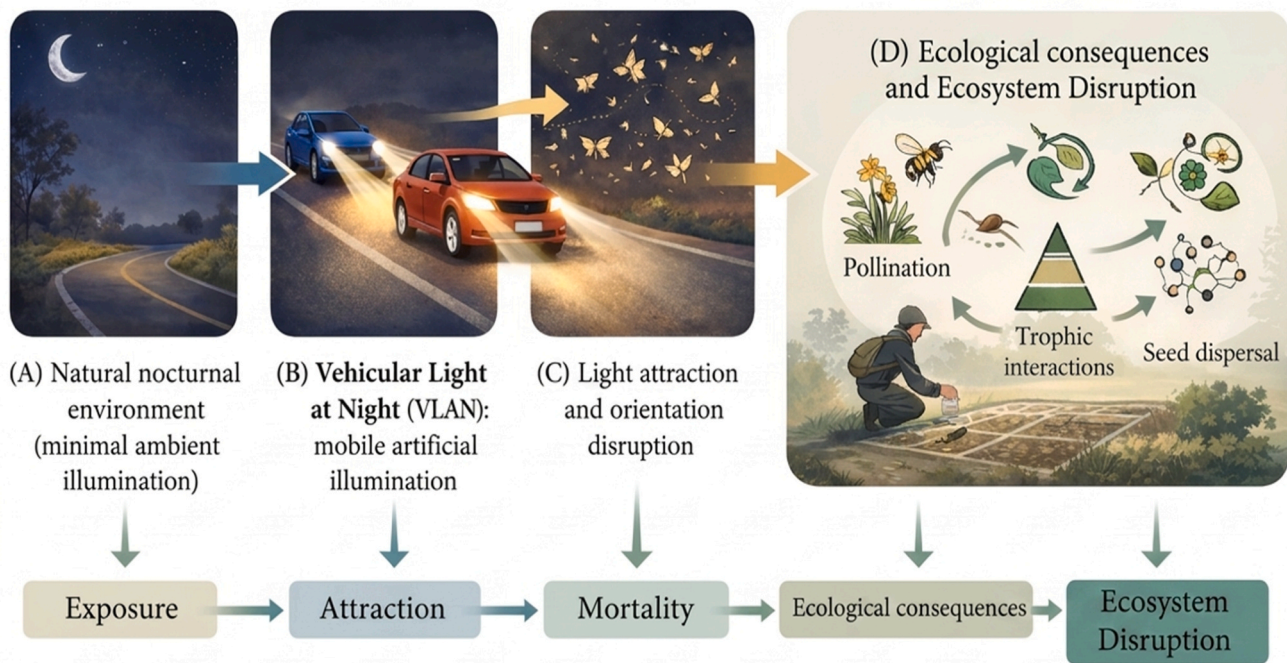


Fig. 1. Conceptual overview of the study design and ecological mechanism linking vehicular light at night (VLAN) to insect mortality and ecosystem implications. The schematic illustrates a minimally illuminated nocturnal environment, exposure of insects to mobile artificial illumination generated by moving vehicles, attraction and orientation disruption, transect-based mortality sampling, and potential ecosystem-level implications including pollination, nutrient cycling, trophic interactions, and seed dispersal processes (Illustration created by the authors).

To ensure consistency of ambient illumination estimates, lux readings were cross-validated using lux meter applications installed on Apple iPhone 7 Plus and iPhone 12 devices (Apple Inc., Cupertino, CA, USA). These auxiliary measurements were used solely for verification purposes and did not replace primary instrument readings.

Portable helmet-mounted lights used by researchers were employed only during specimen collection after vehicle passage and were directed downward to minimize additional attraction effects. Measurement procedures followed approaches previously applied in assessments of artificial light at night impacts on insect mortality [18].

2.4. Transect design

To quantify insect mortality systematically, twenty-five fixed transects were established along the selected highway section. Each transect was 200 m in length, with sampling conducted along the road surface and adjacent margins extending up to 100 m on either side of the carriageway. Transect locations were determined using GPS coordinates to ensure consistency across sampling events (Fig. 2).

Transects were spaced to minimize spatial overlap and to capture variation in traffic intensity, surrounding land use, and roadside structure. All transects were surveyed repeatedly throughout the study period to allow for temporal comparisons within and across years.

2.5. Sampling schedule and survey protocol

Insect mortality surveys were conducted fortnightly from January 2021 to December 2023. Each sampling event encompassed a continuous 24-h period, divided into two standardized intervals: a 12-h daytime period (06:00–18:00), during which mortality was attributed to traffic movement alone, and a 12-h night-time period (18:00–06:00),

during which mortality resulted from traffic in combination with vehicular light at night.

Prior to each survey, all visible insect carcasses within each transect were removed to avoid duplication across sampling periods. During each survey interval, newly killed insects were manually collected from the road surface, shoulders, and adjacent roadside margins. A small proportion of insects that were crushed and adhered to the road surface could not be physically recovered; these individuals were therefore neither enumerated nor included in the mortality counts. All collected specimens were placed in labeled containers corresponding to transect identity, date, and sampling period (day or night).

This paired day–night design enabled direct comparison of insect mortality under conditions of traffic alone versus traffic combined with vehicular illumination, allowing isolation of the amplifying effect of vehicular light at night.

2.6. Specimen processing and identification

Collected insect specimens were transported to the laboratory for processing. Representative individuals were preserved, relaxed, following standard entomological protocols. Identification was carried out to the order level using morphological characteristics, with assistance from taxonomic specialists at the Department of Entomology, University of Agricultural Sciences, Karnataka.

Insects were subsequently classified into functional groups, including pollinators, herbivorous pests, predators, and parasitoids, based on established ecological roles. This functional categorization enabled assessment of differential impacts of road traffic and vehicular lighting on ecosystem service providers.

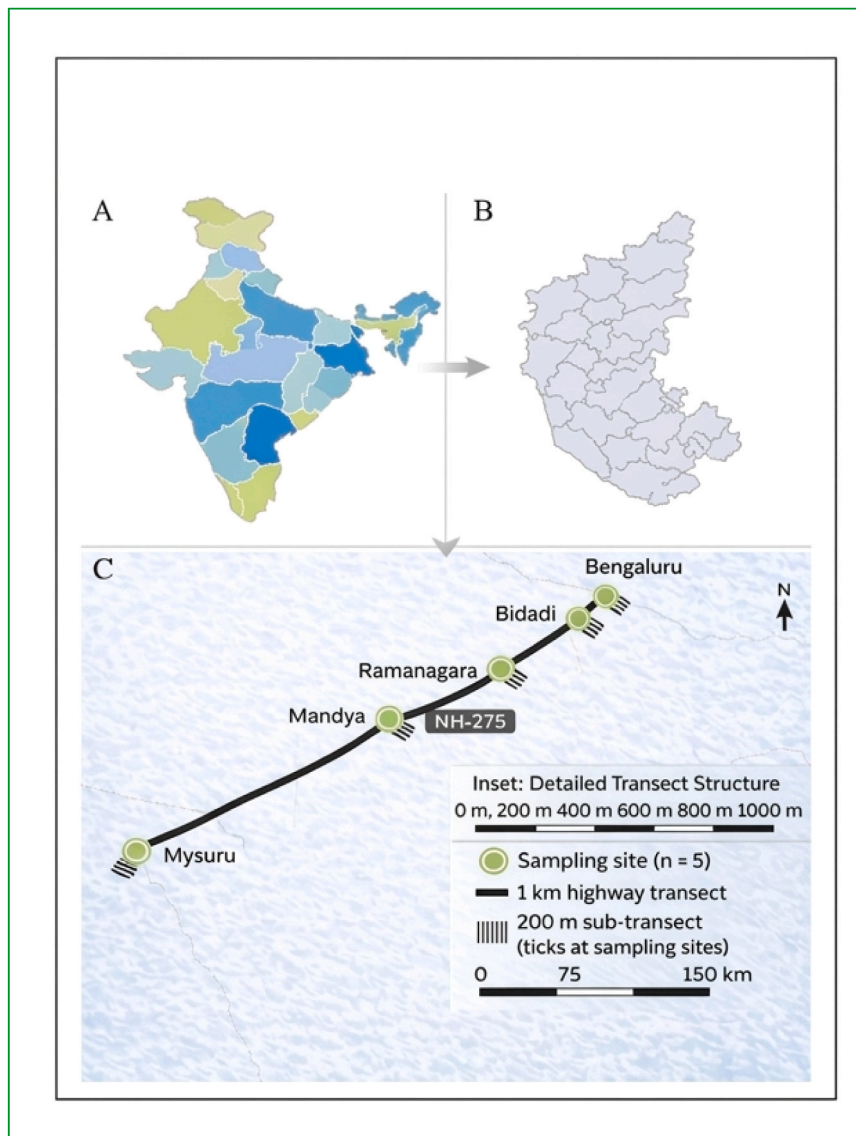


Fig. 2. Spatiotemporal study design and highway transect architecture. (A) National and (B) regional context of the study area in Karnataka, India. (C) Deployment of five 1-km high-resolution sampling transects along the NH-275 industrial corridor. The inset details the 200-m sub-transect discretization used to quantify carcass accumulation across the urban–rural gradient.

2.7. Statistical analysis

Mortality data were compiled for each transect, sampling period, and year. Descriptive statistics, including means and variances, were calculated separately for daytime and night-time mortality. Paired *t*-tests were used to test whether mean insect mortality differed significantly between day and night periods within transects.

Pearson correlation analysis was conducted to examine the relationship between daytime and night-time mortality and to assess associations between traffic intensity and insect deaths. Temporal trends were evaluated using compound annual growth rates (CAGR) to compare changes in mortality over the three-year study period for daytime and night-time conditions.

All data of insects collected was saved in Microsoft Excel and later statistical analyses were performed using Python, and JMP. Statistical significance was assessed at $\alpha = 0.05$.

3. Results

3.1. Overall insect mortality patterns

Across the three-year sampling period (2021–2023), fortnightly surveys along the 5-km highway transect yielded a cumulative total of 25,296 insect carcasses, revealing a pronounced disparity between diurnal and nocturnal mortality. Of the total individuals recorded, 3146 were documented during daytime surveys, when mortality could largely be attributed to vehicle movement alone, whereas 22,150 carcasses were detected during night-time surveys, when traffic operated in conjunction with vehicular illumination. Consequently, nearly 88% of all recorded mortality occurred under nocturnal conditions, underscoring the substantial intensification of insect deaths during the night (Table S1 and S2).

Patterns of mean mortality per transect further highlight this disparity. Daytime surveys produced an average of 36.60 insects per transect, whereas nocturnal sampling yielded a substantially higher mean of 171.74 insects per transect, representing an almost fivefold increase in mortality during night-time conditions. Statistical evaluation

using a paired *t*-test confirmed that this difference was highly significant ($t = -3.89$, $df = 10$, $p < 0.01$), indicating that the elevated nocturnal mortality cannot be attributed to random variation. The magnitude of this effect was also considerable (Cohen’s $d = 1.53$), and the 95% confidence interval (63.4–206.9) indicates a consistently higher mortality rate at night across sampling intervals. Collectively, these findings provide strong quantitative evidence that insect mortality along the studied roadway is markedly amplified during night-time periods, likely reflecting the combined influence of traffic and vehicular lighting on insect attraction and collision risk (Table 1 & 2).

3.2. Taxonomic composition of mortality

Insect mortality comprised representatives from seven orders. Hymenoptera dominated the assemblage, accounting for 14,804 individuals (58%) of total mortality, followed by Lepidoptera with 5710 individuals (23%). The remaining mortality was distributed among Orthoptera (1805 individuals), Isoptera (988), Coleoptera (846), Odonata (721), and Heteroptera (422) (Fig. 3 and Fig. 5, S2 and S3).

For all insect orders, night-time mortality substantially exceeded daytime mortality. Lepidoptera exhibited the strongest nocturnal bias, with more than 95% of recorded deaths occurring at night. Hymenoptera also showed a pronounced night-time skew, indicating heightened vulnerability to nocturnal road conditions.

3.3. Functional group responses

Functional classification revealed that pollinators constituted approximately 43% of all recorded insect deaths (18,914 individuals). Pollinator mortality was overwhelmingly concentrated during night-time surveys, particularly among nocturnally active Lepidoptera and Hymenoptera. Lepidopteran pollinators showed an extreme night-to-day mortality ratio, with night-time deaths exceeding daytime deaths by more than thirtyfold (Figs. 4 and 5 and Fig.S3)

Herbivorous pests accounted for approximately 16% of total mortality, while predators and parasitoids together represented a smaller fraction of deaths (approximately 3%). Although pest taxa also exhibited increased night-time mortality, the magnitude of amplification was greatest for pollinator groups.

3.4. Statistical comparison of day and night mortality

A clear disparity in insect mortality emerged between daytime and night-time sampling intervals. Across the study period, the mean number of insect carcasses recorded per transect during night-time surveys (171.74) was substantially higher than the corresponding daytime mean (36.60). Statistical comparison using a paired two-sample *t*-test confirmed that this difference was significant ($t = -3.89$, $df = 10$, $p < 0.01$), indicating that mortality recorded under nocturnal conditions consistently exceeded that observed during daylight hours. These results reject the null hypothesis that mortality rates are equivalent between the two periods and demonstrate a pronounced increase in insect mortality when traffic occurs under illuminated night-time conditions.

Table 1

Comparative analysis of diurnal and nocturnal insect mortality across the study corridor (2021–2023). Descriptive and inferential statistics comparing 12-hour daytime (traffic only) and night-time (traffic plus vehicular light) intervals. The table presents mean carcass counts per transect, including effect size (Cohen’s $d = 1.53$) and 95% confidence intervals. Significance was determined via paired *t*-test ($t = -3.89$, $p < 0.01$).

Year	Daytime Mortality Mean ± SD	Night-time Mortality Mean ± SD	Mean Difference (Night – Day)	Effect Size (Cohen’s <i>d</i>)	95% Confidence Interval	Significance
2021	32.58 ± —	161.73 ± —	129.15	—	—	—
2022	47.85 ± —	324.88 ± —	277.03	—	—	—
2023	40.58 ± —	379.92 ± —	339.34	—	—	—
Overall	36.60 ± 69.71	171.74 ± 143.05	135.14	1.53	[63.4, 206.9]	p < 0.01 **

Statistical test: Paired *t*-test ($t = -3.89$, $df = 10$, $n = 12$); Significance codes: $p < 0.01$, $p < 0.05$, ns = not significant.

Table 2

High-resolution temporal distribution of insect carcass accumulation over a 24-hour cycle. Mean insect mortality recorded across six distinct four-hour time intervals, aggregated across the three-year study period. These data illustrate the peak mortality periods occurring during nocturnal hours (18:00–06:00), correlating with active vehicular light emission.

Time Interval	Mean Mortality
06:00–10:00	17.19
10:00–14:00	3.55
14:00–18:00	19.59
18:00–22:00	132.97
22:00–02:00	45.77
02:00–06:00	108.92

The table integrates descriptive and inferential statistics to compare insect mortality between daytime (traffic only) and night-time (traffic with vehicular light) periods. Results of the paired *t*-test ($t = -3.89$, $p < 0.05$) indicate that night-time mortality is significantly higher, confirming the amplifying effect of vehicular light at night on insect deaths.

The variability of mortality also differed markedly between the two periods. Night-time mortality displayed a variance of 20,458.35, considerably greater than the variance recorded during daytime surveys (4859.44). This difference indicates that nocturnal mortality events were not only higher in magnitude but also more unevenly distributed across sampling intervals and transects. Such variability likely reflects fluctuations in nocturnal insect activity together with spatial variation in vehicular illumination along the roadway.

Correlation analysis further revealed a moderate positive relationship between daytime and night-time mortality (Pearson $r = 0.60$), suggesting that baseline traffic activity contributes to insect mortality during both periods. Nevertheless, the markedly greater mortality observed at night indicates that the combination of traffic and vehicular illumination substantially increases the intensity of insect–vehicle collisions relative to daytime traffic alone (Table 3).

3.5. Temporal trends and growth rates

Temporal analysis of insect mortality across the study period revealed clear differences in growth dynamics and distribution patterns between daytime and night-time conditions. Compound annual growth rate (CAGR) analysis indicated that daytime mortality increased only modestly between 2021 and 2023, with an overall average growth rate of approximately 8%. In contrast, night-time mortality increased much more rapidly during the same period, exhibiting an average growth rate of 33%, indicating a substantially stronger upward trajectory of mortality under nocturnal conditions (Fig. S4 and S5).

Growth rates calculated across defined temporal intervals further illustrate this divergence. During daytime periods, mortality increased moderately across intervals, with growth rates of 14%, 9%, and 3% across the respective time segments. By comparison, night-time

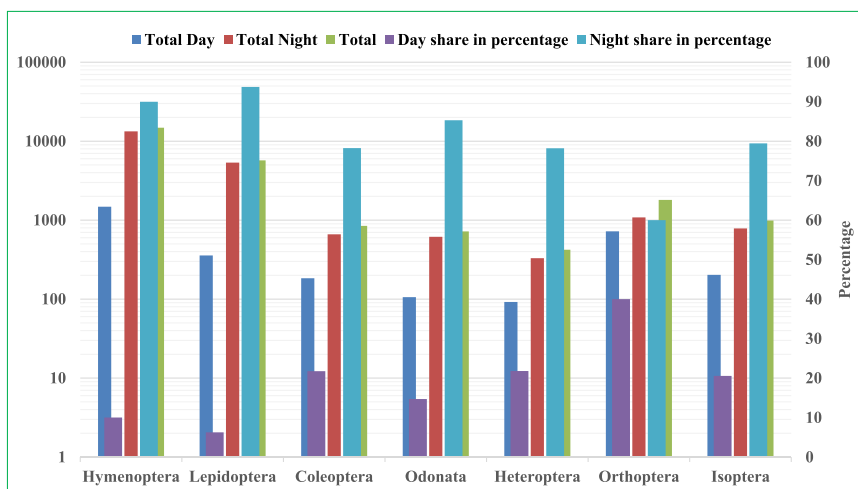


Fig. 3. Taxonomic composition of insect mortality recorded during daytime and night-time surveys. Distribution of insect carcasses across seven orders collected along a 5-km highway transect between 2021 and 2023. Bars show total mortality and relative contributions during daytime (traffic only) and night-time (traffic plus vehicular light at night).

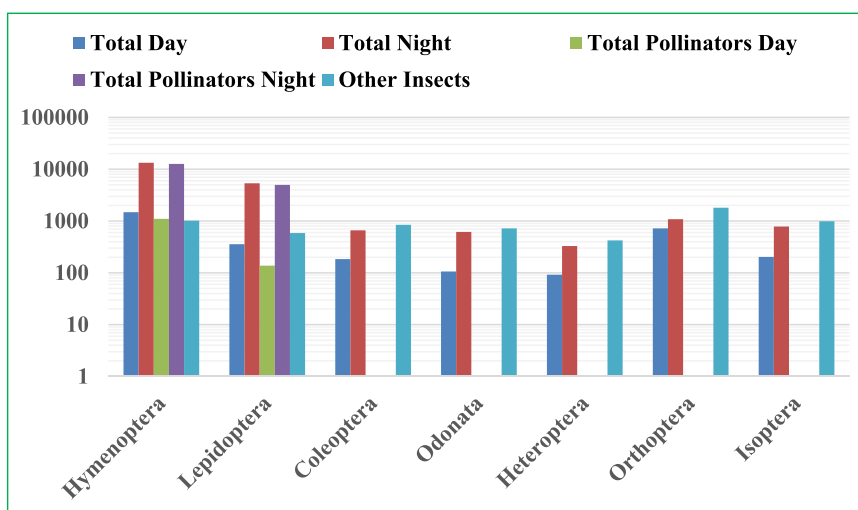


Fig. 4. Functional composition of insect mortality. Proportion of pollinators, herbivorous pests, predators, parasitoids, and other insects recorded during daytime and night-time sampling periods, highlighting the disproportionate contribution of pollinators to nocturnal mortality.

mortality exhibited consistently higher increases across the same intervals, with growth rates of 31%, 22%, and 41%, with the most pronounced increase occurring during the 02:00–06:00 interval. These results indicate that the pre-dawn period experienced the fastest escalation in insect mortality during the study period (Table 4).

Temporal partitioning of mortality across the 24-hour cycle revealed distinct peaks in insect deaths during specific intervals. The highest mean mortality was recorded during the 18:00–22:00 interval (132.97), followed by a secondary peak during 02:00–06:00 (108.92). In contrast, the lowest mortality occurred during the 10:00–14:00 interval (3.55), indicating minimal insect–vehicle collision activity during midday hours. These temporal patterns correspond with periods characterized by sustained vehicular illumination and heightened nocturnal insect activity.

Probability distribution modeling further highlighted the contrasting patterns between daytime and night-time mortality. Fitted lognormal and Weibull models showed that the estimated location parameter for night-time mortality (365) greatly exceeded that of daytime mortality (44.5), indicating a pronounced shift toward higher mortality intensities during nocturnal conditions. This rightward shift in the distribution demonstrates that high-magnitude mortality events occur more

frequently at night (Fig. 6).

Kernel density analysis provided additional insight into the distribution of mortality events across sampling periods. The density plot showed that daytime mortality exhibited a broad and diffuse distribution, reflecting relatively low and dispersed mortality events. In contrast, night-time mortality displayed a pronounced density peak, indicating the clustering of high-intensity mortality events during nocturnal sampling intervals. This concentrated density pattern further reinforces the observed temporal and statistical differences between the two periods and highlights the increased frequency and magnitude of insect mortality events occurring at night (Fig. 7).

3.6. Summary of key results

Collectively, these results demonstrate that insect mortality along highways is strongly structured by time of day. While traffic alone causes background insect mortality throughout daylight hours, the addition of vehicular light at night produces a distinct and amplified mortality regime. This regime disproportionately affects pollinators, exhibits rapid growth over time, and transforms road corridors into zones of concentrated insect loss.

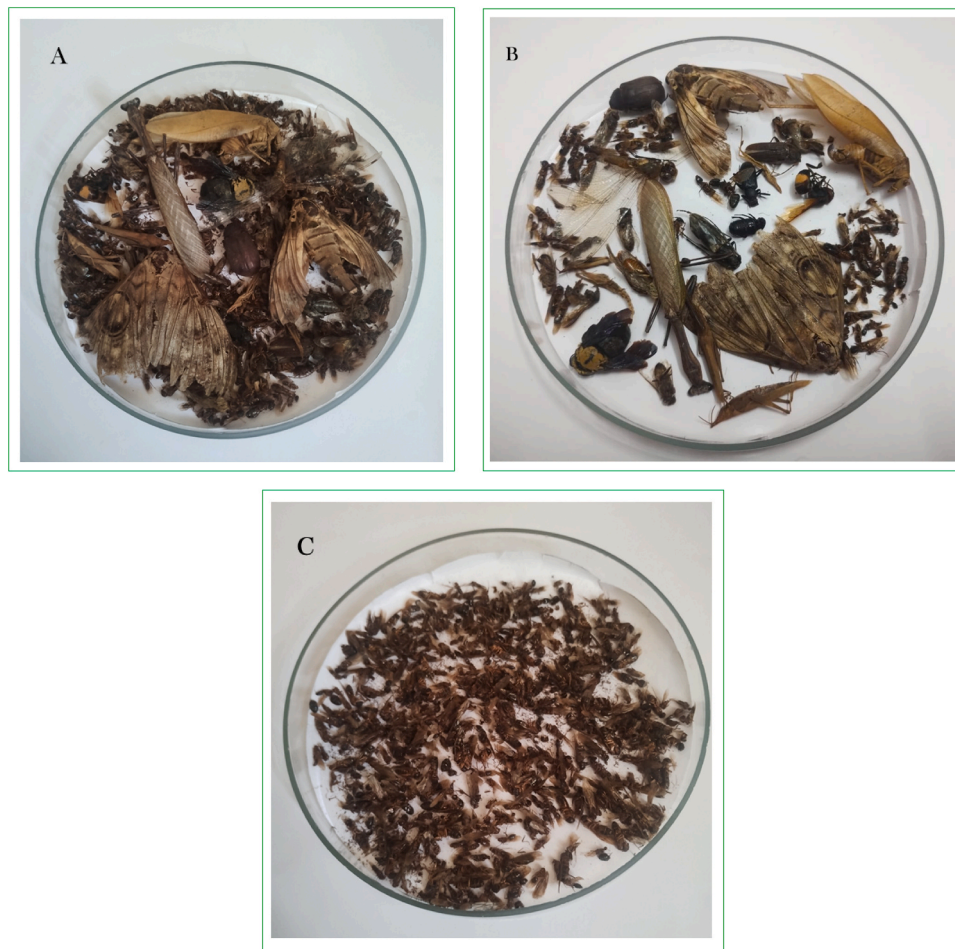


Fig. 5. Morphological characterization of highway-induced insect biomass loss. Representative specimen samples recovered from highway transects. (A, B) Heterogeneous biomass recovered during day and nocturnal intervals, featuring high-fidelity specimens of Lepidoptera and Hymenoptera. (C) High-density accumulation of small-bodied taxa typical of mass recruitment events driven by VLAN.

Table 3

Statistical summary and correlation analysis of insect mortality driven by traffic mobility versus vehicular light pollution. Comparison of mean variance and observation frequency between daytime traffic mobility and nocturnal vehicular light at night (VLAN). The Pearson Correlation ($r = 0.60$) and paired two-sample *t*-test results further quantify the significant divergence in mortality drivers between light and dark periods.

Insects mortality by traffic mobility	Insects mortality by Vehicular light pollution at Night	
Mean	36.60	171.74
Variance	4859.44	20,458.35
Observations	12.00	12.00
Pearson Correlation	0.60	
Hypothesized Mean Difference	0.00	
Df	10.00	
t Stat	-3.89	
P(T ≤ t) one-tail	0.00	
t Critical one-tail	1.81	
P(T ≤ t) two-tail	0.00	
t Critical two-tail	2.23	

t-Test: Paired Two Sample for Means

4. Discussion

This study provides long-term empirical evidence that vehicular light at night substantially amplifies insect mortality along highway corridors, far exceeding mortality attributable to road traffic alone. Across

Table 4

Divergent Compound Annual Growth Rates (CAGR) of insect mortality during diurnal and nocturnal periods (2021–2023). Analysis of temporal growth trajectories for insect carcass accumulation. The data demonstrate a substantial acceleration in nocturnal mortality (Overall CAGR: 33%) compared to diurnal baselines (Overall CAGR: 8%), highlighting the intensifying ecological footprint of vehicular illumination.

	CAGR (Compound annual growth rates) during the study period			
	Average of sum	Average of 06–10	Average of 10–02	Average of 02–06
CAGR (Day 2021-23)	8%	14%	9%	3%
CAGR (Night 2021-23)	33%	31%	22%	41%

three years of replicated sampling, night-time insect deaths were consistently higher than daytime deaths, revealing a distinct nocturnal mortality regime driven by the interaction between traffic and vehicle-emitted artificial light. These findings indicate that illuminated roads function not merely as linear disturbances but as ecological traps that concentrate and remove insect biomass from surrounding landscapes. We acknowledge that intrinsic nocturnal insect activity and environmental variability may also contribute to the observed increase in night-time mortality.

Artificial light at night (ALAN) is increasingly recognized as a

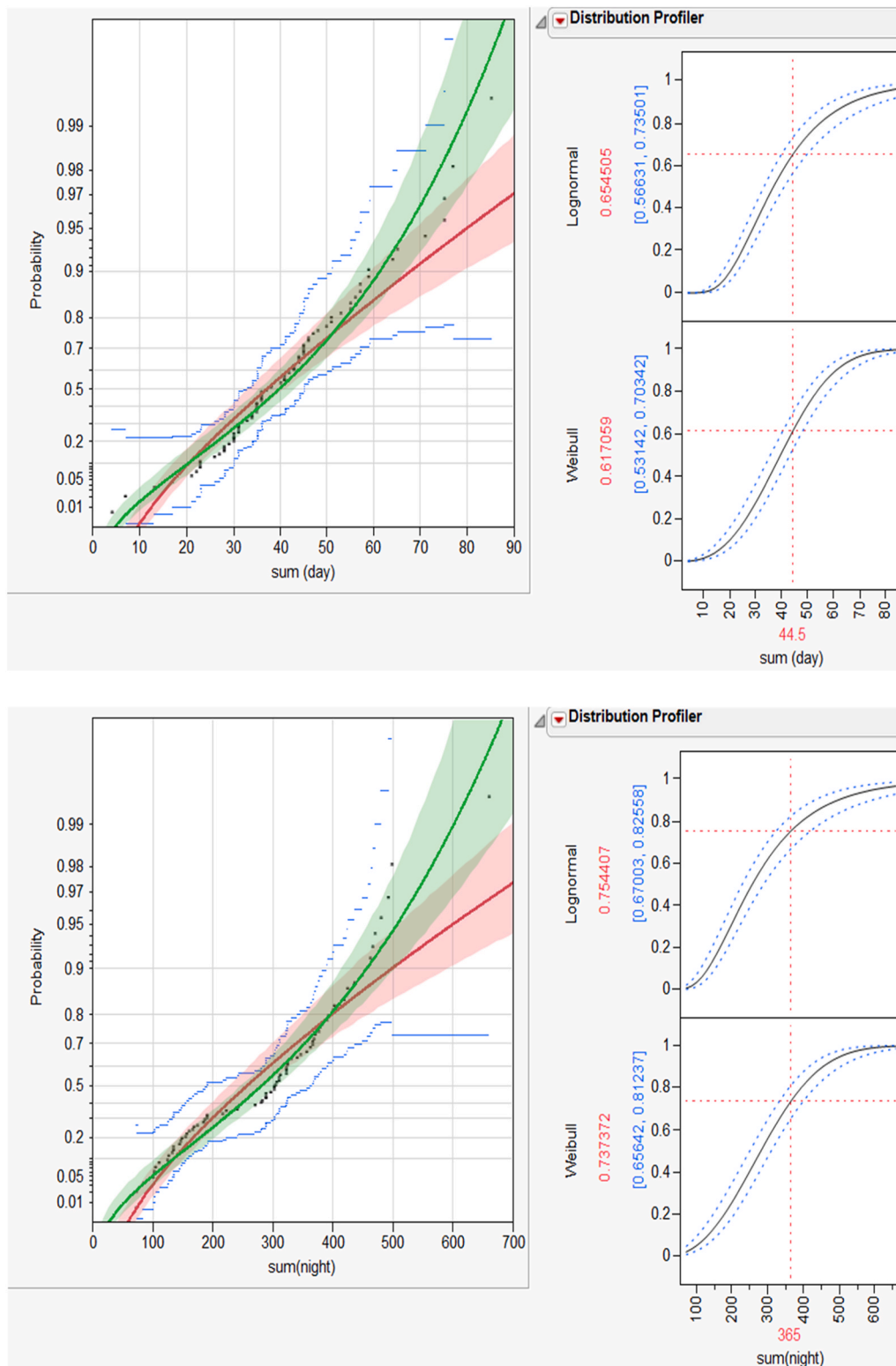


Fig. 6. Probability distribution of insect mortality across the 24-h cycle. The fitted lognormal and Weibull models describe the cumulative probability distribution of insect mortality during daytime and night-time sampling periods. The values 44.5 (day) and 365 (night) represent the estimated location parameters (central tendency) of the fitted distributions, indicating the mortality intensity at which approximately 50% cumulative probability is reached. The substantially higher parameter value under nocturnal conditions reflects a strong rightward shift in the distribution, demonstrating that insect mortality events are both **more frequent and more intense at night**, consistent with the amplifying influence of vehicular light on collision risk.

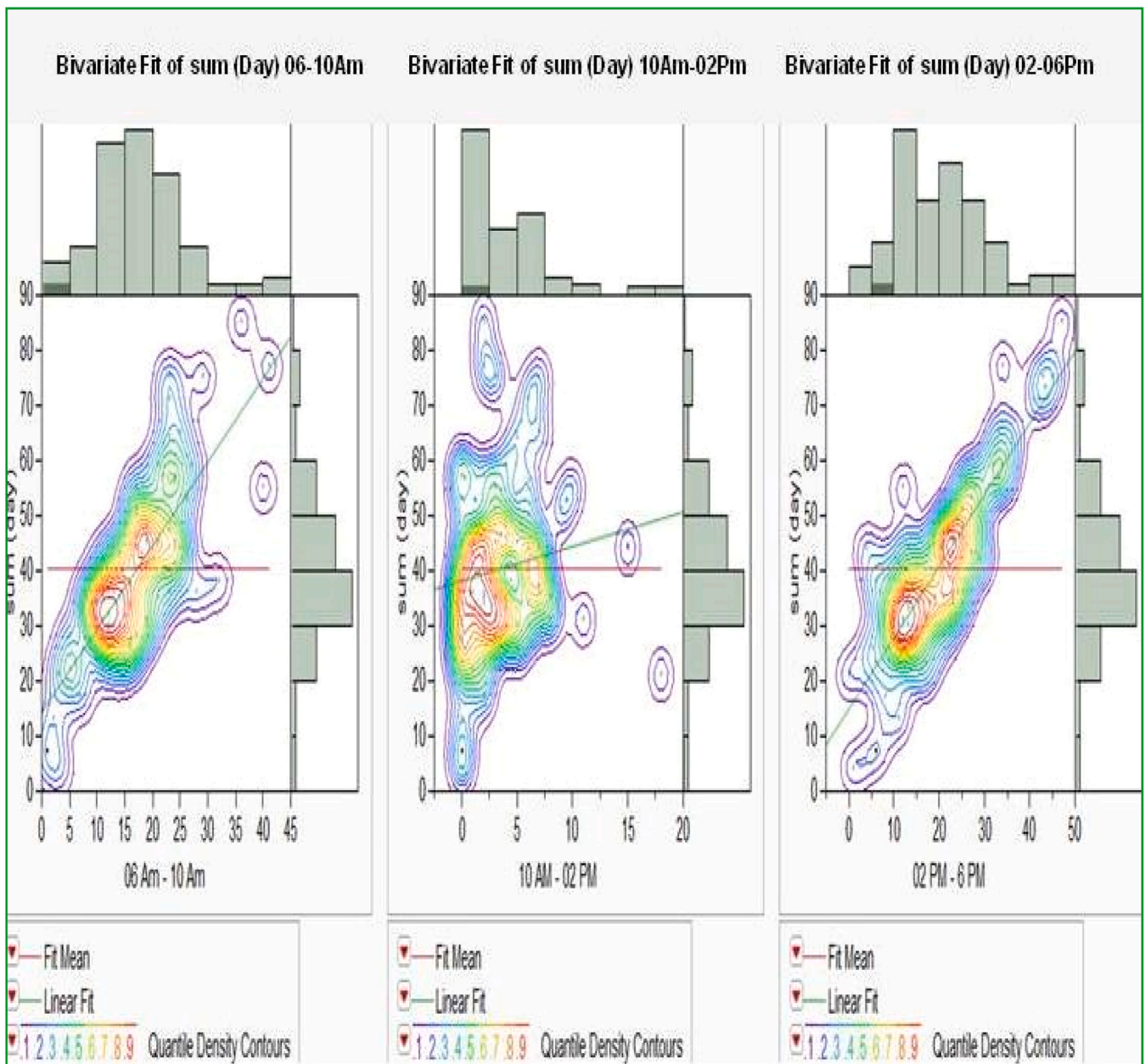


Fig. 7. Kernel density estimation of spatiotemporal mortality hotspots. Bivariate fit and non-parametric density contours comparing daytime (diffuse) and night-time (concentrated) mortality. The high-density "peaks" in nocturnal plots reveal the formation of localized hotspots where VLAN-driven recruitment overrides stochastic background mortality.

pervasive environmental pollutant with wide-ranging ecological effects [9,10]. Most research has focused on stationary illumination sources such as streetlights and industrial installations, which attract insects, disrupt behavior, and elevate predation risk [3,8,32], including earlier assessments demonstrating ALAN-associated insect mortality under fixed lighting environments [18]. Stationary lamps may generate a high-frequency "sweeping" effect that repeatedly draws insects from the surrounding landscape into traffic pathways. In contrast, vehicle headlights penetrate the "dark corridors" between streetlights, effectively eliminating any safe refuge for insects attempting to cross the highway. Our findings extend this framework by demonstrating that vehicle-emitted illumination represents a fundamentally different form of ALAN characterized by mobility and repeated spatial propagation. Unlike fixed lighting that creates localized zones of attraction, mobile illumination travels across landscapes, exposing insects to transient but

intense light pulses over extensive road networks spanning rural, agricultural, and semi-natural habitats. This dynamic exposure increases the frequency with which insects encounter hazardous illuminated environments and may amplify mortality beyond that associated with stationary light sources. To distinguish this mobile component from fixed illumination, we refer to it here as *vehicular light at night (VLAN)*, a transient form of ALAN generated by moving transport systems. Viewed in this context, VLAN expands the ecological footprint of artificial lighting by extending light disturbance into otherwise dark environments, representing a spatially dynamic dimension of ALAN that has been largely overlooked.

4.1. Sensory misorientation in the anthropocene

The intersection of linear infrastructure and nocturnal biodiversity is

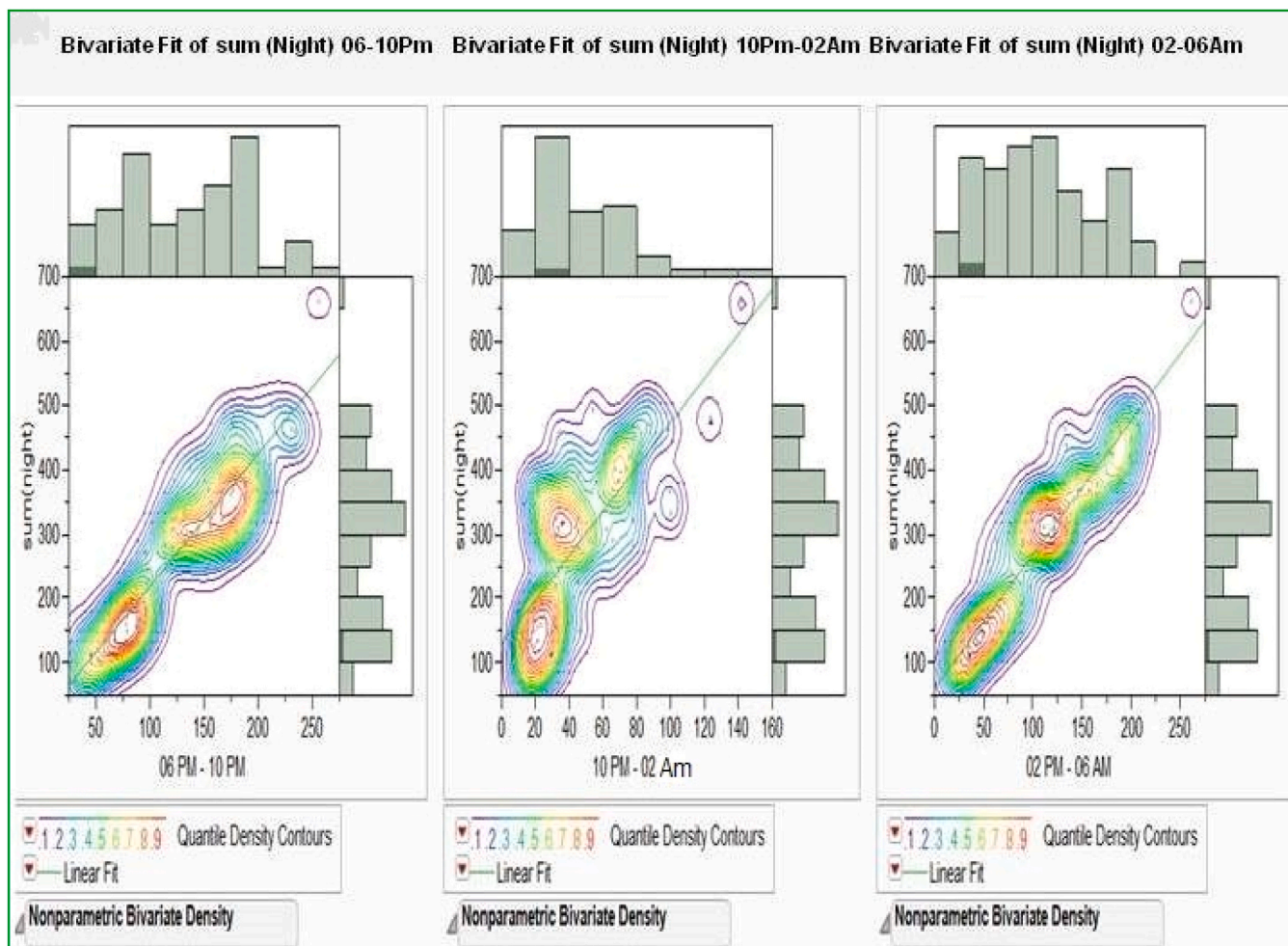


Fig. 7. (continued).

increasingly defined by the displacement of ancestral navigational cues by pervasive anthropogenic signals. Historically, the Transverse Orientation Hypothesis [7] posited that insects maintain flight stability via a fixed-angle celestial compass; however, modern high-speed kinematic analyses suggest a more profound physiological failure. The recently elucidated Dorsal Light Response [5] demonstrates that flying insects do not merely steer toward light but inadvertently tilt their dorsum toward the brightest source to maintain vertical orientation.

When confronted with the transient, high-intensity pulses of Vehicular Light at Night (VLAN), this innate reflex triggers a catastrophic 'inversion motif,' leading to the rapid loss of flight control and subsequent collision. This phenomenon represents a lethal evolution of Ecological Trap Theory [2], wherein a mobile anthropogenic signal uncouples evolved sensory behaviors from survival outcomes. Our work identifies this 'moving trap' as a potentially significant driver of biomass attrition along rapidly expanding tropical highway networks, where the 33% CAGR in nocturnal mortality suggests that the sensory disruption caused by modern automotive lighting is fundamentally restructuring the ecological integrity of roadside matrices globally.

The pronounced taxonomic and functional biases observed in this study highlight the ecological significance of vehicular light-driven or vehicular light at night (VLAN) driven mortality. Hymenoptera and Lepidoptera together accounted for the majority of recorded deaths, with pollinators representing nearly half of all insect carcasses. Nocturnally active Lepidoptera were particularly vulnerable, with the overwhelming majority of deaths occurring at night. These patterns are consistent with known light-attraction behaviors in insects, which

involve disruption of celestial navigation, chromatic discrimination, and polarized-light perception [12,15]. Attraction to artificial lights may be further intensified by localized warming and aggregation effects mediated through pheromonal cues [16,25].

Beyond mitigation, these findings offer a provocative blueprint for targeted ecological engineering. If the phototactic mechanisms driving vehicular mortality can be inverted, they may serve as a precision tool for agricultural enhancement. We hypothesize that spectrally-optimized, low-intensity lighting placed at the base of nocturnal entomophilous plants could function as a 'sensory conduit,' directing pollinators toward reproductive structures to augment seed set and fruit yield. Validating this 'Directed Pollination' model represents the primary utility of future controlled trials, where light intensity and floral phenology can be precisely calibrated. Such a transition from viewing light as an anthropogenic pollutant to harnessing it as a catalyst for ecosystem resilience is vital for reconciling global transport infrastructure with the urgent mandate of conservation in the Anthropocene.

Roads already impose multiple stressors on insect populations, including habitat fragmentation and direct mortality from collisions [20]. Our findings suggest that vehicular light fundamentally alters the nature of road-associated mortality by increasing its intensity, predictability, and spatial concentration during nocturnal hours. The higher variance and right-skewed distributions observed at night indicate recurrent mass-mortality events rather than sporadic incidental deaths. This transformation of road corridors into predictable sinks for insect populations has important implications for landscape-scale biodiversity patterns.

As global transport networks continue to expand, understanding the indirect ecological consequences of mobile artificial illumination becomes increasingly important for predicting biodiversity ecosystem function relationships under anthropogenic change. Insects underpin multiple ecosystem processes that sustain ecological stability and human well-being. As primary components of terrestrial food webs, they facilitate energy transfer across trophic levels and serve as essential prey for birds, amphibians, reptiles, and small mammals. In addition, insects regulate nutrient cycling through decomposition and organic matter turnover, contribute to natural biological control by suppressing agricultural pests and parasitic organisms, and support plant reproduction through pollination and seed dispersal. The disproportionately high mortality observed under vehicular illumination therefore extends beyond localized population loss and may influence broader ecosystem function. Elevated mortality among functionally important groups, particularly pollinators and nocturnally active taxa, suggests potential cascading effects on plant–pollinator interactions, trophic dynamics, and ecosystem resilience. Although ecosystem processes were not directly quantified in this study, the magnitude and functional composition of observed mortality indicate that mobile artificial lighting associated with transport infrastructure may represent an emerging pathway linking biodiversity decline with ecosystem disruption.

The disproportionate loss of pollinators observed here raises important concerns for ecosystem functioning and agricultural sustainability. Pollinators play a central role in maintaining plant reproduction, crop yields, and biodiversity [1,22,23]. Removal of pollinator biomass at the scale documented here may disrupt plant–pollinator networks resulting in “Biomass Vacuum”, alter flowering phenology, and reduce reproductive success in both wild and cultivated plants [4,21]. In parallel, increased mortality among predators and parasitoids may weaken natural pest control, potentially intensifying pest pressures in agricultural landscapes adjacent to highways.

The accelerating growth in night-time insect mortality observed over the study period coincides with broader socio-economic trends, including rapid expansion of vehicle ownership and road infrastructure in India [11,17](Fig S6). Comparable global trends suggest that vehicular light-driven insect mortality may increase unless explicitly addressed in transport planning and environmental governance. Recent assessments indicate that the ecological impacts of global road expansion may be substantially underestimated, particularly for less-studied taxa such as insects [29].

In near-absolute nocturnal conditions, the acute luminous contrast between the ambient environment and localized artificial light (AL) transforms even minimal emissions into dominant, maladaptive visual cues. The propensity for insect recruitment into these phototactic sinks is a function of both biological and technical parameters. The proximal presence of high-quality resource matrices including larval habitats, floral nectararies, and essential foraging grounds ensures a constant influx of individuals into the road-effect zone. During peak phenological events, such as mass eclosion or synchronized breeding seasons, these habitats act as high-density biotic reservoirs, providing a vast pool of susceptible individuals. Simultaneously, the intensification of Artificial Light at Night (ALAN) manifested through increased radiant flux, beam collimation, and the cumulative spectral emissions of multiple sources compounds the attractive force. This convergence of rich ecological interfaces and concentrated anthropogenic signals accelerates the rate of biomass attrition, effectively uncoupling ancestral navigation from survival.

The intensification of nocturnal mortality may be further exacerbated by hydrologically-induced emergence events. Precipitation and increased soil moisture levels act as critical environmental cues, triggering the synchronized emergence of burrowing and soil-dwelling insects such as many Coleopterans and Gryllidae into the terrestrial matrix [18]. This pulse of dispersal-phase biomass significantly increases the density of susceptible individuals within the road-effect zone. When these emergence events coincide with high-traffic nocturnal intervals,

the high luminous contrast of vehicular headlights provides a localized, high-intensity signal that overrides natural orientation cues. Consequently, rainfall does not merely introduce 'noise' into the dataset; it functions as a biological catalyst that feeds the VLAN-driven ecological trap, leading to the concentrated mass-mortality events reflected in our right-skewed nocturnal distribution models.

While this longitudinal study does not explicitly decouple the granular effects of fluctuating meteorological variables such as anemometric shifts, precipitation, or the heterogeneous architecture of roadside flora we contend that nature remains the ultimate, albeit stochastic, laboratory. Within the operational complexity of a major highway corridor, environmental fluctuations represent the 'ecological noise' inherent to open-system research. Our three-year dataset reveals that the attractive force of Vehicular Light at Night (VLAN) functions as a dominant biological signal that consistently overrides this noise. By prioritizing ecological realism over the sterility of clinical isolation, we demonstrate that the fatal attraction of insects to mobile light is not a conditional event, but a robust, invariant driver of biodiversity attrition across the urban–rural gradient.

Importantly, vehicular light pollution represents a potentially tractable sustainability challenge. Unlike diffuse drivers such as climate change, vehicle-emitted lighting can be mitigated through targeted engineering and policy interventions. Measures such as improved headlight shielding, spectral optimization, reduction of unnecessary auxiliary lighting, speed regulation, and the establishment of dark corridors in ecologically sensitive regions may substantially reduce insect attraction and collision risk.

The three years fortnightly field surveys results further suggest that this 'ecological trap' is modulated by the spectral heterogeneity of modern automotive lighting. The current findings serve as a critical primary assessment of VLAN-induced mortality and future should integrate automated traffic sensors and infrared vehicle counters to correlate insect strike rates with fluctuating traffic density. The global transition toward high-intensity, blue-rich LEDs may or may not likely exacerbate phototactic recruitment, creating a more potent sensory trap than traditional halogen sources. The influence of varying moonlight conditions on the effects of VLAN on insects requires further investigation, as increased ambient illumination during full-moon nights may reduce the contrast between artificial light and the environment. Consequently, insects may rely more on natural celestial cues and exhibit reduced attraction or distraction to VLAN, potentially lowering mortality rates. However, such responses are species-specific and influenced by environmental factors, indicating that this relationship is not universally consistent. Consequently, investigating differential spectral sensitivities through controlled experimental frameworks is the next essential frontier. Decoupling the behavioral responses of key pollinator taxa across monochromatic and polychromatic spectra will be fundamental to engineering 'bio-adaptive' illumination profiles.

5. Hypothesis

5.1. Daylight hypothesis

Under daylight conditions, insects are not attracted to artificial light because of the intensity and uniform distribution of sunlight overwhelms any artificial source. Natural irradiance provides superior navigational cues, preventing insects from orienting toward any artificial source of light (AL). Only when sunlight is significantly reduced such as during heavy cloud cover might artificial lights exert a detectable attractive influence.

5.2. Night-light hypothesis

In darkness, even minimal artificial illumination can become a dominant visual cue. At night, the strong contrast between the surrounding dark environment and localized artificial light (AL) draws

insects toward the light source. Increased ALAN, light intensity, beam concentration, or cumulative emissions from multiple sources further intensify this attraction, accelerating mortality.

5.3. Chromatic and achromatic theory

Many insects possess limited chromatic resolution due to the optical constraints of compound eyes, making them prone to confusion when encountering large, bright light sources. Such lights can mimic floral cues, prompting approach or probing behavior that brings insects into contact with lethal heat or collision zones. Localized warming around lights may attract thermophilic species or individuals seeking microclimatic refuge. Aggregating females attracted to artificial light may release pheromonal cues that further intensify conspecific attraction. Under artificial light at night (ALAN), insects often fail to distinguish chromatic and polarization cues when the subtended visual angle falls below approximately 13–15° [12,15]. Consequently, artificial light sources can be misinterpreted as biologically relevant visual signals, such as floral or celestial cues, eliciting persistent approach behavior that frequently results in mortality.

5.4. Diurnal and nocturnal theory

Diurnal insects may approach artificial lights when the light intensity (brightness), spectral composition (color) and temperature resemble daylight, disrupting their normal orientation cues. Nocturnal insects, by contrast, may interpret lights as bright floral patterns against a dark background, or follow pheromone trails from conspecifics already aggregated around the light. In both cases, artificial light at night (ALAN) interferes with celestial navigation cues, polarized-light perception, and other orientation mechanisms, causing insects to become disoriented and increasingly attracted toward hazardous illuminated environments.

5.5. Synthesis of mechanistic drivers: the sensory trap model

The convergence of these hypotheses suggests that Vehicular Light at Night (VLAN) does not merely act as a physical barrier, but as a complex sensory ecological trap that hijacks evolved navigational systems. This phenomenon can be summarized through four primary mechanistic pillars:

5.5.1. Daylight-mimicry response

For diurnal taxa, high-intensity, blue-rich vehicular emissions trigger a false solar-orientation signal. This disrupts the Daylight Hypothesis framework, as the concentrated radiant flux of modern LEDs overrides natural nocturnal cues, forcing a "daytime" navigational state in a nighttime environment.

5.5.2. Hyper-stimulant recruitment

In the absence of solar irradiance, concentrated artificial sources act as hyper-stimulants for nocturnal specialists. By mimicking the high-contrast UV-reflectance patterns of floral nectararies or celestial bodies, these lights elicit persistent approach behaviors. This maladaptive sensory convergence uncouples millions of years of evolutionary orientation from survival, as insects interpret lethal illumination as high-value biological resources.

5.5.3. Chromatic and achromatic failure

The biological "trap" is exacerbated by the optical limitations of the compound eye. When the visual angle of a light source falls below the critical threshold for chromatic discrimination, insects suffer a total loss of polarized-light perception. This results in the "inversion motif" and catastrophic flight failure observed in modern kinematic studies.

5.5.4. Social facilitation of entrapment

The initial recruitment of individuals generates a secondary biological signal. The release of pheromonal cues and acoustic signatures from insects already aggregated around the light source creates a feedback loop. This Social Facilitation of Entrapment exponentially increases the "capture zone" of the vehicle, recruiting conspecifics from the surrounding resource matrices into the high-risk collision zone.

6. Recommendations to reduce vehicular light pollution (VLP)

Reducing vehicular light pollution requires a combination of engineering solutions, regulatory frameworks and broader changes in transportation practice. Headlights should be redesigned to restrict beam spread and illuminate only essential road regions, with shielding and directional control to prevent unnecessary lateral or upward projection. Lower-intensity, eco-friendly lighting technologies and spectrum-adjusted headlights may further reduce attraction distances. In ecologically sensitive regions, restricting night-time vehicle movement would substantially reduce insect mortality.

Broader transport reforms could also help. Moderating private vehicle ownership, shifting freight transport from roads to rail or water routes and encouraging public or shared mobility would reduce cumulative vehicle emissions, including light. Emerging technologies such as infrared-based detection systems, driver displays and autonomous vehicle platforms may eventually enable safe night driving with minimal or no visible light. Complementary road-design strategies such as enhanced fluorescent paints or reflective markings that reduce the need for intense headlights or streetlights could further lower attraction of insects to illuminated corridors.

6.1. Measures to mitigate light pollution

Mitigating light pollution more broadly requires coordinated public awareness, effective governance and technological adaptation. Recognizing artificial light as an environmental pollutant is an essential first step, followed by the establishment of strict limits on illumination intensity, spectral characteristics and operating hours across residential, commercial and industrial zones. Implementing graded illumination zones differentiating rural, peri-urban and metropolitan needs would ensure context-appropriate lighting rather than uniform, excessive brightness.

Reducing surplus light emissions from households, commercial establishments and industry is equally important. Shielded fixtures that prevent upward or horizontal light leakage should be mandated for streetlights, parking areas and public facilities, while upward-facing billboards and façade lighting should be eliminated. Modern light-management systems, including automation, adaptive dimming and curfews, can significantly reduce unnecessary emissions. Energy-saving technologies such as infrared-activated sensors for security lighting and outdoor installations may further reduce the ecological footprint of artificial illumination. Limiting new light installations and phasing out obsolete or redundant fixtures would help restore the natural nocturnal environment over time.

7. Conclusion

This study establishes Vehicular Light at Night (VLAN) as a primary, yet previously obscured, catalyst of insect attrition along global road networks. While diurnal traffic volume contributes to a mechanical baseline of insect mortality, vehicle-emitted illumination fundamentally alters the ecological equation dramatically amplifying mortality during nocturnal hours and disproportionately recruiting pollinators and other functionally vital taxa. By transforming illuminated corridors into active ecological traps, vehicular lighting facilitates the large-scale removal of biomass from the surrounding matrix, directly threatening the ecosystem services essential to global sustainability.

While our findings provide a robust quantification of this phenomenon, the observational nature of this research conducted within the stochastic environment of an operational highway serves as a necessary precursor to more granular investigations. The inherent variability in vehicle-specific spectral signatures and transit speeds highlights the complexity of light dynamics in situ, establishing a baseline that necessitates prolonged, multi-decadal longitudinal studies to fully decode the resulting vegetation dynamics and shifts in floral community architecture. Furthermore, by integrating high-resolution field data with controlled behavioral experiments, future research can bridge the gap between observed mortality and ecosystem-function measurements, such as pollination efficacy and trophic biomass transfer.

As global vehicle numbers and lighting technologies specifically blue-rich LEDs continue to expand, the ecological footprint of VLAN will inevitably intensify. Recognizing vehicular light pollution as a distinct anthropogenic pollutant and integrating its mitigation into transport planning and biodiversity conservation are therefore urgent priorities. Addressing this emerging pollutant offers a rigorous framework to resolve the mechanistic pathways linking anthropogenic light with long-term ecological flux, providing a practical pathway toward reversing insect decline and safeguarding the essential ecosystem functions upon which human societies depend in the Anthropocene.

Ethical Approval

This study involved observational field surveys of naturally occurring insect mortality along public roadways and did not involve experimental manipulation, protected species, or vertebrate animals. Therefore, formal ethical approval was not required according to the institutional guidelines of Annamalai University.

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CRedit authorship contribution statement

D Raajasubramanian: Writing – review & editing, Visualization, Validation, Supervision, Resources. **Varadi Vijay Kumar:** Writing – review & editing, Visualization, Validation, Software, Resources, Formal analysis, Data curation. **K Narendra:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used AI-assisted tools (e.g., ChatGPT, Perplexity, and Gemini) to improve the clarity and articulation of certain sections of the manuscript. In addition, the graphical abstract and Fig. 1 were generated with the assistance of artificial intelligence tools. All outputs were critically reviewed, refined where necessary, and approved by the authors, who take full responsibility for the accuracy and integrity of the content.

Declaration of Competing Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Conflict Of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.nxsust.2026.100321](https://doi.org/10.1016/j.nxsust.2026.100321).

Data availability

Data will be made available on reasonable request

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