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From Glow to Decline: Firefly Population Dynamics as Indicators of Environmental Change in India with Insights from Assam

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ABSTRACT

Fireflies (Coleoptera: Lampyridae) are important bioluminescent insects and sensitive indicators of environmental change. This review demonstrates their diversity, distribution, and population trends in India, with insights from Assam. India hosts over 90 species with high endemism, though they remain understudied. Firefly populations are influenced by environmental factors such as temperature, humidity, and rainfall, which regulate their life cycle and activity. However, increasing declines are driven by habitat loss, pesticide use, climate change, and Artificial Light at Night (ALAN), which disrupts mating communication. Due to their ecological sensitivity, fireflies serve as effective bioindicators, reflecting ecosystem health through changes in abundance and behavioral pattern. Northeast India, particularly Assam, provides suitable habitats but faces growing anthropogenic pressures. Limited regional data highlight the need for systematic research and conservation strategies to monitor and protect firefly populations.

Keywords Fireflies (Lampyridae), Bioindicators, Environmental change, Population decline, Artificial light at night (ALAN).

INTRODUCTION

Biodiversity patterns across ecosystems are shaped by the complex interplay of abiotic and biotic factors that filter species based on their ecological traits and adaptive capacities. Abiotic stressors such as temperature, moisture, soil composition, and disturbance regimes regulate community structure by selecting species whose life-history traits are best suited to local environmental conditions (Kraft *et al.* 2015). However, in the Anthropocene, natural environmental gradients are increasingly modified by human activities, which not only alter the intensity and distribution of existing stressors but also introduce novel pressures such as pollution and artificial light. These combined natural and anthropogenic influences play a crucial role in shaping biodiversity patterns, yet their interactive effects on species distribution and functional traits remain inadequately understood (McGill *et al.* 2015,

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Aronson *et al.* 2016).

Fireflies (family Lampyridae) are one of the most charismatic groups of insects, widely recognized for their ecological, evolutionary, and cultural significance. They provide a unique model for understanding these ecological dynamics. Fireflies are bioluminescent beetles belonging to the order Coleoptera, comprising over 2,200–2,500 species distributed across diverse habitats worldwide (Ohba 2004, Lloyd 2008, Ballantyne *et al.* 2019). Their ability to produce light through the luciferin–luciferase reaction is not only a remarkable evolutionary adaptation but also a critical component of their communication and reproductive behavior. Fossil evidence dating back approximately 99 million years, along with molecular studies, suggests a long evolutionary history with multiple independent origins of bioluminescence within related beetle lineages (Day *et al.* 2009, Auld *et al*. 2010, Oba *et al*. 2020). Beyond their aesthetic appeal, fireflies play important ecological roles as predators of soft-bodied invertebrates during their larval stages and as components of complex food webs (Stork 2018).

In recent decades, firefly populations have shown alarming declines worldwide due to a combination of environmental variability and anthropogenic pressures. Seasonal factors such as temperature, humidity, and rainfall regulate their life cycle, activity, and reproductive success, and as ectothermic organisms, fireflies are highly sensitive to microclimatic changes (Kraft *et al.* 2015, Khattar *et al.* 2022). At the same time, human-induced disturbances including habitat loss and fragmentation from urbanization, agriculture, wetland degradation, and deforestation have reduced suitable habitats. Chemical pollution from pesticides further affects larval survival and trophic interactions. Among these threats, Artificial Light at Night (ALAN) is particularly critical, as it disrupts bioluminescent communication and reduces mating success (Owens and Lewis 2021b, Owens and Lewis 2022, Gaston *et al.* 2021).

Due to their sensitivity, habitat specificity, and ease of observation, fireflies are increasingly recognized as effective bioindicators of ecosystem health. Variations in their abundance, distribution, and behavior reflect cumulative environmental stress, making them valuable for monitoring ecological integrity (Lewis *et al.* 2024, Shen *et al.* 2022).

In India, despite high ecological diversity, fireflies remain relatively understudied, with recent assessments reporting over 90 species and significant endemism (Parvez *et al.* 2026). Their populations are strongly influenced by monsoonal seasonality, with peak activity during humid periods, but are increasingly threatened by anthropogenic pressures and climate variability. Northeast India, particularly Assam, provides highly suitable habitats due to its high rainfall, wetlands, and forest ecosystems; however, rapid land-use change, agricultural intensification, and urbanization pose growing threats. Despite its importance, systematic studies on firefly population dynamics and their role as bioindicators in this region remain limited.

Against this backdrop, the present study, "Firefly Population Dynamics as Indicators of Environmental Change in India, Insights from Assam," aims to synthesize existing knowledge on firefly ecology, seasonal dynamics, and environmental sensitivities. It further seeks to highlight the potential of fireflies as bioindicators for assessing environmental change, while emphasizing the urgent need for region-specific research and conservation strategies in Assam and the broader Northeast Indian landscape.

Diversity and distribution of fireflies

Fireflies (family Lampyridae) are highly diverse and are widely distributed across tropical and temperate regions. They exhibit considerable diversity in morphology, behavior, and life history traits, including the presence of both fully winged and larviform (wingless) adults, particularly among females (Lewis *et al.* 2020, Lewis *et al.* 2024). The diversity of fireflies largely depends on environmental factors like humidity, temperature, vegetation structure, and the availability of suitable microhabitats (Lewis *et al.* 2020, Khattar *et al.* 2022). Over 2500 described species are recorded globally which are predominant in tropical and subtropical regions where humid forests, wetlands, and riparian zones support larval development and adult survival (Stork 2018, Lewis *et al.* 2024, Wattanachaiyingcharoen *et al.* 2016). Tropical regions such as Central and South America and Southeast Asia harbor the highest species richness, likely due to favorable climatic conditions and habitat heterogeneity. In contrast, temperate regions including North America, Europe, and East Asia support fewer species but still maintain ecologically significant populations (Martin *et al.* 2019). Studies suggest that fireflies are not evenly distributed across ecosystems, with more diversity and abundance in relatively undisturbed habitats, while disturbed landscapes support significantly fewer individuals, with abundance declining by 40–60% in agricultural or modified ecosystems (Ghosh *et al.* 2025; Potulwar *et al.* 2025). Many species depend on specific habitats and have limited distributions, which makes them very sensitive to environmental disturbances such as habitat loss, climate change, and artificial light pollution (Owens and Lewis 2022, Lewis *et al.* 2020).

Firefly diversity in India is relatively high because of the country's diverse climatic and ecological conditions; however, it remains insufficiently documented due to limited taxonomic research and the lack of long-term ecological monitoring (Pandey *et al.* 2025, Paul 2025). A study by Parvez *et al.* (2026) documented 92 firefly species across four subfamilies Luciolinae, Ototretinae, Lampyrinae, and Cyphonocerinae with Luciolinae identified as the most dominant group in India. They reported that approximately 60.86% of these species are endemic, indicating India's rich and unique biodiversity. Moreover, firefly distribution in India shows clear regional variation, with the highest occurrence recorded in the Western Ghats (25.33%) followed by North East India (22.66%), both representing major diversity hotspots, while the Gangetic Plain (17.33%) and the Coast and Deccan Peninsula (13.33%) exhibit moderate occurrence. In contrast, regions such as the Himalayas, Trans-Himalayas, and islands show low occurrence, and fireflies are notably absent in desert and semi-arid regions, reflecting their strong dependence on moist and suitable habitats (Parvez *et al.* 2026) (Table 1).

Northeast India, particularly Assam, supports highly favorable environmental conditions for fireflies because of its humid climate, heavy rainfall, and diverse ecosystems like wetlands, floodplains, and forests. These habitats support a wide variety of fireflies, with their populations peaking during the monsoon season. Surveys reported 40–60 firefly species in Assam, with peak populations observed during the monsoon when humidity and water availability are optimal (Chakravarthy and Parvez 2024, Ghosh *et al.* 2025). Choudhury *et al*. (2025) studied two firefly species, *Abscondita chinensis* and *Asymmetricata circumdata*, in grassland and woodland habitats of Assam (Bodoland University). They found higher firefly density in grasslands, where individuals mostly flew close to the ground, while in woodlands they flew higher due to dense vegetation. Activity was greater in warmer conditions and reduced in higher humidity. The study highlights the need for habitat-specific conservation, focusing on ground-level protection in grasslands and canopy management in woodlands.

Despite favorable ecological conditions, systematic research on firefly diversity, distribution patterns, and abundance remains limited in the region. The limited scientific data highlights a major research gap and shows the importance of this study in documenting firefly diversity and understand their distribution

Table 1. Geographical distribution of firefly species in India.

Region	Percentage of species occurrence	Occurrence / Diversity	Reference
Western Ghats	25.33%	Highest occurrence	Parvez *et al.* (2026)
Gangetic Plain	17.33%	Moderate occurrence	
Coast and Deccan Peninsula	13.33%	Moderate occurrence	
Trans-Himalayas	1.33%	Low occurrence	
Himalayas	1.33%	Low occurrence	
Islands	2.66%	Low occurrence	
Desert & Semi-arid regions	0%	Fireflies absent	
North East India	22.66%	High diversity	

in relation to environmental and human.

Ecology and bioluminescent significance of fireflies

Fireflies are soft-bodied beetles that belong to the order Coleoptera and family Lampyridae, with over 2,200 known species that are found in temperate, subtropical, and tropical parts of the world (Lewis *et al.* 2020, Ghosh *et al.* 2021). Fireflies are known for their extraordinary ability to produce bioluminescent light, making them one of the most fascinating groups of insects and a special place where ecology, evolution, and environmental science meet. The production of light in fireflies is not just a beautiful sight but also a biologically optimal chemiluminescent reaction that involves luciferin, luciferase, adenosine triphosphate (ATP), oxygen, and magnesium ions, producing light with very little heat production (Inouye 2010, Rabha *et al.* 2021).

Fireflies are holometabolic insects that go through complete metamorphosis, from egg to larva, pupa, and adult. One of the unique aspects of their life cycle is that the larval stage is the longest, sometimes lasting several months to years, while the adult stage is short-lived, lasting only a few weeks, mainly for the purpose of reproduction (Faust 2017, Riley *et al.* 2021). Most firefly species are semelparous, expending a lot of energy on a single reproductive episode. Bioluminescence is found in all larval stages and adults in many firefly species, which are used for defense, recognition, attraction, and communication (Lewis and Cratsley 2008).

Habitat diversity and life history traits

Fireflies display an impressive range of habitat and life history traits. The larvae are terrestrial, semi-aquatic, or fully aquatic, depending on the species, and are mainly carnivorous, preying on soft-bodied invertebrates like snails, slugs, earthworms, and other firefly larvae. These prey species, in turn, require wet and chemically unpolluted habitats, thus indirectly connecting the survival of fireflies to habitat quality. The adults, on the other hand, have very short lifespans and are usually non-feeding, depending on energy reserves built up during the larval stage (Lewis 2016, Riley *et al.* 2021). Larval fireflies thus occupy an important position in soil food webs, and their abundance tracks soil moisture, organic matter content, and prey availability.

The production of firefly behavior, for example, that exhibited in synchronized flashing patterns of males around trees found at wetland sites along the banks of rivers or in brackish water coastal areas, has been documented in numerous genera (Ballantyne *et al.* 2019). Fireflies are regarded as semi-aquatic due to the fact that their larvae develop in muddy substrate that is found on the bottom of water bodies and can withstand temporary flooding (Thancharoen *et al.* 2007). In terms of ecological function, fireflies serve as predators, prey, and regulators of invertebrate populations, playing a role in nutrient cycling and trophic dynamics. The reliance of fireflies on the soil-water-vegetation interface emphasizes their role as integrative elements of wetland and forest ecosystems.

Seasonal variation in firefly population dynamics

Firefly populations exhibit pronounced seasonal fluctuations across different biogeographic regions, largely influenced by environmental factors such as temperature, humidity, rainfall, hydrological stability, and the availability of suitable larval habitats. These abiotic and biotic factors collectively regulate their life cycle, emergence patterns, and reproductive activity. Studies from Southeast Asia demonstrate that seasonal habitat conditions play a critical role in determining firefly species richness and abundance, particularly in riparian and forest ecosystems (Wattanachaiyingcharoen *et al.* 2016). Favorable environmental conditions, especially those associated with increased moisture, stable water regimes, and dense vegetation, support higher population densities and enhanced bioluminescent activity.

In the Indian context, firefly population dynamics are strongly governed by the monsoonal climate. Several studies have reported that firefly activity peaks during the monsoon and immediate post-monsoon periods, when environmental conditions such as high humidity and moderate temperatures are optimal for survival and reproduction (Paul 2025, Ghosh *et al.* 2025). A bio-ecological study from Karnataka similar-

Table 2. Environmental and anthropogenic drivers affecting firefly populations (Global).

Year	Area / Location	Factor Type	Specific Factor	Affected (%)	Causes	Reference
2022	Global	Environmental	Temperature stress	~30% activity reduction	Thermal stress reduces flashing & metabolism	Shen *et al.* (2022)
2016	Thailand Highlands	Environmental	Elevation & habitat variation	15–35% diversity variation	Vegetation structure & temperature gradients	Wattanachaiyingcharoen *et al.* (2016)
2020	Global	Anthropogenic	Combined threats (habitat + pollution + light)	20–50% decline	Synergistic environmental stressors	Lewis *et al.* (2020)
2021	North America	Anthropogenic	Habitat loss	~33% species at risk	Urbanization, wetland degradation	Fallon *et al.* (2021)
2022	Global	Anthropogenic	Artificial Light at Night (ALAN)	40–70% reduction in mating success	Disruption of bioluminescent communication	Khattar *et al.* (2022)
2023	Malaysia (Klias River)	Environmental	Monsoon variability	25–60% fluctuation	Rainfall & humidity influence life cycle	Poukin *et al.* (2023)
2024	Global	Anthropogenic	Multiple global threats	20–50% decline	ALAN, pesticides, habitat loss	Lewis *et al.* (2024)

ly documented increased adult emergence and mating activity during humid months, further emphasizing the importance of seasonal climatic factors (Chakravarthy and Parvez 2024).

The northeastern region of India, characterized by high annual rainfall, extensive wetland systems, and rich biodiversity, is likely to exhibit pronounced seasonal variation in firefly populations. The monsoon season plays a crucial role in sustaining firefly life cycles in this region, as increased precipitation ensures adequate soil moisture and stable aquatic or semi-aquatic conditions required for larval development. Additionally, the accumulation of organic matter during this period enhances the availability of prey such as snails, slugs, and other soft-bodied invertebrates, which are essential for larval growth (Chakravarthy and Parvez 2024, Ghosh *et al.* 2025). Dense vegetation and relatively undisturbed habitats further create favorable microclimatic conditions, including high humidity and reduced temperature variability, supporting adult emergence and mating displays.

In contrast, firefly populations tend to decline during the dry season due to reduced soil moisture and limited food availability (Poukin *et al.* 2023). In India, lower abundance is typically observed during winter and pre-monsoon periods, likely due to decreased humidity and greater temperature fluctuations (Paul 2025, Ghosh *et al.* 2025). During winter, fireflies may significantly reduce their activity or enter a state of diapause as an adaptive survival strategy (Chakravarthy and Parvez 2024, Ghosh *et al.* 2025).

Despite these insights, significant research gaps remain. The lack of long-term monitoring and systematic seasonal datasets has been identified as a major limitation in understanding firefly population dynamics across Indian landscapes (Pandey *et al.* 2025). Addressing these gaps is essential for developing effective conservation strategies, particularly in ecologically sensitive regions such as Northeast India.

Fireflies as bioindicators of environmental quality

Fireflies are widely recognized as reliable bioindicators of environmental quality due to their high sensitivity to ecological disturbances and their close association with specific habitats, particularly wetlands and forest ecosystems. These environments, characterized by stable hydrological conditions and rich organic matter, provide suitable niches for firefly development and survival, making them valuable systems for ecological monitoring (Chakravarthy and Parvez 2024, Ghosh *et al.* 2025). Rayal (2022) reported that fireflies are increasingly used as indicators of ecosystem health, and their abundance can be assessed through flash-count surveys and citizen science programs.

Table 3. Environmental and anthropogenic drivers affecting firefly populations (India).

Year	Area / Location	Factor Type	Specific Factor	Affected (%)	Causes	References
2024	India	Anthropogenic	Artificial Light at Night (ALAN)	35–65% decline in abundance	Disruption of mating signals	Ghosh *et al.* (2024)
2024	India	Environmental	Climate variability	20–40% reduction	Changes in rainfall & temperature	Paul (2025)
2025	India	Anthropogenic	Pesticides & agrochemicals	20–45% population loss	Toxic effects on larvae & prey	Potulwar *et al.* (2025)
2024	Karnataka	Mixed	Habitat fragmentation + climate	30–50% decline	Land-use change & microclimate alteration	Chakravarthy and Parvez (2024)

The effectiveness of fireflies as bioindicators stems from their biological and ecological characteristics. They possess limited dispersal capacity and strong dependence on specific microhabitats, which makes them highly vulnerable to environmental changes. Studies have shown that factors such as habitat destruction, light pollution, and chemical contamination significantly contribute to the decline of firefly populations (Lewis *et al.* 2020; Fallon *et al.* 2021). As a result, changes in their abundance and distribution can serve as early warning signals of ecosystem degradation.

Fireflies respond to a wide range of environmental stressors, including variations in soil quality, water conditions, and atmospheric factors. Their physiological and behavioral traits, particularly bioluminescence used in communication and mating, are closely influenced by environmental conditions. Evolutionary studies further support their role as ecological indicators, demonstrating that their adaptations are tightly linked to habitat stability and environmental quality (Oba *et al.* 2020, Martin *et al.* 2021).

In the Indian context, fireflies are increasingly being explored as bioindicators for assessing ecosystem health. Studies have reported that firefly abundance is positively correlated with undisturbed, pollution-free environments, while degraded habitats tend to show reduced populations (Potulwar *et al*. 2025, Ghosh *et al.* 2024). Additionally, fireflies have been proposed as flagship indicator species for monitoring environmental conditions in wetland and forest ecosystems, highlighting their ecological and conservation significance (Paul 2025).

Despite the high biodiversity and ecological importance of regions such as Northeast India, em-

Table 4. Environmental and anthropogenic drivers affecting firefly populations (Regional).

Year	Area / Location	Factor Type	Specific Factor	Affected (%)	Causes	References
2022	Assam (urban gradient)	Anthropogenic	Artificial light pollution	45–65% signaling disruption	Interference with courtship communication	Khattar *et al.* (2022)
2023	Guwahati, Assam	Environmental	High temperature (>33–34°C)	30–50% activity reduction	Heat stress reduces flashing efficiency	Barua (2023)
2024	Assam (urban–rural gradient)	Anthropogenic	ALAN intensity variation	20–60% abundance variation populations	Urban light suppresses	Ghosh *et al.* (2024)
2025	Northeast India	Anthropogenic	Habitat destruction	30–55% decline	Wetland & forest loss	Pandey *et al*.(2025)
2025	Assam (monsoon ecology)	Environmental	Humidity & seasonal variation	40–70% fluctuation	Breeding cycle linked to monsoon	Ghosh *et al*. (2025)
2025	Assam (tea garden ecosystems)	Anthropogenic	Pesticide exposure	25–50% larval mortality	Soil & water contamination	Potulwar *et al.* (2025)

pirical data on the use of fireflies as bioindicators remains limited. This lack of region-specific studies underscores the need for systematic research and long-term monitoring to better understand their potential in assessing environmental quality and guiding conservation strategies.

Firefly population dynamics: environmental and anthropogenic factors

Firefly population dynamics are shaped by a combination of environmental factors such as temperature, humidity, and habitat quality, along with anthropogenic pressures including habitat loss, light pollution, pesticide use, and urbanization (Table 2, 3 and 4).

Environmental factors

Environmental factors such as temperature, humidity, rainfall, and habitat characteristics play a crucial role in shaping firefly population dynamics. These abiotic variables regulate their life cycle, activity patterns, and overall survival across different ecosystems.

Among these factors, temperature and humidity are particularly significant in determining firefly abundance and activity. Studies indicate that firefly populations are highest under humid conditions, especially during the monsoon season, while dry conditions and extreme temperatures reduce their activity and survival (Paul 2025, Ghosh *et al.* 2025). Temperature variations directly influence firefly physiology, particularly the luciferin–luciferase reaction responsible for bioluminescence, which is essential for communication and mating success (Oba *et al.* 2020, Barua 2023). Elevated temperatures above 33–34°C have been reported to reduce adult activity and signaling efficiency by 30–50%, thereby affecting reproductive success (Barua 2023, Ghosh *et al.* 2025).

Rainfall and moisture availability also play a fundamental role in firefly ecology. Most firefly species depend on moist soil or aquatic environments during their larval stages, making them highly sensitive to changes in precipitation patterns. Variations in rainfall influence larval development, survival, distribution, and seasonal population peaks (Lewis *et al*. 2020; Khattar *et al.* 2022, Ghosh *et al.* 2025, Paul 2025). Consequently, climate change–induced alterations in temperature and precipitation regimes are considered major drivers affecting global firefly population dynamics (Fallon *et al.* 2021, Shen *et al.* 2022).

In addition to climatic factors, habitat characteristics and microenvironmental conditions significantly influence firefly distribution and abundance. Factors such as seasonal flooding, soil moisture, and vegetation structure determine the suitability of habitats for both larval and adult stages (Chakravarthy and Parvez 2024, Ghosh *et al.* 2025). The availability of specific microhabitats, including wetlands, forest floors, and organic-rich soils, is particularly important for larval development and successful adult emergence (Pandey *et al.* 2025, Potulwar *et al.* 2025).

Anthropogenic factors

Firefly populations are declining globally due to human activities such as habitat loss, chemical pollution, and artificial light at night (ALAN).

Artificial Light at Night (ALAN) has been identified as a key threat, leading to approximately 45–65% disruption in bioluminescent signalling and thereby interfering with courtship communication 50-70%. Experimental studies indicate that artificial light can impact firefly growth, development, and dispersal (Gaston *et al.* 2021, Khattar *et al*. 2022; Owens and Lewis 2021a, Merckx *et al*. 2023). Artificial light alters firefly behaviour and reduces population density in tropical habitats, and also highlighting the growing impact of rural electrification and urbanization on their survival. Changes in ALAN intensity between urban and rural areas result in 20–60% variation in firefly abundance, with lower populations in urbanized regions (Ghosh *et al.* 2024). Moreover, higher temperatures above 33–34°C leads to a 30–50% decline in adult activity, as thermal stress reduces flashing efficiency and behavioral responses (Barua 2023).

Landscape-level studies show that changes in land use, especially due to ecotourism and urban expansion, can significantly affect firefly distribution (Idris *et al*. 2021). Wetland ecosystems in Assam are facing increasing anthropogenic pressures, including habitat encroachment and tourism-related disturbances.

Human activities such as agricultural intensification, pesticide use, wetland degradation are major threats to firefly populations. Potulwar *et al.* (2025) observed a significant decline in firefly abundance in areas affected by chemical runoff and habitat disturbance. Additionally, studies have shown that pesticide exposure and water pollution can reduce larval survival and affect overall population stability (Shen *et al.* 2022). Barua (2023) reported that increased temperatures and urban heat effects can impair the luciferin-luciferase reaction, thereby reducing light emission efficiency.

However, only a limited number of scientific studies have examined how these pressures affect firefly populations in the region. This shows the need for more local studies to understand anthropogenic impacts using fireflies as sensitive ecological indicators (Chakravarthy and Parvez 2024, Ghosh *et al.* 2025).

Habitat loss, agricultural intensification, and urbanization have led to 20–55% declines in species richness and up to 40% reductions in adult abundance in disturbed or illuminated areas, both globally and regionally in Assam (Potulwar *et al.* 2025, Khattar *et al.* 2022). Habitat loss in Northeast India, has caused a 30–55% decline in firefly populations, mainly due to the destruction of wetlands and forests needed for breeding and larval development (Pandey *et al.* 2025). Moreover, pesticide use in tea gardens also leads to 25–50% larval mortality due to soil and water contamination, which further threatens population stability (Potulwar *et al.* 2025).

Global variations in firefly conservation status and associated anthropogenic pressures

A comparison of firefly species across different parts of the world shows that their conservation status varies widely. India has the highest proportion of threatened species (25%), indicating serious ecological pressure and the need for immediate conservation action (Parvez *et al.* 2026). Southeast Asia (20%) and South America (18%) rank next, with rising anthropogenic pressures such as deforestation, habitat fragmentation, and agricultural expansion driving higher threat levels (Lewis *et al.* 2020). In North America, the threat level is moderate (14%), due to both declining populations and better monitoring systems (Fallon *et al.* 2021). By comparison, Europe (10%) and Australia (5%) exhibit lower levels of threatened species, likely due to improved conservation efforts, lower habitat disturbance, and more effective environmental policies (Lewis *et al.* 2020) (Table 5).

Present status of firefly population: insights from assam

The present status of firefly populations in Assam indicates a gradual yet spatially uneven decline, influenced by a combination of climatic variability, habitat alteration, and increasing anthropogenic pressures. Although comprehensive long-term datasets are limited, regional observations and recent field studies suggest that firefly populations are undergoing measurable changes in both distribution and abundance.

Studies conducted in the Bodoland Territorial Region and other parts of Northeast India reveal that firefly populations in Assam are declining, but they

Table 5. Global comparison of firefly conservation status across regions.

Region	Percentage of threatened species (%)	Interpretation	References
Australia	5	Lowest threat level	Lewis *et al.* (2020)
Europe	10	Moderate threat	Lewis *et al.* (2020)
North America	14	Increasing concern	Fallon *et al.* (2021)
South America	18	High threat due to habitat loss	Lewis *et al.* (2020)
United State and Kanada	18	Habitat loss, light pollution and pesticide use	Sidik (2023)
Southeast Asia	20	High anthropogenic pressure	Lewis *et al.* (2020)
India	25	Highest threat level	Parvez *et al.* (2026)

are not yet critically endangered. Fireflies are still relatively abundant in ecologically stable habitats such as wetlands, riparian zones, paddy fields, and forest edges. These environments provide optimal conditions including high humidity, suitable vegetation cover, and minimal artificial disturbance, which are essential for larval development and adult bioluminescent communication. However, a noticeable decline has been documented in urban and semi-urban areas, particularly in and around Guwahati. This decline is primarily attributed to rapid urban expansion, habitat fragmentation, and increasing levels of artificial light at night (ALAN), which disrupt mating signals and reduce reproductive success (Choudhury *et al.* 2025).

Seasonal variation is another key characteristic of firefly populations in Assam. Peak abundance is typically observed during the pre-monsoon and monsoon seasons, when temperature and humidity conditions are favorable for adult emergence and mating activity. Conversely, populations decline sharply during the dry winter months, reflecting the sensitivity of fireflies to microclimatic conditions. Such seasonal dynamics highlight the dependence of fireflies on specific environmental thresholds for survival and reproduction. The study by Barua (2023), focusing on Assam, demonstrates that elevated temperatures above 33–34°C significantly reduce flashing activity and mating success. Under extreme thermal conditions, adult activity may decline by as much as 30–50%. With Assam experiencing increasing summer temperatures and altered climatic patterns due to climate change, these thermal stress effects are becoming more pronounced. In addition, fluctuations in humidity further exacerbate stress on firefly populations, leading to irregular emergence patterns and localized population declines.

Conservation, mitigation measures, and sustainable management

Habitat protection and sustainable practices

Global conservation strategies focus on habitat protection, reducing light pollution, and promoting sustainable land-use practices. It also highlights the need for integrated conservation approaches, such as habitat restoration, community involvement, and long-term monitoring (Lewis *et al.* 2020, Fallon *et al.* 2021).

IUCN and global initiatives

The IUCN Firefly Specialist Group has initiated Red List assessments to assess extinction risks and inform conservation priorities (Fallon *et al.* 2021). Studies on insect-friendly lighting indicate that changes in light intensity and spectrum can significantly minimise ecological impacts (Owens *et al.* 2022a, Owens *et al.* 2022b).

Landscape-level and community conservation

Fireflies are increasingly being incorporated into biodiversity management frameworks in India as part of ongoing conservation efforts. The Karnataka firefly project showed that habitat conservation and local community participation play an important role in increasing firefly populations. Effective conservation requires policy support, awareness programmes, control of artificial lighting, and promotion of eco-friendly farming methods (Paul 2025, Pandey *et al.* 2025).

Additionally, the importance of landscape-level conservation approaches in preserving firefly distribution and diversity has been highlighted (Ghosh *et al.* 2025). Effective conservation requires habitat preservation, control of tourism and artificial lighting, reduced agrochemical use, and continuous long-term environmental monitoring.

Urbanization and changes in land use break up natural habitats, making it difficult for fireflies to move and maintain gene flow, which increases their risk of extinction. To address this, conservation efforts should focus on preserving ecological corridors and maintaining landscape connectivity (Ghosh *et al.* 2025, Pandey *et al.* 2025).

Adaptive lighting and light pollution management

Artificial Light at Night (ALAN) represents a major anthropogenic threat to fireflies, as it interferes with bioluminescent communication and compromises reproductive success. The adoption of adaptive lighting systems characterized by low intensity, shielding, and narrow spectral ranges (amber or red LEDs) can substantially mitigate ecological disruption. These approaches reduce interference with mating signals and maintain natural nocturnal behavioral patterns (Owens *et al.* 2022a, Van *et al.* 2024, Van *et al.* 2026).

Hydrological and microclimatic regulation

Maintaining natural water systems is important for fireflies because their larvae rely on moist habitats like wetlands and riverbanks. Changes in water flow, drainage, or seasonal patterns can harm larval survival and reduce food availability. For this reason, conservation efforts should focus on restoring wetlands and maintaining natural moisture levels (Poukin *et al*. 2023, Ghosh *et al.* 2025).

Temperature also plays a key role, as higher temperatures can reduce flashing activity and interfere with reproduction. Protecting vegetation and maintaining canopy cover can help regulate local temperatures and reduce extreme conditions (Barua 2023, Khattar *et al.* 2022).

Sustainable agricultural practices and agrochemical control

Reducing the use of pesticides and chemical fertilizers is important for protecting fireflies because these agrochemicals can harm directly their larvae and reduce the availability of their food. Using methods like integrated pest management (IPM) and organic farming practices can help reduce chemical use and improve soil health, which in turn supports firefly populations (Pandey *et al.* 2025, Potulwar *et al.* 2025).

Monitoring, modelling, and data standardization

Standard methods like flash count surveys, transect sampling, and seasonal observations are important for collecting reliable and comparable data on fireflies. When combined with proper scientific validation, citizen science programs can greatly improve large-scale monitoring (Lewis *et al.* 2024).

In addition, predictive models that include factors like climate change, land use, and light pollution can help estimate future population trends and identify areas at risk, allowing for better conservation planning (Ghosh *et al.* 2025, Lewis *et al.* 2024).

Species-specific and genetic conservation approaches

Conservation strategies for fireflies should take into account species-specific traits like habitat preference, movement ability, and signaling behavior. Using trait-based approaches can help in setting better conservation priorities (Khattar *et al.* 2022).

Moreover, the use of molecular tools such as DNA barcoding and luciferase gene analysis enhances species identification and genetic diversity assessment. These approaches are particularly important for detecting cryptic (hidden) species and understanding how fireflies adapt over time (Oba *et al.* 2020, Martin *et al*. 2021).

Habitat connectivity and fragmentation control

Habitat fragmentation caused by urbanization and land-use change restricts dispersal and gene flow, increasing extinction risk. Conservation strategies should therefore focus on maintaining ecological corridors and landscape connectivity to ensure long-term population sustainability (Ghosh *et al.* 2025; Pandey *et al.* 2025).

Inclusion in environmental policy and eia frameworks

Fireflies should be incorporated into Environmental Impact Assessment (EIA) frameworks, particularly for projects affecting wetlands and forest ecosystems. Since they are very sensitive to environmental changes, they can help in assessing ecological impacts and planning sustainable development (Potulwar *et al.* 2025, Lewis *et al.* 2024).

Linking firefly conservation with larger wetland and forest policies can also improve protection efforts and support overall ecosystem health (Ghosh *et al.* 2025, Lewis *et al.* 2020).

Protection of larval prey base

Conservation efforts should also focus on protecting prey species like mollusks and other soft-bodied invertebrates, as they are important for firefly larvae. Habitat loss and pesticide use can reduce these food sources, which in turn affects firefly survival (Pandey *et al*. 2025, Potulwar *et al*. 2025).

Future perspectives

Fireflies (family Lampyridae) are increasingly recognized as sensitive bioindicators of ecosystem integrity, particularly under the combined influence of environmental variability and anthropogenic pressures. Their dependence on specific ecological conditions such as temperature, humidity, vegetation structure, and low-light environments makes them effective and economically viable tools for ecological monitoring. Future research should further validate their role across different habitats and varying levels of Artificial Light at Night (ALAN). Beyond their ecological importance, fireflies also hold significant cultural and economic value. Studies from South Korea highlight how fireflies have been transformed into symbols of conservation and cultural identity through ecotourism and public engagement. Events such as the Muju Firefly Festival demonstrate their role in promoting environmental awareness while supporting local communities (Gang-Hoan *et al.* 2005). Thus, fireflies function both as indicators of environmental health and as flagship species that can enhance conservation efforts through community participation, education, and regulated ecotourism.

Future research should prioritise long-term monitoring of anthropogenic stressors such as ALAN, tourism, pesticide use, and land-use change, as these significantly influence firefly populations. Conservation efforts must focus on protecting and restoring critical microhabitats, including wetlands, riparian zones, moist soils, and undisturbed forest floors essential for larval development. Species-level and trait-based approaches are needed to better understand resilience, particularly traits such as dispersal ability, signalling behavior, and habitat specificity. The integration of advanced tools like GIS, remote sensing, genetic barcoding, and luciferase analysis can further improve habitat mapping, species identification, and long-term monitoring.

Incorporating fireflies into biodiversity monitoring frameworks and Environmental Impact Assessments (EIAs) using standardized methods can strengthen their application as ecological indicators. Managing light pollution through dark-sky initiatives and eco-friendly lighting systems is essential to preserve natural bioluminescent communication. Similarly, promoting sustainable agricultural practices, including reduced pesticide use and organic farming, will enhance larval survival and prey availability. Community participation and citizen science can support data collection and awareness, although ecotourism must be carefully managed to avoid habitat disturbance. Addressing knowledge gaps, particularly the large number of Data Deficient species, remains a priority, requiring focused research on distribution, population trends, and climate change responses.

The decline of firefly populations reflects broader environmental degradation and highlights the responsibility of the present generation. Without timely intervention, future generations may lose these bioluminescent organisms that once symbolized healthy ecosystems. Effective conservation will require integrated and interdisciplinary approaches combining habitat protection, sustainable land-use practices, scientific innovation, and policy support, along with collaboration among governments, researchers, NGOs, and local communities. International initiatives, such as the World Firefly Day webinar organized by EMPRI, Bengaluru, 2022 demonstrate the importance of global knowledge exchange and collaborative conservation strategies. Such efforts, including proposals for firefly parks and breeding programs, can serve as models for regions like Assam, ensuring long-term conservation through coordinated research, awareness, and community engagement.

CONCLUSION

In the coming decades, fireflies will continue to serve as valuable bioindicators of environmental health and ecosystem stability. Their abundance and diversity are closely associated with key environmental quality indicators, including low levels of artificial light pollution, good water quality, high soil moisture, intact vegetation cover, suitable microclimatic conditions, and minimal pesticide contamination. Firefly populations generally thrive in habitats characterized by high dissolved oxygen levels, low organic and chemical pollution, and the presence of healthy wetland and forest ecosystems that support their larval and adult life stages. Consequently, declines in firefly abundance may provide early warning signals of habitat degradation, biodiversity loss, and environmental disturbance. Conservation measures aimed at preserving natural habitats, maintaining water quality, reducing light pollution, and minimizing the use of agrochemicals can significantly contribute to the long-term sustainability of firefly populations. In regions such as Assam, where wetlands and forest ecosystems support diverse firefly assemblages, the protection of these environmental quality parameters is essential not only for firefly conservation but also for maintaining overall ecosystem integrity and biodiversity. Thus, conserving fireflies represents an important step toward promoting sustainable environmental management and safeguarding natural heritage for future generations.

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