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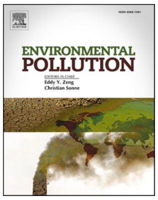

Part-night lighting fails to restore natural song rhythms in urban European Robins

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ABSTRACT

Artificial Light at Night (ALAN) disrupts the natural circadian rhythms of animals, often extending the activity of diurnal species into nocturnal periods. To mitigate ALAN's ecological impacts and reduce energy consumption, many municipalities have implemented Part-Night Lighting (PNL), which involves switching off streetlights during core nighttime hours. However, the effects of such temporal lighting reductions on animal activity patterns remain poorly understood. We investigate how PNL influences daily singing behavior in European Robins *Erithacus rubecula* during spring in an urban area of France, where streetlights are turned off between 11 p.m. and 6 a.m., creating brief illumination windows at dawn and dusk. We hypothesized that PNL would reduce the effects of ALAN on Robin vocal activity compared to Full-Night Lighting (FNL). Using passive acoustic monitoring, we recorded Robin song activity across three types of sites (unlit, PNL, and FNL) and four time periods (dawn, morning, afternoon, dusk). Robins sang significantly earlier at FNL and PNL sites than at unlit sites during dawn and morning, and later during dusk, with no significant differences between FNL and PNL. In the afternoon, song activity tended to be delayed at PNL sites compared to both FNL and unlit sites. Our findings indicate that even short illumination periods at dawn and dusk under PNL do not replicate unlit conditions. In an urban context, the similarity in vocal activity between PNL and FNL sites suggests that residual light from nearby lit areas and/or lingering effects of ALAN may continue to influence animal behavior under PNL regimes.

1. Introduction

The effects of Artificial Light at Night (ALAN) on animal activity patterns have been extensively reviewed (Gaston et al., 2017). In temperate regions, ALAN is known to advance the onset of the dawn chorus and even induce nighttime singing in birds (Miller, 2006; Nordt and Klenke, 2013; Ki, Hong, and Gim, 2015; Godet et al., 2025), although these effects appear to be less pronounced in tropical areas (Dorado-Correa, Rodriguez-Rocha, and Brumm, 2016; Marin-Gomez and MacGregor-Fors, 2019).

Given the impacts of ALAN, several mitigation strategies have been reviewed by several authors (see Gaston et al., 2012), including reducing the number of light sources, lowering light intensity, shifting spectral output toward warmer color temperatures, and switching off lights during specific periods—whether seasonally or nightly. The effects of these measures have been partially studied in a limited number of bird species. Since the number of light points is strongly correlated with earlier song onset (Godet et al., 2025), reducing lighting density should help return to a pattern of vocal activity similar to a state without ALAN. However, changing the spectral composition of light (*e.g.*, color temperature) appears to have no significant effect on dawn singing (Da Silva et al., 2016a), and this area remains underexplored. In contrast, modifications to lighting schedules can have immediate and noticeable effects, with birds reverting to natural song timing as soon as lights are turned off (Da Silva et al., 2016b). This suggests that Part-Night Lighting (PNL)—where lights are turned off during the central hours of the night—may be an effective strategy for mitigating ALAN's impact on biodiversity.

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However, the effects of PNL on animal activity rhythms remain understudied and are still subject to debate. In marine environments, PNL has been shown to alleviate some of the negative consequences of Full-Night Lighting (FNL) on the activity rhythms of organisms such as Oysters *Magallana gigas* (Botté et al., 2023). However, when combined with urban skyglow, PNL can be more detrimental to oysters than FNL alone (Botté et al., 2023), highlighting the importance of the surrounding light context. In terrestrial environments, various studies have examined PNL's impact on bats. Lights are often turned off too late at evening and turned back on too early in the morning to benefit species that are more active during twilight periods. As a result, early-emerging species that are active at dusk and dawn are less likely to benefit from PNL compared to late-emerging species (Azam et al., 2015; Hooker, Lintott, and Stone, 2022). Some researchers have therefore recommended tailored switch-off schedules optimized for specific taxa (*e.g.*, Day et al., 2015). To date, however, to our knowledge, no studies have specifically investigated the effects of PNL on urban birdsong activity rhythms.

In France, around 40% of municipalities have implemented PNL (ADEME, 2021), primarily for energy savings and biodiversity protection. Lights are typically switched off during core nighttime hours—usually from 11:00 p.m. to 6:00 a.m.—although implementations may vary by neighborhood. This variation in lighting regimes provides a valuable opportunity to compare the effects of different lighting conditions, including FNL, PNL, and unlit areas.

In this study, we examined the impact of these three lighting conditions on the singing behavior of the European Robin *Erithacus rubecula* in the Nantes metropolitan area (western France). This species is known for its sensitivity to artificial lighting (Da Silva, Valcu, and Kempenaers, 2015, 2016b; Godet et al., 2025). It is also an ideal model species, as it is a generalist and therefore likely to be present along the entire gradient of urbanization and light pollution. Our objective was to determine whether PNL can mitigate the impacts of FNL and whether it can produce behavioral patterns similar to those observed under unlit areas.

2. Materials and methods

2.1. Study area

The study was conducted in Nantes—the sixth-largest metropolitan area in France with approximately 325,000 inhabitants—and its southwestern suburbs, encompassing seven municipalities (Nantes, Bouaye, Bouguenais, Saint-Aignan-Grandlieu, Rezé, Les Sorinières, and Vertou). The study area covered approximately 90 km^2 of predominantly residential zones (Fig. 1).

2.2. Sampling design

We used the Nantes metropolitan area GIS database, grouping all public lighting points categorized by major luminaire type (mainly Light-Emitting Diode (LED) and High-Pressure Sodium (HPS) in our study area) and switch-on/switch-off periods (either switched on all night (FNL), or switched off between 23:00 and 6:00 (PNL)).

Using GIS, ten stations were randomly selected in LED-lit FNL areas, ensuring that only LED-lit FNL points were present within a 100 m radius of each station. Ten additional stations were randomly selected in LED-lit PNL areas, with the same criterion that only LED-lit PNL points occurred within a 100 m radius. Finally, ten stations were randomly selected in areas located more than 200 m away from any light source. To select these stations, we did not take into account potential land cover differences between the three treatments, since the entire sampling area is in a **(peri)urban** environment, and the species' singing onset timing is known to be determined primarily by ALAN but not by the level of urbanization (Godet et al., 2025). However, note that we did not observe any significant differences in the areas covered by the main land-cover types between the PNL and FNL treatments (Appendix 1).

Our study was conducted from May 3 to May 9, 2024. This period was chosen because it corresponds to the breeding period of our model species, during which it is vocally active. The singing individuals detected can therefore be considered territorial, and the same throughout the study period. This period is also one during which the sun rises after 6:00 a.m. (after the PNL sites are lit) and sets before 11:00

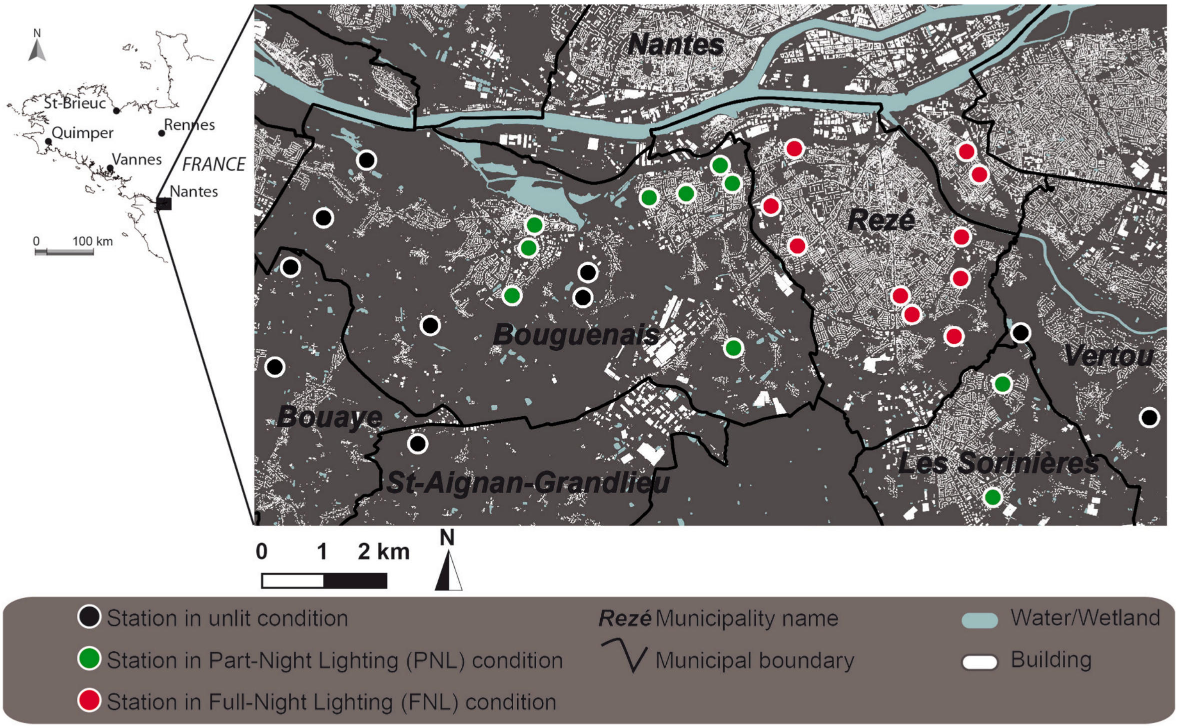

Fig. 1. Study site and sampling design.

p.m. (after the PNL sites are switched off), enabling us to test the influence of short morning and evening lighting periods.

At each station, we installed and programmed an AudioMoth device (Open Acoustic Devices) to record sound for 1 min every 5 min, from 2:00 a.m. on May 3, 2024, to 2:00 a.m. on May 9, 2024—a total duration of 6 days. This setup yielded almost 29 h of recordings per station, amounting to 288 h for each treatment (FNL, PNL, and unlit), and 864 h in total, which constitutes the total dataset analyzed in this study. We used a sampling rate of 24 kHz. Each AudioMoth was powered by three AA batteries and had a maximum storage capacity of 32 GB. All recordings were saved in WAV format. To protect the devices from weather conditions, we placed them in IPX7-rated waterproof AudioMoth cases.

2.3. *Automatic detection of Robins*

Bird vocalizations were extracted from each recording using BirdNET (offline version), an open-source deep-learning system developed by the Cornell Lab of Ornithology (Kahl et al., 2021). This system detects the most probable species singing every 3 s. We filtered the detections to isolate only those corresponding to European Robins. The system was configured with the geographical coordinates of our study area (47.212 N, 1.551 W), with a default sensitivity of 1 and overlap of 0. We ran the analysis at 10 different confidence levels (0 to 0.9) as the optimal confidence thresholds are debated in the literature depending on species and acoustic context (Tseng, Hodder, and Otter, 2025). By doing this, BirdNET returns all song occurrences beyond each confidence level.

Although BirdNET is already recognized as a powerful bird sound identifier (Pérez-Granados, 2023), especially for Robins (Singer et al., 2024; Godet et al., 2025), in order to select the appropriate BirdNET confidence threshold, we randomly extracted 200 recordings from each treatment (FNL, PNL and unlit). Each recording was then listened to in the laboratory using an EPOS Sennheiser Adapt 360 headphone, which enabled us to note the presence/absence of the species. These presences/absences noted manually during the listening were then compared with the presences/absences detected by BirdNET at each of the 10 confidence levels (from 0 to 0.9). For each recording and each of the confidence levels, we then documented whether BirdNET produced a True Positive (TP) (when Robins were detected both by BirdNET and listening), a True Negative (TN) (neither detected by BirdNET nor by listening), a False Positive (FP) (detected by BirdNET but not by listening) or a False Negative (FN) (not detected by BirdNET but detected by listening). Finally, we calculated the recall (TP/(TP + FN)) and the precision (TP/(TP + FP)) for each confidence level. Here we chose to retain the BirdNET confidence threshold that provided a recall of at least 0.5 (i.e., at least 50% of robin songs are detected) and a precision of at least 0.75 (i.e., at least 75% of robin songs are indeed robin songs).

2.4. *Song timing indices*

Astronomical dawn and dusk times, sunrise and sunset times and solar noon and midnight times were collected for each day. Each day was divided into six periods according to the times of astronomical dawn and dusk, sunrise and sunset, and solar noon and midnight, as follows:

- late night: from solar midnight (included) to astronomical dawn (excluded)
- dawn: from astronomical dawn (included) to sunrise (excluded)
- morning: from sunrise (included) to solar noon (excluded)
- afternoon: from solar noon (included) to sunset (excluded)
- dusk: from sunset (included) to astronomical dusk (excluded)
- early night: from astronomical dusk (included) to solar midnight (excluded)

The raw dataset consists of the number of Robin vocal events detected by BirdNET for each station, each date, and each period of 1 min. Because BirdNET detect birds in 3-s periods, the number of Robin vocal events for each 1-min period ranges from 0 to 20.

The song timings are expressed in minutes before (negative values) or after (positive values) sunrise time for the first part of the day (solar midnight to solar noon, including late night, dawn and morning) and in minutes before (negative values) or after (positive values) sunset time for the second part of the day (solar noon to solar midnight, including afternoon, dusk and early night).

2.5. *Statistical analyses*

As a preliminary step, we plotted the mean number of songs per station (± standard deviation) over time, from solar midnight to solar midnight, for each lighting treatment (FNL, PNL, and unlit).

Then, we tested the effect of light treatments on bird song timing using generalized linear mixed models (GLMMs) (*glmmTMB* R package), including the time of Robin vocal events as the response variable. To respect the application conditions of the models (*i.e.* a normal distribution and a homoscedasticity of the residuals, no dispersion or outlier issue), we normalized the vocal event time variable using the *orderNorm* transformation from the *bestNormalize* R package, and we used a Gaussian distribution in the models. Then, to assess if light treatments induced a modification of song timing, we included in models as a fixed explanatory variable the light treatments (*i.e.* unlit, full-night lighting, part-night lighting). As all sites were simultaneously monitored during six consecutive days, we included the site identity nested in the date as a random intercept in models to control for pseudo-replication and inter-site/date variation sources. This random effect structure was retained because it produced the smaller Akaike information criterion (AIC) among the other possibilities (*i.e.* date only, site only, or both in separated random effects). We ran this model for each period separately (*i.e.* dawn, morning, afternoon, dusk). For dawn and morning models, the song time was expressed in minutes before and after sunrise, respectively, and for afternoon and dusk models it was expressed in minutes before and after sunset, respectively. We did not include late- and early-night periods to the modelling since the statistical power was insufficient. Finally, for each GLMM model, we performed a type-II anova test to assess the global significance of the light treatment variable, and then a pairwise comparison (*lsmeans* R package) using Tukey's method to test for differences in light treatments. The residuals of each model were checked using the *DHARMa* R package.

All statistical analyses were performed using R software 4.3.3 (R Core Team, 2024). The significance threshold was set at an alpha value of 0.05.

3. Results

3.1. *BirdNET outputs*

We selected a BirdNET confidence threshold of 0.2, as this threshold yielded a precision of 0.80 and a recall of 0.52 (Appendix 2). Neither precision nor recall differed significantly between treatments (FNL, PNL, unlit) at this threshold: (precision: anova F(2,24) = 0.47, p = 0.63; recall: F(2,23) = 0.39, p = 0.68). At this confidence threshold, Robins were detected in every station (mean number of detections per station: 958 ± 1085 s.d.) although detections were significantly higher in unlit sites than in PNL sites (Tukey HSD, p = 0.03).

3.2. *Song chronology*

Across all treatments, European Robin vocal activity displayed a consistent bimodal pattern, with a pronounced dawn chorus occurring approximately 40 min before sunrise and a secondary, less intense dusk chorus around 20 min after sunset (Fig. 2). Nocturnal singing remained minimal during both the early and late-night periods, that prevented us

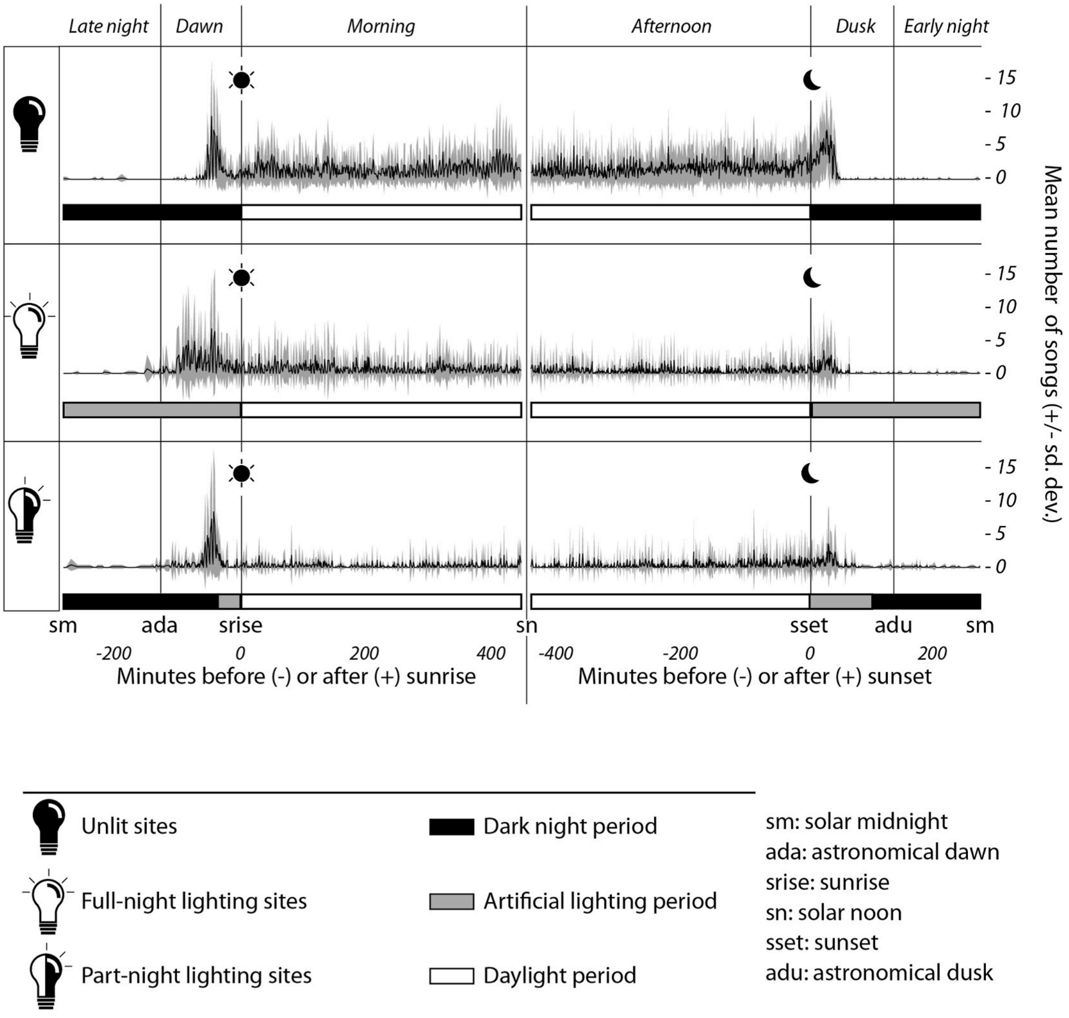

Fig. 2. Average daily singing chronology of European Robins under three artificial lighting conditions: unlit conditions, Full-Night Lighting, and Part-Night Lighting.

from testing the effect of light treatment in these periods (Appendix 2). The dawn chorus tended to be more temporally extended in both lit treatments compared to unlit conditions, and the dusk chorus was less pronounced at both lit treatments compared to unlit conditions (Fig. 2).

Overall, lighting conditions significantly affected the song timing of Robin in dawn (Anova Chisq $= 19.37$, $p < 0.001$), morning (Anova Chisq $= 22.70$, $p < 0.001$), afternoon (Anova Chisq $= 6.39$, $p = 0.041$), and dusk (Anova Chisq $= 16.05$, $p < 0.001$) periods. Specifically, during the dawn period, Robins began singing significantly earlier at both FNL and PNL sites (without significant difference between them) compared to unlit conditions (Fig. 3; Table 1), often as early as astronomical dawn (Fig. 2). A similar pattern was observed in the morning period, with significantly earlier singing times under both FNL and PNL conditions (Fig. 3; Table 1). In contrast, during the afternoon, Robins tended to sing later under PNL conditions compared to both FNL and unlit sites, although this difference was not statistically significant. At dusk, Robins sang significantly later under both FNL and PNL conditions than under unlit conditions (Fig. 3; Table 1).

4. Discussion

Part-Night Lighting alters the daily song timing of urban European Robins in a manner similar to Full-Night Lighting, indicating that even brief or indirect exposure to artificial light can significantly disrupt natural vocal behavior in an urban context.

1. Part-night lighting does not replicate unlit conditions

As previously demonstrated (Da Silva, Valcu, and Kempenaers, 2015; Godet et al., 2025), we confirm that European Robins tend to sing earlier in the morning and later in the evening at illuminated sites, including both partially lit (PNL) and fully lit (FNL) locations. Artificial light at night (ALAN) thus appears to simulate an earlier sunrise and a delayed sunset, by extending the activity period of diurnal species.

The primary objective of our study was to assess the impact of switching off lights during the middle of the night. Our results show that turning off the lights between 11:00 p.m. and 6:00 a.m. in early May does not significantly reduce the influence of ALAN on the daily singing schedule of European Robins. Residual light from nearby fully lit (FNL) areas could contribute to maintaining elevated ambient light levels in PNL zones, especially in urban settings where light pollution spreads spatially. However, we did not measure ambient illuminance or spectral composition at the sampling points and future studies incorporating quantitative light measurements (e.g., using ground-based photometers) are needed to directly test the role of skyglow and light spillover in driving these behavioral patterns. Although unstudied in birds, it has been shown for other taxa such as bats that the spread of light pollution beyond light sources, exacerbated by atmospheric conditions such as the presence of aerosols or clouds, intensifies the effects of artificial light (Mariton et al., 2022). This background illumination may reduce the contrast between PNL and FNL in terms of actual light exposure experienced by birds, whose response strength depends greatly on the

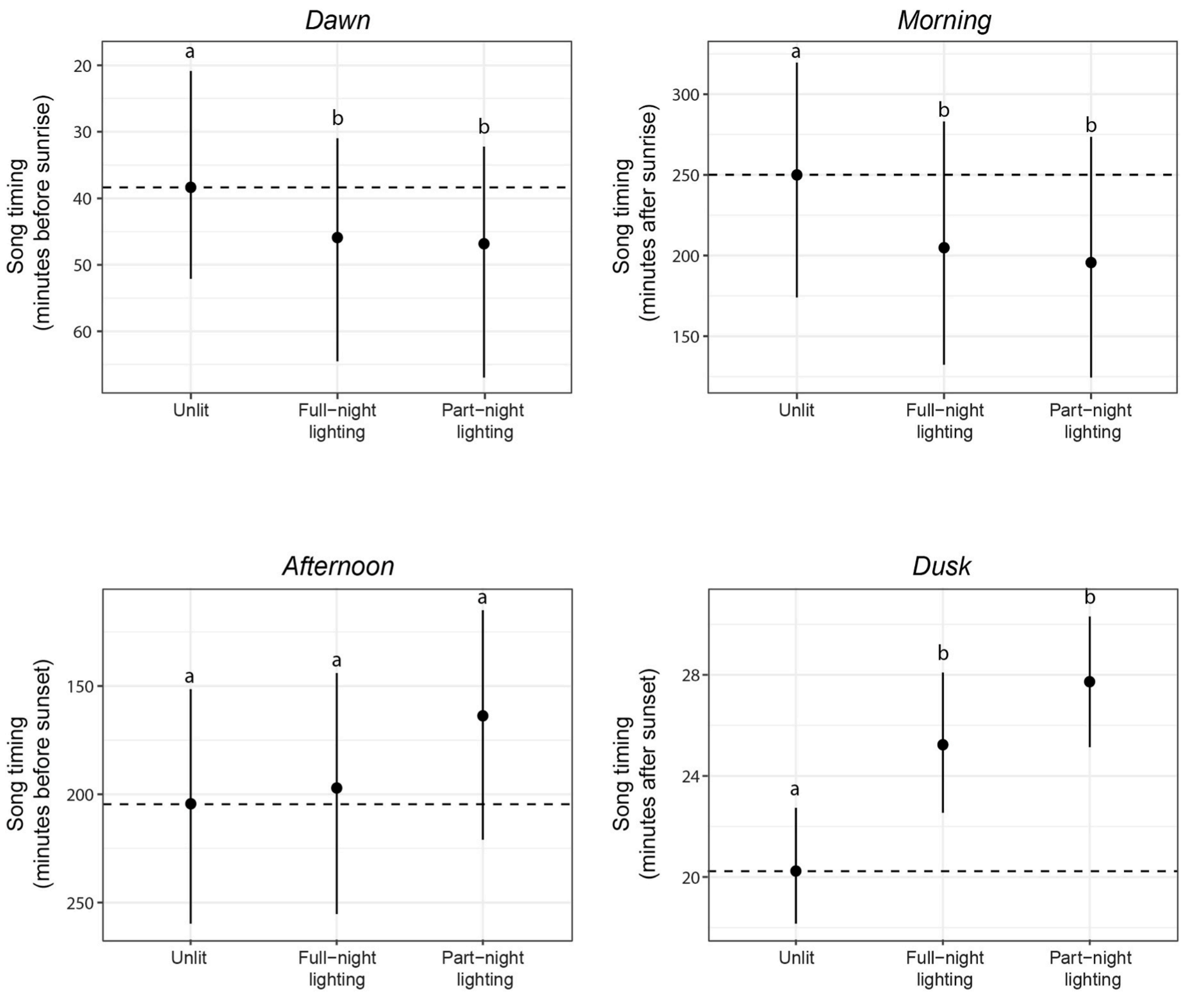

Fig. 3. Predicted singing times of European Robins and associated 95% confidence intervals from generalized linear mixed models, across four time periods—dawn, morning, afternoon, and dusk—under three lighting conditions: unlit, Part-Night Lighting, and Full-Night Lighting. The differences in letters depict the significant differences in the singing times between light treatments.

Table 1
Estimates, standard error and p-values from pairwise comparison tests (using Tukey's method for p-value adjustment) on generalized linear mixed models when unlit sites (A) and part-night lighting sites (B) were used as intercept. The delta AIC of underlying models is also reported, when the value is negative the AIC value of the model is smaller than the null model. Significant p-values are shown in bold.

Period	Light treatments	Estimate	SE	P	Delta AIC
Dawn	(A) Unlit *vs.* FNL	0.396	0.125	**0.005**	−6.73
	(A) Unlit *vs.* PNL	0.318	0.124	**0.029**	
	(B) FNL *vs.* PNL	−0.078	0.130	0.819	
Morning	(A) Unlit *vs.* FNL	0.359	0.010	**0.001**	−17.64
	(A) Unlit *vs.* PNL	0.443	0.103	**<0.0001**	
	(B) FNL *vs.* PNL	0.083	0.110	0.728	
Afternoon	(A) Unlit *vs.* FNL	0.018	0.094	0.980	−2.22
	(A) Unlit *vs.* PNL	−0.213	0.095	0.062	
	(B) FNL *vs.* PNL	−0.232	0.105	0.069	
Dusk	(A) Unlit *vs.* FNL	−0.334	0.125	**0.021**	−11.41
	(A) Unlit *vs.* PNL	−0.455	0.121	**0.001**	
	(B) FNL *vs.* PNL	−0.121	0.138	0.657	

perceived light intensity (de Jong et al., 2017). Moreover, although PNL provides artificial light only during short periods at dawn and dusk, the similarity in song timing between PNL and FNL conditions suggests that even brief exposures to artificial light at biologically sensitive times can have disproportionately strong effects on behavior. Dawn and dusk are critical windows for circadian entrainment, and light during these transitions is known to have a powerful influence on the internal clock of animals (Gaston et al., 2017). Thus, the limited light exposure under PNL—precisely timed with these sensitive phases—may be sufficient to shift or entrain the circadian system in a manner similar to continuous Full-Night Lighting.

The only difference between FNL and PNL conditions could be during the afternoon as Robins tended to sing later under PNL conditions than in both FNL and unlit conditions. Although these differences did not reach statistical significance, they showed a trend toward later singing under PNL conditions. The observed delay in afternoon singing under PNL conditions, despite the absence of artificial lighting during that period, suggests that the effects of ALAN may persist beyond the immediate times of illumination. Exposure to artificial light at dawn or dusk may induce residual shifts in circadian rhythms or disrupt the stability of daily behavioral patterns, leading to downstream changes later in the day (this point is discussed in more detail in Section 3 of the discussion). Unlike FNL, where the light regime is constant and may allow animals to adapt or entrain to a stable cue, the intermittent nature of PNL could act as a more disruptive signal, preventing proper circadian adjustment.

2. The mitigating effect of part-night lighting is likely to vary throughout the year

Part-Night Lighting operates on fixed switch-on and switch-off times throughout the year, with lights turned off during daylight hours. Consequently, the duration of artificial lighting varies markedly over the annual cycle, as it depends on the changing timing of sunrise and sunset. These variations are further complicated by the biannual transitions between standard time (UTC+1) and daylight-saving time (UTC+2). The overall length of artificial lighting under PNL conditions follows the seasonal pattern of daylength—reaching a maximum around the winter solstice and a minimum around the summer solstice (Fig. 4).

For example, in mid-December (Fig. 4), the morning lighting period lasts approximately 341 min, starting at 6:00 a.m. local time (UTC+1, i.e., 5:00 a.m. UTC) and ending at sunrise around 8:50 a.m. local time (UTC+1, i.e., 7:50 a.m. UTC). The evening lighting period extends for about 511 min, beginning at sunset around 5:19 p.m. local time (UTC+1, i.e., 4:19 p.m. UTC) and ending at 11:00 p.m. local time (UTC+1, i.e., 10:00 p.m. UTC). In contrast, around the summer solstice in mid-June (Fig. 4), the morning lighting period is significantly shorter—approximately 11 min—starting at 6:00 a.m. local time (UTC+2, i.e., 4:00 a.m. UTC) and ending at sunrise around 6:11 a.m. local time (UTC+2, i.e., 4:11 a.m. UTC). The evening lighting period is also much shorter, lasting about 65 min, from sunset around 10:06 p.m. local time (UTC+2, i.e., 8:06 p.m. UTC) until switch-off at 11:00 p.m. local time (UTC+2, i.e., 9:00 p.m. UTC).

We can therefore expect the mitigation effects of the PNL to be stronger (compared to the FNL) as we approach the summer solstice, because the duration of artificial lighting is shorter and tends to align more closely with the natural hours of sunrise and sunset, and therefore the unlit conditions.

It is thus important to note that our study, conducted over six days in early May, reflects conditions specific to the spring breeding season; however, the effects of PNL may vary substantially across seasons, particularly during periods of shorter daylight (from late summer autumn to early spring), when extended artificial lighting could exert even stronger influences on species with flexible breeding or singing phenology.

3. What benefits can Robins gain from part-night lighting?

The fact that European Robins sing earlier at dawn and later at dusk can be seen as a reduction in the individuals' resting time. Inferring a decrease in individual fitness remains a hypothesis, as artificial light can suppress melatonin and increase virus-induced mortality (Kernbach et al., 2020), and increase corticosterone level (Ouyang et al., 2015; Grunst et al., 2020) in other urban songbirds, all being physiological stresses that directly rely on fitness (*i.e.* survival and reproductive success). Artificial light can even cause direct neuronal death of individuals in Zebra finches (Moaraf et al., 2019). Moreover, beyond birds the literature confirms these impacts on the fitness of other taxa such as insects (Costin and Boulton, 2016; Firebaugh and Haynes, 2016; McLay, Green, and Jones, 2017; McLay et al., 2018) and amphibians (Touzot et al., 2020).

While extended daily activity under ALAN may intuitively benefit reproductive success—through increased mate attraction, better resource acquisition, or nestling provisioning (Gaston et al., 2013; Titulaer et al., 2012; McGlade et al., 2023)— emerging evidence suggests potential trade-offs, including potential reduced parental fitness, impaired chick survival and growth (de Jong et al., 2015; Raap et al., 2016; Jha et al., 2021), and disrupted neuroendocrine process that can delay or even suppress the reproduction (Jha et al., 2021, 2024; Helm et al., 2024). These conflicting outcomes highlight the need for further research to disentangle the context-dependent costs and benefits of ALAN on avian life history traits.

Finally, while most research on the effects of ALAN focuses on nocturnal, dawn, or dusk activity, we also hypothesize that ALAN may also disrupt biological rhythms outside these periods. For example, this may be mediated by different mechanisms, including a damping of corticosterone rhythms alongside melatonin rhythms under ALAN (Mishra et al., 2019). These hormonal shifts, linked to increased hypothalamus-pituitary-adrenal (HPA) axis activity (Grunst and Grunst, 2023), can induce residual changes in an animal's activity patterns throughout the entire day.

Part-Night Lighting (PNL) may therefore help mitigate the impacts of ALAN, although in urban context exposed to skyglow, we were not able to detect a significant difference in Robin singing timing between FNL and PNL conditions.

4. Management proposals

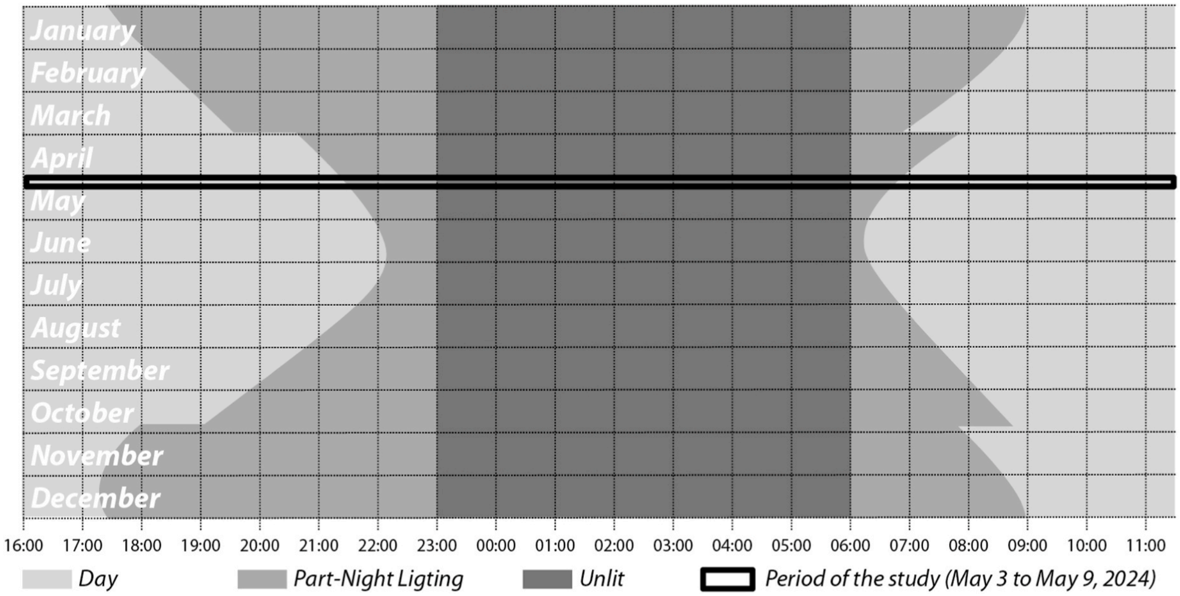

Fig. 4. Duration of night, day, and artificial light switch-on periods under Part-Night Lighting (PNL) conditions, in which lights are turned off during the middle of the night at fixed local times (23:00 to 06:00), for the year 2024. Days of the year are shown from top to bottom, and hours of the day from left to right. The shifts in morning switch-on and evening switch-off times of artificial lighting are due to daylight saving time changes: from standard time (UTC+1) to summer time (UTC+2) in March, and back to standard time (UTC+1) in October.

We propose seven complementary recommendations to improve the ecological effectiveness and social acceptability of PNL schemes.

4.1. Shift from rigid to seasonally adaptive lighting schedules

Most PNL programs operate on fixed switch-off periods (often 11 p.m. to 6 a.m.), without accounting for seasonal changes in daylength or the biannual transitions between standard and daylight-saving times. This can result in prolonged lighting during the sensitive pre-dawn period in winter and early spring, when the mismatch between artificial and natural light cues is greatest. Many modern lighting systems already incorporate astronomical clocks, enabling switch-off times to be set relative to sunrise and sunset (e.g., 60–90 min before sunrise), thus aligning better with the diel activity patterns of local fauna (Jägerbrand and Bouroussis, 2021). Our results suggest that such adaptive schedules could avoid exposure precisely at the crepuscular windows when birds are most light-sensitive, reducing circadian disruption.

4.2. Prioritize ecologically sensitive areas and periods

Part-Night lighting should be deployed preferentially where artificial lighting is likely to cause the most ecological harm—urban parks, riparian corridors, wetland edges, and other habitats supporting high biodiversity or serving as ecological corridors (Gaston et al., 2013). Sensitivity is not constant throughout the year: light impacts can be particularly strong during breeding, migration, or overwintering, when energy budgets are tight and behavioral synchrony is critical (Dominoni, Borniger, and Nelson, 2016). Integrating seasonal ecological calendars into PNL design would allow stricter lighting reductions at these critical times, while maintaining some flexibility when biological sensitivity is lower (Jägerbrand and Bouroussis, 2021). This targeted approach could maximize conservation benefits without imposing uniform restrictions.

4.3. Embed part-night lighting within a broader lightscape management framework

Our data indicate that residual illumination from neighboring lit zones—through direct spillover or skyglow—could significantly undermine PNL. This implies that interventions at the city or urban neighborhood scales may be insufficient if they are isolated. Instead, PNL planning should be integrated into spatially coordinated lighting strategies that explicitly map and manage the cumulative lightscape. Such strategies could connect dark refuges across administrative boundaries, ensuring that nocturnal habitats are not fragmented by pockets of residual illumination.

4.4. Reduce overall illumination where part-night lighting is not feasible

In certain areas—due to traffic safety, security concerns, or public opposition—PNL switch-off regimes may not be viable. In such contexts, reducing light intensity, narrowing beam spread, using shielding, and limiting operating hours can still meaningfully lower ecological impacts (Gaston et al., 2012). Given that our results suggest even indirect light can shift behavioral rhythms, these measures should be considered as an essential complement to PNL, not merely a secondary option.

4.5. Combine temporal reductions with spectral adjustments

Part-night lighting addresses the timing of light exposure but not its spectral composition. Light with low correlated color temperature (≤2000 K) is generally less disruptive, but warm white LEDs still emit short-wavelength blue light known to affect circadian physiology (Grubisic et al., 2018; Falcón et al., 2020; Dimovski et al., 2025). Additional measures, such as monochromatic amber LEDs or long pass filters, could further reduce biological disruption during illuminated periods. While the literature remains mixed regarding the effect of spectrum on birdsong specifically, studies across taxa consistently show lower ecological impacts for warmer and spectrally narrowed lighting.

4.6. Monitor ecological responses to guide adaptive management

The effectiveness of PNL should not be assumed: it must be verified through systematic, site-specific ecological monitoring, especially as very few studies to date have assessed PNL schemes. We thus recommend intensifying the monitoring of behavioral and physiological responses across seasons and species, and this for a variety of PNL schedules. This evidence base can inform the iterative adjustment of lighting schedules, spectral settings, and spatial targeting, ensuring that interventions are both effective and accountable.

4.7. Integrate participatory governance into lighting decisions

Lighting management is as much a social and governance challenge as it is a technical one (Challéat et al., 2021). Public acceptance is more likely when residents, local associations, and other stakeholders are actively involved in designing, implementing, and evaluating PNL schemes (Tardieu et al., 2025). Co-produced strategies can enhance legitimacy, reduce conflict, and foster shared responsibility for nocturnal environment conservation. Transparent communication about the ecological rationale, coupled with citizen science monitoring, can further strengthen public engagement.

CRediT authorship contribution statement

Laurent Godet: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Samuel Challéat:** Writing – review & editing, Methodology, Conceptualization. **Kévin Barré:** Writing – review & editing, Methodology, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Laurent Godet reports a relationship with Foundation of France that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.127837.

Data availability

Data will be made available on request.

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