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RESEARCH ARTICLE

Minimizing aviation lighting duration reduces bat attraction to wind turbines

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Abstract

1. Wind turbines negatively affect bats through mortality, which can be exacerbated by attraction behaviours, and loss of habitat use caused by avoidance behaviours. However, potential mechanisms driving bat responses to wind turbines are still poorly understood. This is especially true of red aviation lighting, designed to prevent aircraft collisions and implemented in many countries, that could be perceived by bats from a long distance and lead to a response at a large spatial scale.
2. We assessed the role of wind turbine red aviation lighting in the behavioural responses (attraction and avoidance) of bats. To this end, we acoustically quantified the activity of three functional bat guilds (long-, medium- and short-range echolocators) at three wind farms using a triplet sampling design: recordings were conducted simultaneously at (i) wind turbines illuminated throughout the night, (ii) wind turbines equipped with the aircraft detection lighting system (ADLS) and illuminated an average of 12% of the night and (iii) control sites without nearby wind turbine. Thirteen and nine triplets were sampled at wooded edges ~250 m from the nearest wind turbine and in open habitats at the base of the turbine, respectively, during two consecutive nights in June 2021 in the Uckermark district (north-east Germany).
3. We found that acoustic activity was higher overall at sites near wind turbines illuminated throughout the night than at control sites for all functional guilds and both at wooded edges and in open habitats, indicating local attraction behaviours towards wind turbines that might increase collision risks.
4. Activity at sites near wind turbines with ADLS was lower overall than at sites near wind turbines illuminated throughout the night, and similar to control sites, suggesting that part-night lighting could contribute to reducing bat attraction towards wind turbines.
5. *Synthesis and applications*. This study provides empirical evidence that attraction behaviour of bats towards wind turbines is driven, at least partially, by red

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aviation lighting. We also demonstrate that smart lighting of wind turbines, such as the ADLS, could cost-effectively help mitigate disruption of bat habitat use and the associated collision risks. Implementing adaptive lighting strategies could therefore represent a practical step towards balancing wind energy development with bat conservation.

KEYWORDS
acoustic activity, ADLS, ALAN, avoidance, Chiroptera, local scale, onshore wind energy, smart lighting

1 | INTRODUCTION

Mitigating climate change requires a major reduction in greenhouse gas emissions (IPCC, 2022). One of the main levers to achieve this reduction is the development of renewable energy sources, such as wind energy, hydropower and solar energy. Among these, wind energy is playing an increasingly key role (IRENA, 2022), with electricity production from wind turbines projected to double in just a few years at the global scale (Hutchinson & Zhao, 2023). However, many articles have reported negative impacts of wind energy production on the environment (Saidur et al., 2011; Wang & Wang, 2015), including biodiversity. This leads to a conflict between climate change mitigation and biodiversity conservation: the so-called *green-green dilemma* (Voigt et al., 2019).

Extensive research has shown that wind turbines can have negative effects on airborne biodiversity, such as birds and bats (Kuvlesky et al., 2007; Schuster et al., 2015), which can contribute to the decline of species populations (Duriez et al., 2023; Frick et al., 2017). Consequences on bats have been particularly investigated and are twofold: (i) mortality caused by collision (Arnett et al., 2008; Kunz et al., 2007; O'Shea et al., 2016; Rydell et al., 2010), that might be exacerbated by attraction behaviours (Cryan et al., 2014; Ellerbrok et al., 2023; Horn et al., 2008; Richardson et al., 2021); and (ii) loss of habitat use caused by avoidance behaviours (Barré et al., 2018; Ellerbrok et al., 2022; Gaultier et al., 2023; Minderman et al., 2017).

Whilst previous studies suggest that all bat foraging guilds can exhibit both attraction and avoidance behaviours towards wind turbines, the prevalence of one behaviour over the other might be attributed to many factors, such as the life cycle stage (Ellerbrok et al., 2022; McKay et al., 2024), the characteristics and operation of wind turbines (Cryan et al., 2014; Ellerbrok et al., 2024; Leroux et al., 2023, 2024), the distance from the turbines (Gaultier et al., 2023; Leroux et al., 2023) and the local habitat (Leroux et al., 2022; Reusch et al., 2022; Scholz et al., 2025; Sotillo et al., 2024). The identification of these multiple factors in recent investigations suggests the co-occurrence of several underlying mechanisms that are currently unknown. Therefore, very few opportunities with limited effectiveness in reducing attraction and avoidance behaviours have been explored so far. For instance, the adequacy of the UNEP/EUROBATS recommendation for the spatial positioning of wind turbines (distance to the nearest wooded edge >200 m; Rodrigues et al., 2015) has been questioned (Barré et al., 2018), in addition to being poorly implemented (Barré et al., 2022). Another widespread mitigation measure is wind turbine curtailment using blade feathering when bats are highly active and energy production is low. Although this measure successfully mitigates collision risks, its effectiveness remains highly variable (Adams et al., 2021; Whitby et al., 2024). Investigating the mechanisms underlying bat responses to wind turbines is therefore necessary to design new mitigation measures for the negative impacts of wind energy on bats.

Various hypotheses, involving different sensory modalities and spatial scales, have been advanced in the literature (Cryan & Barclay, 2009; Guest et al., 2022; Jonasson et al., 2024). For instance, attraction at small spatial scales could be due to the high density of insects at wind turbines (Horn et al., 2008; McKay et al., 2024; Voigt, 2021). Wind turbines may also attract bats because they are perceived as potential trees for roosting or mating (Cryan, 2008). Conversely, airflow disturbance generated by moving blades leads to avoidance behaviour downwind of wind turbines for some species, which could be attributed to poorer flight and foraging conditions (Leroux et al., 2024). Other mechanisms underlying bat responses to wind turbines, such as the effects of red aviation lighting, which is designed to prevent collisions with aircraft, may play a significant role in bat responses to wind turbines (Voigt et al., 2018). However, this mechanism has received far too little attention despite the widely recognized effects of artificial light at night (ALAN) on bats (Stone et al., 2015; Voigt et al., 2021).

The red aviation lighting of wind turbines could be perceived by bats from a long distance, resulting in a response on a large spatial scale (Jonasson et al., 2024). Indeed, it may attract bats, as suggested by Voigt et al. (2018) who described such behaviour in two migrating *Pipistrellus* species towards red lighting in coastal meadows during summer migration. In contrast, red aviation lighting may also result in avoidance behaviour, as suggested by Barré et al. (2021) who demonstrated that all bat guilds seek refuge in cluttered environments when exposed to red streetlighting during foraging. Managing the red aeronautical lighting of turbines may consequently offer an easy-to-implement tool to mitigate the negative impacts of wind turbines on bats. Only four studies, all conducted in North America, have hitherto investigated this mechanism (Arnett et al., 2008; Baerwald & Barclay, 2011; Bennett & Hale, 2014; Horn et al., 2008), three of which suggest neutral behaviour towards wind turbine red aviation lighting, the fourth suggesting avoidance behaviour in one species (*Lasiurus borealis*) (Bennett & Hale, 2014). However, most of these studies were not primarily designed to assess bat responses to wind turbine red aviation lighting, and three of them were conducted only during the migration season (Baerwald & Barclay, 2011; Bennett & Hale, 2014; Horn et al., 2008). Furthermore, three of these studies were based on bat fatalities (Arnett et al., 2008; Baerwald & Barclay, 2011; Bennett & Hale, 2014), addressing the direct consequences of collisions, but could not capture potential disruption of habitat use, such as the loss of habitat caused by avoidance behaviours (Barré et al., 2018; Ellerbrok et al., 2022; Gaultier et al., 2023; Minderman et al., 2017). Finally, these studies all involved both unlit wind turbines and turbines illuminated with red aviation lighting within a single wind farm, sometimes with both modalities located very close to each other, which could be problematic given the potential spatial scale of the effect of aviation lighting on bats (Jonasson et al., 2024).

In this study, we assessed the role of wind turbine lighting in the behavioural responses (attraction and avoidance) of bats. To this end, we acoustically monitored bat activity at three wind farms in north-east Germany in June, outside both the peak mortality period and the migration season, although mortality events can still occur (Rydell et al., 2010). We used a sampling design based on triplets of sites simultaneously sampled: (i) at wind turbines illuminated throughout the night; (ii) at wind turbines illuminated only when an aircraft is detected with the 'Aircraft Detection Lighting System' (ADLS); and (iii) at control sites without wind turbines within a radius of 2 km. To consider potential variations in bat responses to wind turbine lighting depending on the location relative to the turbine, we replicated this design at two different distances (at the base of the turbines in open habitats and at wooded edges located approximately 250 m from the nearest wind turbine). We compared the responses of three functional bat guilds (short-range echolocators, SRE; medium-range echolocators, MRE; long-range echolocators, LRE) representing different levels of sensitivity to wind turbines (Barré et al., 2018; Roemer et al., 2019). We hypothesized that the activity of bats may be different at wind turbines illuminated throughout the night compared to control sites, as a result of attraction or avoidance effects depending on the context (Barré et al., 2018; Ellerbrok et al., 2022, 2023; Leroux et al., 2022, 2024; Richardson et al., 2021; Sotillo et al., 2024). We also hypothesized that the use of the ADLS may mitigate the response of bats to wind turbines, thus potentially providing an easy-to-implement tool to reduce collision risks and habitat loss. We further expected differences in activity between wind turbine lighting modalities to be more pronounced at the base of the turbines in open habitats for MRE and LRE, and to occur only at wooded edges located 250 m from the nearest wind turbine for SRE.

2 | MATERIALS AND METHODS

2.1 | Study area and wind farms sampled

Data were collected at three wind farms in the Uckermark district of Brandenburg, in north-eastern Germany (53°23′6.4″ N, 13°54′22.3″ E) (Figure 1). The land cover of the Uckermark district is dominated by crops, covering 65% of its area, in particular cereals, rapeseed and soya beans. This area was selected because it encompasses one of the few wind farms to be equipped with the ADLS to date.

The ADLS-equipped wind farm ('Kleisthöhe', $n=15$ turbines) is located 11 and 22 km, respectively, from the two other wind farms. All its turbines are equipped with red flashing lights (flash pattern: 1 s ON, 0.5 s OFF, 1 s ON, 1.5 s OFF), as in turbines illuminated throughout the night, but these lighting systems are activated only when an aircraft is detected. Consequently, turbines at this wind farm were illuminated on average 12% ± 4% of the time at night, with no consistent pattern of activation across nights (Appendix 1 in the Supporting Information). Aircraft were detected by the ADLS using RADAR at this wind farm.

The other two sampled wind farms ('Gollmitz-Schönermark' and 'Grünberg', with $n=30$ and $n=14$ turbines, respectively) are equipped with lighting systems that remain continuously activated throughout the night. These wind farms were selected for their similarities to the one equipped with the ADLS in terms of landscape context and turbine characteristics (Appendix 2 in the Supporting Information). Further details on the characteristics of the red aviation lighting at these three wind farms are provided in Appendix 3 in the Supporting Information.

2.2 | Sampling design

To assess whether wind turbine lighting may explain variations in bat activity levels near wind turbines, a triplet sampling design was conducted to simultaneously record bat activity at three sampling sites: (i) near a wind turbine illuminated throughout the night ('Constant WT site' hereafter), (ii) near a wind turbine partially illuminated ('ADLS WT site' hereafter) and (iii) at a site without a wind turbine within a radius of 2 km ('control site' hereafter) (Figure 2). To ensure robust comparisons between wind turbine lighting modalities, we selected sampling locations to minimize differences in wind turbine characteristics (hub height and rotor diameter) between Constant WT sites and ADLS WT sites of the same triplet. Consequently, all sampled wind turbines had the same hub height (i.e. 100 m), and rotor diameter differed by less than 3 m on average within triplets (Appendix 4 in the Supporting Information). We also minimized variations in surrounding landscape features known to influence bat activity between Constant WT sites, ADLS WT sites and control sites of the same triplet (Appendix 5 in the Supporting Information).

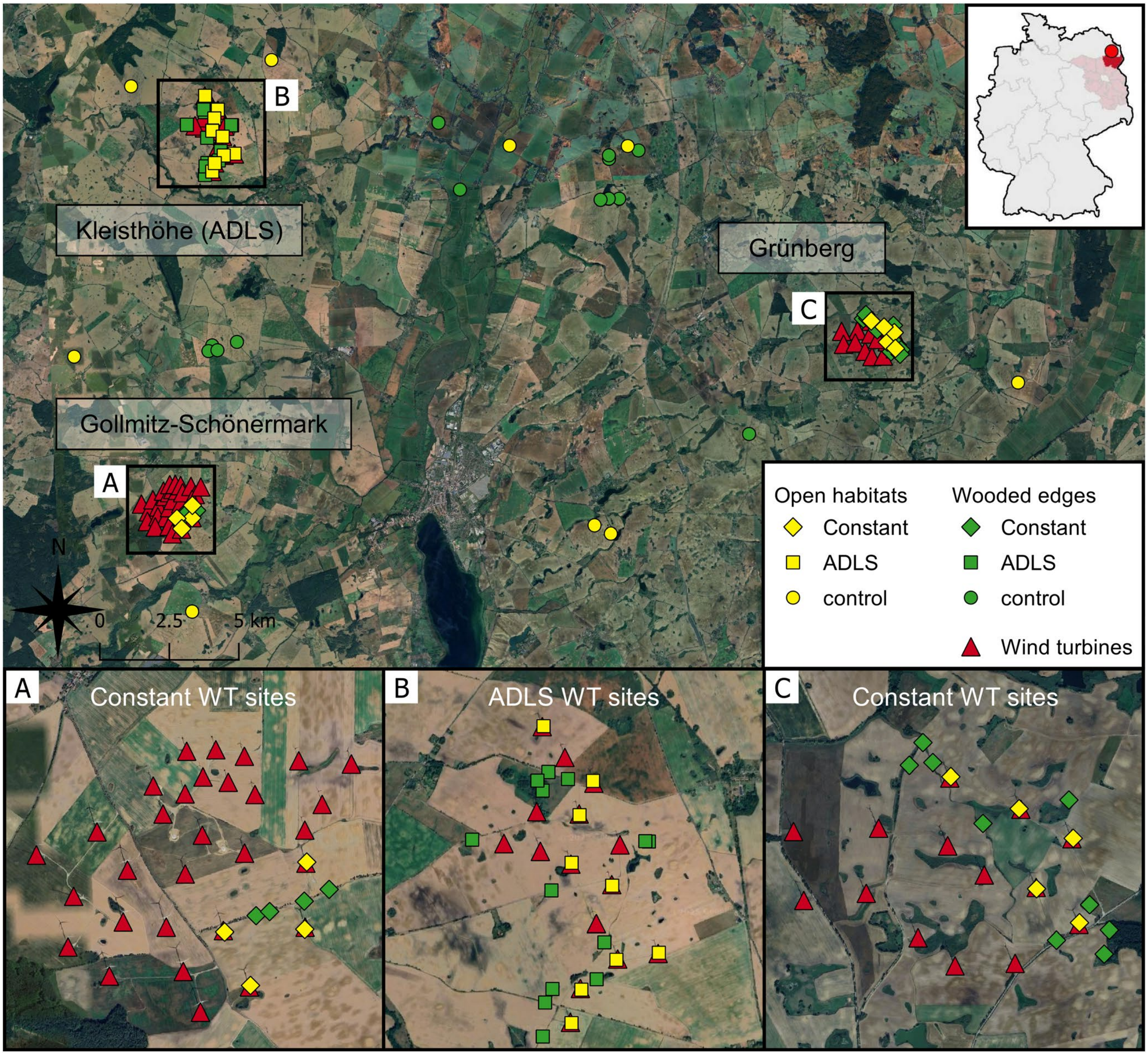

FIGURE 1 Location of the three wind farms sampled and sampling sites (Uckermark, Brandenburg, Germany). (a) Gollmitz-Schönermark wind farm; (b) Kleisthöhe wind farm; (c) Grünberg wind farm. Open habitats: Sites in open habitats at the base of the turbines (OH–10 m); Wooded edges: Sites at wooded edges (hedgerows or forest edges) located between 150 and 300 m from the nearest turbine (WH–250 m); Constant: Sites near a wind turbine illuminated throughout the night (Constant WT sites); ADLS: Sites near a wind turbine partially illuminated (ADLS WT sites); control: Sites without a wind turbine within a radius of 2 km (control sites). Basemap: Google Satellite.

We replicated this design in two different habitats located at two distances from wind turbines (Figure 2). Bat activity was therefore recorded at nine triplets in open habitats at the base of the turbines (hereafter 'OH–10 m' dataset), and at 13 triplets at wooded edges (hedgerows or forest edges) located between 150 and 300 m from the nearest turbine (hereafter 'WH–250 m' dataset) (average distance for Constant WT sites: 231.7 ± 50.7 m; average distance for ADLS WT sites: 243.6 ± 49.2 m). For control sites, the distance to the nearest wind turbine was 2564.8 ± 133.1 m for the WH–250 m dataset and 2498.3 ± 543 m for the OH–10 m dataset. Constant WT sites were sampled in both 'Gollmitz-Schönermark' and 'Grünberg' wind farms as part of both datasets (Gollmitz-Schönermark: $n = 4$ for the OH–10 m dataset, $n = 4$ for the WH–250 m dataset; Grünberg: $n = 5$ for the OH–10 m dataset, $n = 9$ for the WH–250 m dataset) (Figure 1; Appendix 6 in the Supporting Information).

This sampling design was motivated by four main considerations: (i) uncertainties regarding the spatial extent of the potential effect of wind turbine lighting on bats; (ii) the variability of their responses (i.e. attraction or avoidance) with habitat (Leroux et al., 2022); (iii) the limited availability of wooded edges at the base of wind turbines; and (iv) the need to ensure sufficient data for all bat guilds,

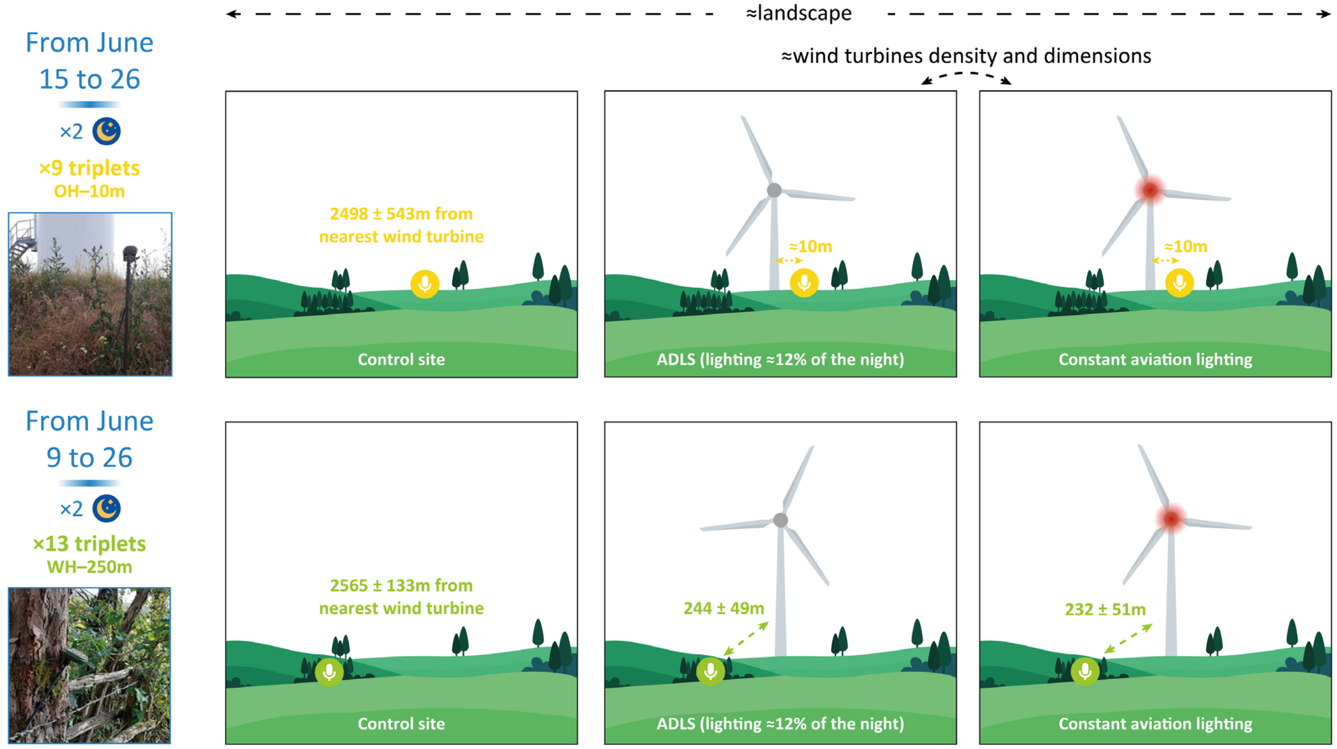

FIGURE 2 Schematic representation of the sampling design. OH–10 m: Sites in open habitats at the base of the turbines; WH–250 m: Sites at wooded edges (hedgerows or forest edges) located between 150 and 300 m from the nearest turbine; Control site: Site without a wind turbine within a radius of 2 km; ADLS: Site near a wind turbine partially illuminated; Constant aviation lighting: Site near a wind turbine illuminated throughout the night.

particularly SRE, which tend to avoid open habitats (Denzinger & Schnitzler, 2013; Frey-Ehrenbold et al., 2013).

Sampling was conducted between 15 and 26 June 2021, with up to four triplets sampled the same night (Figure 1; Appendix 6 in the Supporting Information) for the OH–10 m dataset, and between 9 and 26 June 2021, with up to five triplets sampled the same night (Figure 1; Appendix 6 in the Supporting Information) for the WH–250 m dataset. Each site was sampled over two consecutive nights. For the WH–250 m dataset, only eight different turbines equipped with the ADLS could be sampled due to a lack of hedgerows near other turbines. Consequently, five of these turbines were each involved in the sampling of two different triplets. Similarly, among the seven turbines illuminated throughout the night that were sampled for this dataset, three were sampled multiple times (two, three and four times). However, sites were consistently located at distinct hedgerows, with a minimum distance of 60 m between them. No ethical approval was required for data collection. When needed, fieldwork permissions were discussed and granted directly by the landowners.

2.3 | Wind turbine operation

Because wind turbine operation can influence bat activity, particularly by reducing their activity at high rotation speeds (Cryan et al., 2014; Ellerbrok et al., 2024; Horn et al., 2008; Leroux et al., 2023), potential confounding effects with the tested wind turbine lighting modalities were also assessed (Appendix 7 in the Supporting Information). We found that they should not undermine the findings of this study (see Section 4).

2.4 | Acoustic sampling

We recorded bat echolocation calls using Song Meter SM4Bat FS automatic passive acoustic recorders with omnidirectional SMM-U2 microphones (Wildlife Acoustics, Inc., Concord, MA, USA) placed 1.5 m above the ground. All recorders were configured according to the recommendations of the French bat monitoring program (FBMP) (Millon et al., 2015) and recordings of all sounds above 2 kHz that exceeded the background noise by 12 dB with a sampling rate of 384 kHz were carried out the entire night, from 30 min before sunset until 30 min after sunrise and only under favourable conditions following FBMP recommendations.

We used the number of bat passes per night as a proxy of bat activity (e.g. Barré et al., 2018; Wickramasinghe et al., 2003). A bat pass was defined as the emission of one or more echolocation calls by the same bat species during a 5-s interval. We used the TADARIDA software (Bas et al., 2017) to automatically detect echolocation calls and identify the taxon of each bat pass at the most accurate taxonomic level. A confidence score ranging from 0 to 1 was associated with each automatic identification. We conducted analyses only on bat passes with a confidence score superior to 0.5, and ensured the robustness of our findings by using a more conservative confidence score of 0.9. Indeed, each threshold entails a different trade-off: applying a 0.5 threshold retains most true positives while discarding few false positives, whereas a 0.9 threshold removes most false positives but also a large number of true positives. Therefore, analysing data filtered using both thresholds (i.e. reflecting different trade-offs between false and true positives), and only drawing conclusive interpretations when both yield similar results, ensures the robustness of our findings to automatic identification errors (Barré et al., 2019).

Then, the identified taxa were grouped into three functional guilds based on the structure of their echolocation calls and, consequently, their foraging strategies. In our case, the SRE included *Myotis* spp., *Plecotus* spp., *Rhinolophus* spp. and *Barbastella barbastellus*; the MRE included *Pipistrellus* spp., *Hypsugo savii* and *Miniopterus schreibersii*; and the LRE included *Nyctalus* spp., *Eptesicus* spp. and *Tadarida teniotis* (Denzinger & Schnitzler, 2013). These guilds feature different detection distances and different levels of sensitivity to wind turbines. Indeed, the SRE are particularly vulnerable to habitat loss caused by wind turbines, followed by the MRE (Barré et al., 2018), whereas the LRE are highly sensitive to collision risks, also followed by the MRE (Roemer et al., 2019). This approach also enabled us to include species that are rare or difficult to detect—and therefore difficult to study individually—and to overcome most automatic identification errors by grouping species with similar echolocation calls that can be easily confused (Barré et al., 2019).

We confirmed the absence of difference in identification errors between the different wind turbine lighting modalities by manually checking recordings using a stratified sampling (Appendix 8 in the Supporting Information). Indeed, the presence of a nearby wind turbine at Constant WT sites and ADLS WT sites may have led bats to modify their echolocation calls—particularly by increasing their frequency bandwidth—to better avoid this obstacle. These alterations in call characteristics may increase the acoustic overlap between species, thereby raising the proportion of both false positives and false negatives for these two wind turbine lighting modalities. Differences in bat behaviour between Constant WT and ADLS WT sites (e.g. stronger attraction to Constant WT sites) could also have resulted in differences in identification error rates between these two wind turbine lighting modalities due to the varying proximity of bats to the wind turbines.

2.5 | Statistical analysis

To evaluate the effect of wind turbine lighting modality on bat activity, we fitted generalized linear mixed models (GLMMs) with the *glmmTMB* package (Brooks et al., 2017). Bat activity was included as the response variable (Equation 1). We used a negative binomial error distribution with a logarithmic link function to account for overdispersion. Diagnostics of residuals were used to select between type I and type II negative binomial models. We included the wind turbine lighting modality—our variable of interest—as a three-level fixed effect variable: ADLS WT site, Constant WT site and control site. We also added as a fixed effect the density of hedgerows computed in a buffer zone around the sampling site (expressed in linear length of hedgerows per surface area in km.km^{-2}) to correct for residual but significant differences in landscape composition between sites within the same triplet (Appendix 5 in the Supporting Information). Finally, since our sampling design was based on triplets of sites sampled on the same nights we included the triplet as a random intercept effect.

$$\text{Bat activity}_{i,j} \sim \text{Negative Binomial}\left(\mu_{i,j}, \mu_{i,j} + \frac{{\mu_{i,j}}^2}{k}\right) \quad (1)$$

$$\log(\mu_{i,j}) = \alpha + \sum_m^M (\beta_m \times \text{Lighting modality}_i)$$

$$+ \gamma \times \text{Hedgerow density}_i + \delta_l + \varepsilon_{i,j}$$

$$\delta_l \sim N(0, \sigma)$$

$$\varepsilon_{i,j} \sim N(0, \sigma')$$

where Bat activity$_{i,j}$ is the number of bat passes observed at site i (of wind turbine lighting modality m and triplet l) on night j, and k is the dispersion parameter of the negative binomial.

We fitted a total of 36 models, covering every combination of bat guild (SRE, MRE and LRE), dataset (OH–10 m and WH–250 m), automatic identification confidence score (0.5 and 0.9) and buffer size for computing hedgerow density (200, 500 and 1000 m, see Appendix 5 in the Supporting Information). However, we reported in the main text only the results from the six models based on a confidence score of 0.5 and a buffer size of 200 m, as using a 0.9 confidence score is less conservative and resulted in a more restricted dataset, while a smaller buffer resulted in a lower overlap between sites. The other models were used to assess the sensitivity of our findings to variations in these two parameters and were reported in Appendix 9 in the Supporting Information.

We checked that all explicative variables had a Variance Inflation Factor inferior to 3.5, indicating the absence of multicollinearity (Zuur et al., 2010). We also assessed the quality of fit of models by checking the uniformity of the residual distribution, the homogeneity of variance and the independence of the residuals using the *DHARMA* package (Hartig, 2022).

Likelihood ratio tests (LRTs) (Fisher, 1922) were used to assess the effect of the wind turbine lighting modality on bat activity. When significant, we performed multiple pairwise comparisons using Tukey's post hoc tests (Tukey, 1949) to identify which modalities were significantly different from each other. All statistical analyses and graphs were performed using R 4.4.1 (R Core Team, 2024). Statistical significance was set at $p < 0.05$.

3 | RESULTS

We recorded a total of 28,966 bat passes with a confidence score superior to 0.5 (see Appendix 10 in the Supporting Information for taxonomic composition). The MRE guild was the most abundant (OH–10 m dataset: 83.9% of bat passes, $n = 4659$; WH–250 m dataset: 74.7%, $n = 17{,}492$) and the SRE the least (OH–10 m dataset: 2.1% of bat passes, $n = 115$; WH–250 m dataset: 7.2%, $n = 1691$) (Appendix 10 in the Supporting Information). All guilds were observed at all sampling sites for both datasets, except the SRE in the OH–10 m dataset (occurrence at 77.8% of sites).

We found a significant effect of wind turbine lighting modality on bat activity in four out of six cases (Figure 3; Table 1). The activity of the SRE guild in the WH–250 m dataset, as well as that of the MRE and LRE guilds in the OH–10 m dataset, was significantly higher at sites with wind turbines illuminated throughout the night ('Constant WT' modality) than at sites without wind turbines ('control' modality) and at sites with turbines equipped with the ADLS ('ADLS WT' modality), with no significant difference in activity between control and ADLS WT sites (Figure 3; Appendix 11 in the Supporting Information). A similar but nearly significant pattern was observed for the MRE guild in the WH–250 m dataset and SRE guild in the OH–10 m dataset (Figure 3; Appendix 11 in the Supporting Information). Similarly, in the WH–250 m dataset, the activity of LRE was significantly higher at Constant WT sites compared to ADLS WT sites (Figure 3; Appendix 11 in the Supporting Information). However, we observed no significant difference between Constant WT and control sites in this case and higher activity at control sites compared to ADLS WT sites (Figure 3; Appendix 11 in the Supporting Information). Finally, we found no significant effect of hedgerow density within a 200 m radius on bat activity, except for the MRE in the OH–10 m dataset where the effect was significantly negative (Table 1). Models including hedgerow density at 500, 1000 m or integrating bat passes with a confidence score superior to 0.9 revealed similar patterns despite slight variations in significance (Appendix 9 in the Supporting Information).

4 | DISCUSSION

The role of red aviation lighting in bat responses to wind turbines has so far received little attention. This study provides the first empirical evidence that red aviation lighting drives at least partially attraction behaviour of all bat guilds towards wind turbines. Therefore, our results demonstrate that the ADLS can cost-effectively contribute to mitigating the negative effects of wind turbine red aviation lighting on bats.

4.1 | Bat responses to the ADLS

Several bat genera (*Rhinolophus*, *Hypsugo*, *Miniopterus* and *Tadarida*) were automatically identified by the TADARIDA software, although they do not occur in our study area. However, these identification errors were very unlikely to bias our findings as the correct guild was not identified for only 16 of these bat passes at a confidence score superior to 0.9: identifications of the *Tadarida* genus ($n = 14$) and *Rhinolophus* genus ($n = 2$) (Appendix 10 in the Supporting Information), that were actually non-bat noises (sounds emitted by small mammals for *Rhinolophus*).

For all functional guilds, we observed that the acoustic activity under and 250 m from wind turbines illuminated throughout the night was different (three cases out of six), or tended to be different (two cases out of six), than at sites without a wind turbine within a radius of 2 km, in line with recent studies (Barré et al., 2018; Ellerbrok et al., 2022, 2023; Leroux et al., 2022, 2024; Richardson et al., 2021; Sotillo et al., 2024). The only exception was the LRE guild at 250 m from wind turbines, which exhibited a distinct trend. Surprisingly, in all other cases, the direction of the difference was consistent, with greater bat activity near turbines. This indicates a local attraction behaviour towards wind turbines that might, in turn, increase collision risks. This consistency in bat responses to wind turbines was unanticipated. Indeed, the nature of this response (i.e. attraction or avoidance) has been shown to depend on the distance from the turbines (Gaultier et al., 2023; Leroux et al., 2023), the local habitat (Leroux et al., 2022; Reusch et al., 2022; Scholz et al., 2025; Sotillo et al., 2024) and the species (Ellerbrok et al., 2024; Leroux et al., 2023; McKay et al., 2024). However, this result is in accordance with attraction behaviours that have mostly been reported at relatively small spatial scales, from below the turbine mast in a landscape context similar to that of this study (Leroux et al., 2022; Richardson et al., 2021), to 400 m in forests (Ellerbrok et al., 2022).

Our findings suggest that the red aviation lighting may be an important driving factor of bat attraction behaviour towards wind turbines. Indeed, the activity at sites near wind turbines equipped with ADLS was overall lower (four cases out of six), or tended to be lower (one case out of six), than at sites near wind turbines illuminated throughout the night. Activity at these sites was also overall similar to the activity at control sites without wind turbines (five cases out of six). This difference in activity between wind turbines illuminated throughout the night and those equipped with ADLS cannot be attributed to the sometimes greater operation of the former (Appendix 7 in the Supporting Information). Such differences may, in fact, have resulted in an underestimation of bat activity at sites near wind turbines illuminated throughout the night (Cryan et al., 2014; Ellerbrok et al., 2024; Horn et al., 2008; Leroux et al., 2023), leading to an underestimation of the difference in activity between these two wind turbine lighting modalities. Nor can this difference be attributed to the absence of infrared lights on wind turbines illuminated throughout the night sampled at the 'Grünberg' wind farm, unlike those equipped with ADLS (Appendix 3 in the Supporting Information). This may have indirectly attracted bats, as certain studies suggest that some insect species may respond to infrared light (Callahan, 1965; Takács et al., 2009), thereby leading to an overestimation of bat activity at sites near wind turbines partially

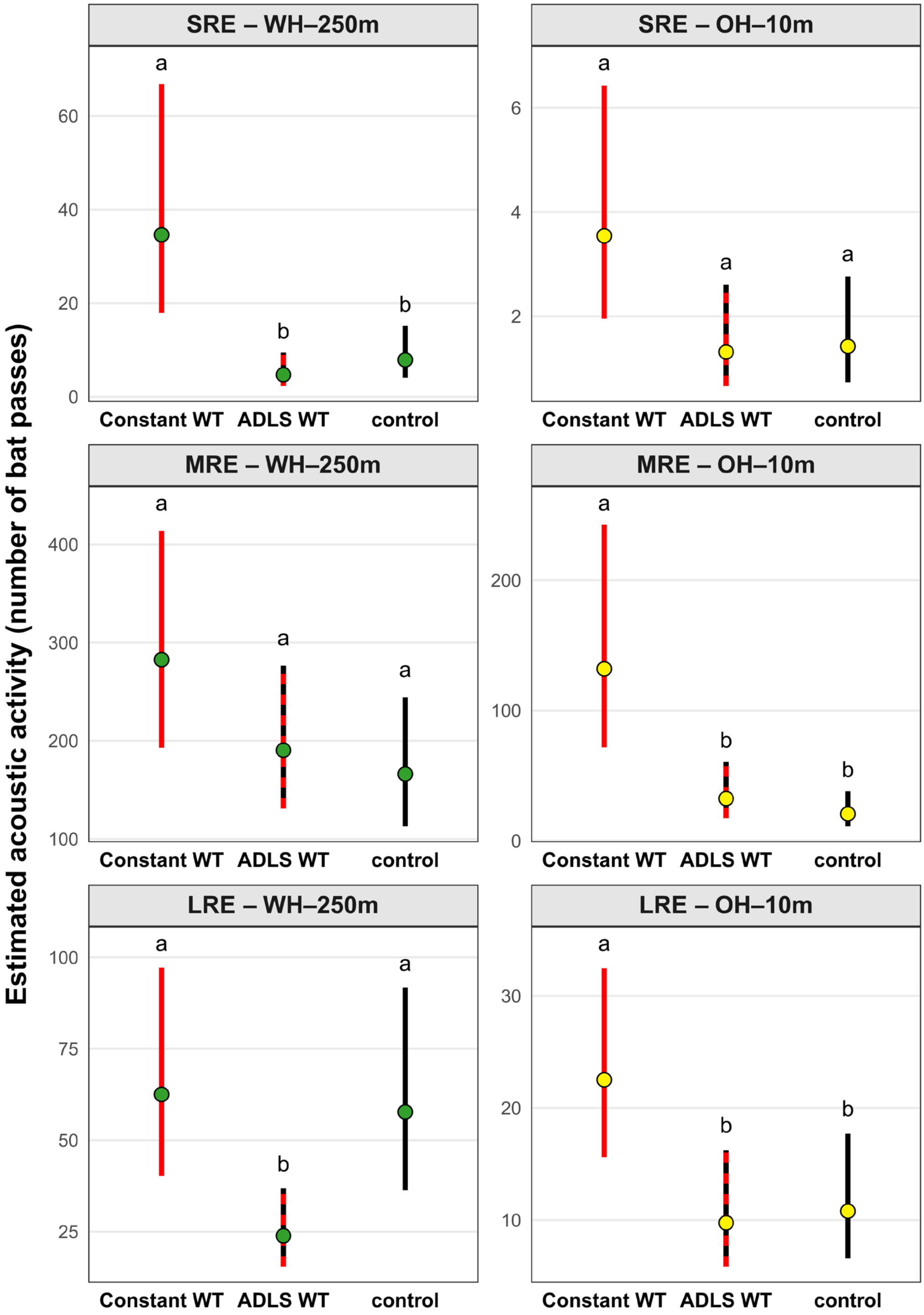

FIGURE 3 Estimated marginal mean of acoustic activity (in number of bat passes per night with an automatic identification confidence score superior to 0.5) per bat guild (LRE, long-range echolocators; MRE, medium-range echolocators; SRE, short-range echolocators), recorded at wooded edges (hedgerows or forest edges) located between 150 and 300 m from the nearest turbine (WH–250 m dataset, left in green) or in open habitats at the base of the turbines (OH–10 m dataset, right in yellow) under the three wind turbine lighting modalities (Constant WT, near wind turbines illuminated throughout the night; ADLS WT, near wind turbines equipped with aircraft detection lighting system; control, without wind turbines within a radius of 2 km) and with a radius buffer of 200 m for hedgerow density. Acoustic activity indices with different letters are significantly different ($p < 0.05$) according to pairwise comparisons (Tukey's method). The vertical bars correspond to the 95% confidence interval. See Appendix 9 in the Supporting Information for results of models fitted with different radius buffers for hedgerow density (i.e. 500 and 1000 m) and acoustic data based on a confidence score superior to 0.9.

illuminated. Implementing ADLS could therefore contribute to maintaining activity levels near wind turbines similar to those observed without wind turbines nearby.

To date, only four studies with contrasting results and conducted in North America on different bat communities have assessed the effect of wind turbine red aviation lighting on bats, most of which

TABLE 1 Results of likelihood ratio tests (LRT) applied to generalized linear mixed models with a buffer of 200 m for the hedgerow density variable (linear length per surface area in km.km^{-2}), for each bat guild (LRE, long-range echolocators; MRE, medium-range echolocators; SRE, short-range echolocators) and for bat passes with an automatic identification confidence score superior to 0.5 recorded at wooded edges (hedgerows or forest edges) located between 150 and 300 m from the nearest turbine (WH–250 m dataset) or in open habitats at the base of the turbines (OH–10 m dataset).

		WH–250 m		OH–10 m	
Guild	Explanatory variable	LRT	*p*	LRT	*p*
SRE	Wind turbine lighting modality	33.04	**<0.001**	5.74	0.06
	Hedgerow density (200 m)	0.07	0.79	0.39	0.53
MRE	Wind turbine lighting modality	5.03	0.08	23.43	**<0.001**
	Hedgerow density (200 m)	0.07	0.80	8.40	**<0.01**
LRE	Wind turbine lighting modality	14.04	**<0.001**	9.40	**<0.01**
	Hedgerow density (200 m)	3.21	0.07	0.41	0.52

Note: Significant *p*-values are shown in bold.

were conducted during the migration period. Of the three based on bat fatalities, two did not report any red aviation lighting effect (Arnett et al., 2008; Baerwald & Barclay, 2011), in contrast to our study that suggests that bat attraction behaviour towards wind turbines could be caused by red aviation lighting. However, these studies were not primarily designed to assess this effect. Our finding also differs from the third study (Bennett & Hale, 2014), which reported avoidance behaviour towards illuminated wind turbines in one species (*L. borealis*) and neutral behaviour for the other species. However, it was carried out in a single wind farm with unlit turbines and turbines illuminated with red aviation lighting sometimes located very close together. Finally, Horn et al. (2008) observed a non-significant attraction behaviour towards red aviation lighting using thermal cameras. Besides, previous research has also assessed the effects of red artificial light on bats in a different context from wind energy (e.g. Barré et al., 2021, 2023; Spoelstra et al., 2017; Voigt et al., 2018). However, these findings are difficult to compare with our own, as the existing literature on this topic offers contradictory findings and wind turbine red aviation lighting is very specific (i.e. light flashes of very high intensity at height). Moreover, few of these studies were conducted in early summer (but see Barré et al., 2021). Therefore, we consider that our research makes a major contribution to understanding the role of wind turbines lighting in the behavioural responses of bats.

Another interesting result is the response pattern of LRE at wooded edges 250 m from the wind turbine, a guild that includes the species most affected by mortality at wind turbines in Germany (*Nyctalus noctula*) (Rydell et al., 2010). In this case, activity was still higher at sites near wind turbines illuminated throughout the night than at sites near partially illuminated wind turbines, as in most other cases, suggesting that wind turbine red aviation lighting drives attraction behaviour. However, in this case, the activity levels at control sites were similar to those at sites near wind turbines illuminated throughout the night. Here, this pattern could suggest the co-occurrence of two antagonistic responses of similar intensity in bats to wind turbines illuminated throughout the night. The first is an attraction behaviour driven by aviation lighting, as described above. The second is an avoidance behaviour, likely driven by another mechanism, that is revealed in the absence of attraction and results in lower activity at sites near partially illuminated wind turbines compared to control sites. This attraction behaviour towards wind turbine red aviation lighting could be direct, or indirect, due to the higher density of insects (Horn et al., 2008; McKay et al., 2024; Voigt, 2021). On the other hand, this avoidance behaviour could be related to the operation of wind turbines and the resulting wake effect (Leroux et al., 2024), although this has not yet been demonstrated for this guild.

4.2 | Implications for conservation

This study revealed that smart lighting such as the ADLS can mitigate the disruption of bat habitat use caused by wind turbines and associated collision risks. Furthermore, the use of the ADLS may also benefit other taxa that are strongly affected by collisions and for which aviation lighting could be a contributing factor, such as insects (Horn et al., 2008; Voigt, 2021) and migratory birds (Rebke et al., 2019).

The ADLS also offers numerous benefits to wind turbine operators. First, this system is relatively easy-to-implement, as it requires no major modifications to existing wind turbines and several certified systems are already commercially available. Furthermore, the emission of light flashes over a reduced part of the night (approximately 12% of the night in this study) and the resulting reduction in the ALAN generated by wind farms is likely to increase their acceptability to neighbouring populations. Last but not least, this potential mitigation measure does not affect the electricity production of wind turbines, unlike curtailment using blade feathering, which is currently the most common mitigation measure applied at wind farms. Consequently, given the ability of ADLS to reduce bat attraction to wind turbines and thus potentially lower bat fatalities, its implementation could represent a win-win conservation measure by avoiding a trade-off between energy production and biodiversity conservation. In light of all these considerations, we advocate for the wider deployment of the ADLS in combination with other existing mitigation measures. The mandatory use of the ADLS in Germany now may set a precedent encouraging broader international adoption.

4.3 | Perspectives

Although promising, our findings should be supplemented by similar studies conducted at different periods of the year as previous research has shown that bat responses to wind turbines may vary between seasons (Ellerbrok et al., 2022; McKay et al., 2024). Studies similar to this one should also be conducted at wind farms with a distinct surrounding landscape (e.g. mostly open fields or forest), as bat responses to wind turbines may also vary between habitats (Reusch et al., 2022; Sotillo et al., 2024). Such complementary studies would allow generalizing the ability of ADLS to mitigate bat attraction behaviour towards wind turbines throughout the year and across different landscapes.

Although our results allow drawing conclusions about the potential of ADLS to reduce bat attraction towards wind turbines, we cannot conclude with certainty about its potential to mitigate bat fatalities since we assessed acoustic activity at ground height and outside the peak mortality period (Rydell et al., 2010). Further research conducted in late summer and monitoring acoustic activity at wind turbine nacelles or, better still, bat carcasses around turbines in late summer, would enable that assertion to be validated.

Finally, the precise mechanism underlying bat attraction towards wind turbine red aviation lighting remains to be elucidated. Future studies with a similar sampling design could compare foraging activity between the different lighting modalities. Such analyses might help to discriminate between direct and indirect attraction of bats towards wind turbines. Similarly, assessing the relationship between acoustic bat activity at wind turbines with ADLS and the time of activation of the system during the night, although it requires a larger dataset, could provide a better understanding of the time scale of this mechanism.

AUTHOR CONTRIBUTIONS

Christian Kerbiriou, Isabelle Le Viol, Pauline Lefebvre, Nicolas Valet, Kévin Barré and Camille Leroux conceived the ideas and designed the methodology; Gaëlle Larnoy, Pauline Lefebvre and Camille Leroux collected the data; Gaëlle Larnoy and Fabien Verniest led the analysis of the data with the support of Christian Kerbiriou, Isabelle Le Viol, Kévin Barré and Camille Leroux; Gaëlle Larnoy and Fabien Verniest led the writing of the manuscript with the support of Christian Kerbiriou, Isabelle Le Viol, Pauline Lefebvre, Nicolas Valet, Kévin Barré and Camille Leroux. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

This work was initiated as part of Camille Leroux's PhD research, which was co-supervised by Christian Kerbiriou, Isabelle Le Viol and Kévin Barré from the National Museum of Natural History (MNHN) and Nicolas Valet from Auddicé biodiversité. Auddicé biodiversité is an environmental consultancy that conducts wind farm impact assessment studies. At the time of submission, one of the authors—Camille Leroux—was working at Auddicé biodiversité. This work continued as part of Gaëlle Larnoy's Master's thesis and Fabien Verniest's postdoctoral position, which were mainly funded by ADEME, a public agency promoting renewable energies. Members of the wind energy sector financed part of the bat recorders and provided some technical data and expertise on wind turbine operation and features, as stated above. Thus, the authors declare a potential conflict of interest. However, sampling design, acoustic data collection, analysis and writing were conducted only by the authors and members of the wind energy sector did not contribute to the draft. Furthermore, sampling design and sampling sites were determined independently from Auddicé biodiversité activities, and identification of bat echolocation calls and bat activity measures were provided by TADARIDA software, a MNHN web portal, except for manual verifications of automatic identification errors that were performed by Elise Trébuchet and Margot Clément-Lacroix, who were working at Auddicé biodiversité at the time of submission. The authors certify that the collaboration did not interfere with the stated hypothesis, the way it was tested or the interpretations and conclusions. Authors take full responsibility for the integrity of the study.

DATA AVAILABILITY STATEMENT

Data available from the Zenodo open repository https://doi.org/10.5281/zenodo.17454526 (Larnoy et al., 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Duration of lighting activation for wind turbines equipped with ADLS.

Appendix S2. Wind turbines characteristics of the three wind farm sampled.

Appendix S3. Lighting characteristics of sampled wind turbines.

Appendix S4. Assessment of confounding effects between lighting modality and wind turbine characteristics.

Appendix S5. Assessment of confounding effects between lighting modality and landscape.
Appendix S6. Sampling dates of triplets.
Appendix S7. Assessment of confounding effects between lighting modality and operation.
Appendix S8. Verification of automatic identification.
Appendix S9. Sensitivity of results to automatic identification confidence score and radius buffer for hedgerow density.
Appendix S10. Number, percentage and occurrence of bat passes by guild and taxon.
Appendix S11. Results of pairwise comparison tests.

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