

RESEARCH ARTICLE

Site-specific curtailment thresholds substantially reduce bat mortality at wind energy facilities

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Abstract

1. Context: Wind energy expansion is central to climate mitigation but poses growing risks to wildlife through turbine collisions. Evidence on the effectiveness of mitigation strategies remains geographically limited and rarely tested at scale. Here we provide the first large-scale, multi-site evaluation of acoustic-informed curtailment across French wind facilities, assessing whether site-specific wind speed and temperature thresholds derived from bat activity can reduce wildlife mortality under operational conditions.
2. Approach and Methods: Using a dataset of mortality monitoring from hundreds of wind energy facilities, we identified sites monitored before and after a curtailment measure was applied, and control sites monitored for multiple years without curtailment. Mortality estimates were derived from raw data, correcting for biases using a standardized method to enable cross-site comparisons. Using a before–after control–Impact design across 16 facilities, followed by validation in a broader before–after comparison spanning 38 facilities, we disentangle curtailment effects from natural temporal variability.
3. Results: Site-specific acoustic-informed curtailment reduced fatalities of long- and mid-range echolocating bats by 83% and 84%, respectively. Nocturnal migratory bird mortality was unaffected by curtailment, demonstrating that environmental thresholds optimized for bats do not extend protection to these bird species.
4. Synthesis and Applications: Our findings demonstrate that site-specific operational thresholds, derived from acoustic data and meteorological conditions, substantially reduce bat mortality at wind energy facilities. As the largest standardized assessment of curtailment effectiveness and the first in Europe, this study supports the widespread adoption of site-specific curtailment measures wherever bat mortality is detected.

KEYWORDS

bat, bird, curtailment, effectiveness, mitigation, mortality, wind energy facilities

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1 | INTRODUCTION

Wind energy production represents an increasingly significant share of global energy generation, driven by the urgent need to reduce greenhouse gas emissions. In this regard, wind energy production increased by 10%–20% per year over the last decades (IRENA, 2023) and is predicted to supply more than one-third of global needs by 2050 (IRENA, 2019). Despite its benefits in terms of climate change reduction, wind energy can negatively impact biodiversity, mainly during the operational phase of wind turbines, affecting flying fauna both indirectly and directly. The avoidance of wind facilities by flying fauna during migration can lead to disruption of long-distance movements, resulting in increased energetic costs for these species (Marques et al., 2020, 2021). They may also induce habitat loss when turbines have a repellent effect (Barré et al., 2018; Leroux et al., 2022, 2024; Rehling et al., 2023) or increase the likelihood of direct impacts by collision when turbines generate an attraction effect (Kirkpatrick et al., 2017; McKay et al., 2024). Indeed, wind facilities directly impact flying fauna through collisions with turbine blades, resulting in mortality that can significantly affect population dynamics (Carrete et al., 2009; Duriez et al., 2023; Frick et al., 2017; Friedenbergs & Frick, 2021). The impact of this additional source of mortality on population dynamics depends partly on species' life-history traits and the affected age classes. Populations of long-lived species with late sexual maturity and low reproductive rates—such as bats or raptors—are particularly vulnerable to such accidental mortality, especially when adults are affected, thus increasing the risk of local population extinction (Duriez et al., 2023; Frick et al., 2017).

Numerous wind energy facilities have been established in areas of significant conservation concern (Froidevaux et al., 2025), underscoring the need for rigorous post-construction mitigation strategies. This is particularly critical given that many wind turbines are already operational, and their continued operation can lead to substantial bat mortality when mitigation measures are not implemented (Voigt, Kaiser, et al., 2022). Since bat activity is concentrated at night, primarily in the warmer months of the year, and under specific conditions of high temperatures and low wind speeds, stopping turbines' operation under these periods and conditions avoids high-risk activity windows while restricting shutdowns to brief, targeted intervals, thus minimizing impacts on wind energy production (Adams et al., 2021; Barré et al., 2023; Hayes et al., 2019; Whitby et al., 2024). This widely applied mitigation method used in the minimization phase is referred to as curtailment.

Although a few studies have demonstrated the effectiveness of curtailment in reducing bat fatalities—providing critical insights into mitigation strategies—most suffer from critical limitations. For example, some studies are spatially confined to a single wind facility or temporally limited to a single year, making their findings likely to be strongly dependent on local context (e.g. Baerwald et al., 2009; Bennett et al., 2022; Măntoiu et al., 2020; Martin et al., 2017; Peterson et al., 2025; Smallwood & Bell, 2020). The two major studies to date on the effectiveness of curtailment (Adams et al., 2021; Whitby et al., 2024) attempted to overcome these limitations by

conducting meta-analyses. However, these two studies also have limitations, as they relied on pre-existing data rather than designing their own experiments. This constrained their ability to control the experimental design or access raw mortality data, requiring them to use mortality estimates already calculated in local reports. As a result, these analyses aggregated mortality estimates derived from varied estimators. This heterogeneity in estimation approaches—each with distinct assumptions regarding carcass persistence and searcher efficiency (Bernardino et al., 2013; Ravache et al., 2026)—can introduce biases and limit the comparability of results across surveys. Additionally, Adams et al. (2021) meta-analyses—like the majority of single-site studies—are based on before–after design protocols, without control sites, which increases vulnerability to confounding factors such as large-scale population trends that may obscure the true impact of curtailment. The only study conducted on multiple sites and employing a control treatment design is that conducted by Whitby et al. (2024) across a relatively low number of sites ($n=6$). Finally, the majority of research evaluating curtailment effectiveness has been conducted in North America, and these findings should be validated in other regions, where bat communities often differ. Despite the large-scale expansion of wind energy in Europe and its ambitious decarbonization targets for electricity production (RePower EU, European Commission, 2022), very few studies have been conducted in this region, and to the best of our knowledge, no studies have rigorously estimated the effectiveness of curtailment in Europe by using the number of fatalities on multiple sites estimated from a standardized methodology.

Some countries have implemented curtailment protocols based on bat acoustic activity recorded at nacelle height, assuming that bat activity levels can serve as a reliable predictor of collision risk at wind facilities. In Europe, a common practice involves stopping or feathering turbines when wind speed falls below a certain threshold and temperature rises above another, with the combination of thresholds calibrated to protect approximately 80 to 90% of the bat activity recorded during the previous year (Beucher et al., 2023). However, acoustic activity is not a consistent proxy for mortality, particularly when measured prior to construction (Solick et al., 2020). While some studies have reported strong associations between activity recorded under turbine operation conditions and fatality rates (Peterson et al., 2025), this relationship remains debated, as it may depend on the methods used to record activity (Behr et al., 2023; Voigt et al., 2021) and vary across bat guilds and study sites (Sivault et al., in prep.). The main advantage of these curtailment measures is that the combined use of wind speed and temperature allows shutdowns to be targeted to specific periods of the night, thereby minimizing the loss of energy production (Behr et al., 2017; Martin et al., 2017). Moreover, these measures are site-specific, allowing adaptation to the variability in bat activity, which may depend on surrounding habitat, migration corridors or the local species assemblages. However, it is crucial to evaluate the actual effectiveness of such curtailment strategies in reducing bat mortality through a robust, rigorous and generalizable framework. It is also necessary to ensure that this approach is effective across all bat functional guilds

sensitive to collisions, which differ in their ecology, flight behaviour and spatial movement patterns (Denzinger & Schnitzler, 2013).

While curtailment measures are specifically designed to protect bats, their implementation during nighttime operations could also incidentally reduce collision risks for nocturnal migratory birds, although this remains purely hypothetical as birds are not the intended targets.

In order to thoroughly test the effectiveness of the curtailment measures, we leveraged an extensive database of bat mortality surveys conducted as part of regulatory environmental monitoring across wind facilities throughout France. All mortality data were collected using a standardized protocol recommended by the French Ministry of the Environment (MTES, 2018). Mortality estimates were recalculated using the most robust estimators currently available, ensuring full comparability across sites and surveys. This dataset allowed us to identify surveys conducted on wind facilities where curtailment was implemented, before and after their implementation, as well as to mobilize control sites surveyed over the same period but not subjected to curtailment measures. By comparing mortalities before and after on treatment and control sites (before–after control–impact, hereafter: BACI), we can isolate the effect of curtailment on bat mortality, ensuring that observed reductions are attributable to the curtailment rather than natural variability that could stem from climatic fluctuations or temporal declines in mortality unrelated to curtailment.

Using this BACI design, we systematically evaluated whether curtailment based on wind speed and temperature thresholds—calibrated to protect 90% of bat activity recorded at nacelle height—effectively reduces bat and nocturnal migratory bird fatalities. We hypothesized that curtailment measures would lead to a greater reduction in mortality at curtailed wind facilities compared to paired control sites. If this hypothesis was confirmed by the BACI analyses, we extended our analysis to a broader set of wind facilities, comparing mortality rates before and after curtailment implementation without the constraint of requiring paired control sites. This complementary approach not only facilitates comparisons with other before–after studies but also allows us to leverage a larger dataset, enabling broader inferences about the effectiveness of curtailment measures across diverse operational contexts.

2 | MATERIALS AND METHODS

The entire workflow used in this study, from data collection to statistical analysis, is summarized in Figure 1.

2.1 | Data collection

In France, a national protocol established in 2015 by the French Ministry for Ecological Transition and revised in 2018 (MTES, 2018), regulates the collection of mortality data at wind energy facilities. The existence of such a protocol enables consistency during the

data collection process and the comparison of fatality monitoring across different wind facilities. It requires conducting a minimum of 20 surveys at the base of turbines, at least between weeks 20 and 43 (May to October), typically at weekly intervals. The survey area, a square with sides of 100 m—or twice the blade length for turbines with blades longer than 50 m—is systematically searched using transects spaced 5–10 m apart to detect carcasses on the ground. To account for biases related to carcass removal or displacement, persistence tests are performed twice annually at two different seasons (spring, summer or autumn). Carcasses (typically chicks or mice) are placed beneath selected turbines, and their disappearance rate is monitored through repeated visits: once the day after deployment, followed by twice-weekly visits over a 14-day period. The protocol also includes search effectiveness tests, where 15–20 dummy carcasses—either real animal carcasses obtained from pet stores (to mimic the size classes of birds or bats likely to be found) or decoys—are dispersed to evaluate the detection rates of observers conducting mortality surveys.

French Regional Directorates for the Environment, Planning and Housing (DREAL), responsible for centralizing environmental reports of these monitoring at a regional scale, were contacted to gather mortality monitoring data from wind facilities collected in France. Only reports conducted between 2019 and 2024 that were fully compliant with the protocol and included all necessary data for mortality estimation were retained for analysis. A total of 640 usable mortality monitoring reports from 11 administrative regions were collected, including 141 wind facilities monitored over 2 years or more. Raw data on carcass observations, survey dates, actual surveyed areas, results of persistence and search effectiveness tests, and the type of curtailment implemented were retrieved from the reports.

Ethical approval was not required for this study, as we exclusively used pre-existing data collected during ecological impact assessments and did not conduct any new field data collection.

2.2 | Functional guilds

Bat species exhibit distinct echolocation strategies, habitat preferences and flight behaviours, allowing them to be classified into functional guilds based on their echolocation range and foraging ecology (Denzinger & Schnitzler, 2013). These guilds reflect adaptations to specific environmental niches and vary in their vulnerability to wind turbine collisions. Short-Range Echolocators (SRE) emit high-frequency, broadband calls optimized for cluttered environments, such as forests or dense vegetation, and typically fly at low altitudes (below 20–25 m), minimizing their exposure to turbine rotors. Mid-Range Echolocators (MRE) use intermediate-frequency calls, foraging in semi-open habitats like forest edges and open woodlands, with flight altitudes ranging from 1 to 50 m, occasionally intersecting with turbine rotor zones. Long-Range Echolocators (LRE) produce low-frequency, narrowband calls adapted for open spaces, flying at higher average altitudes (40–180 m), which frequently overlap with

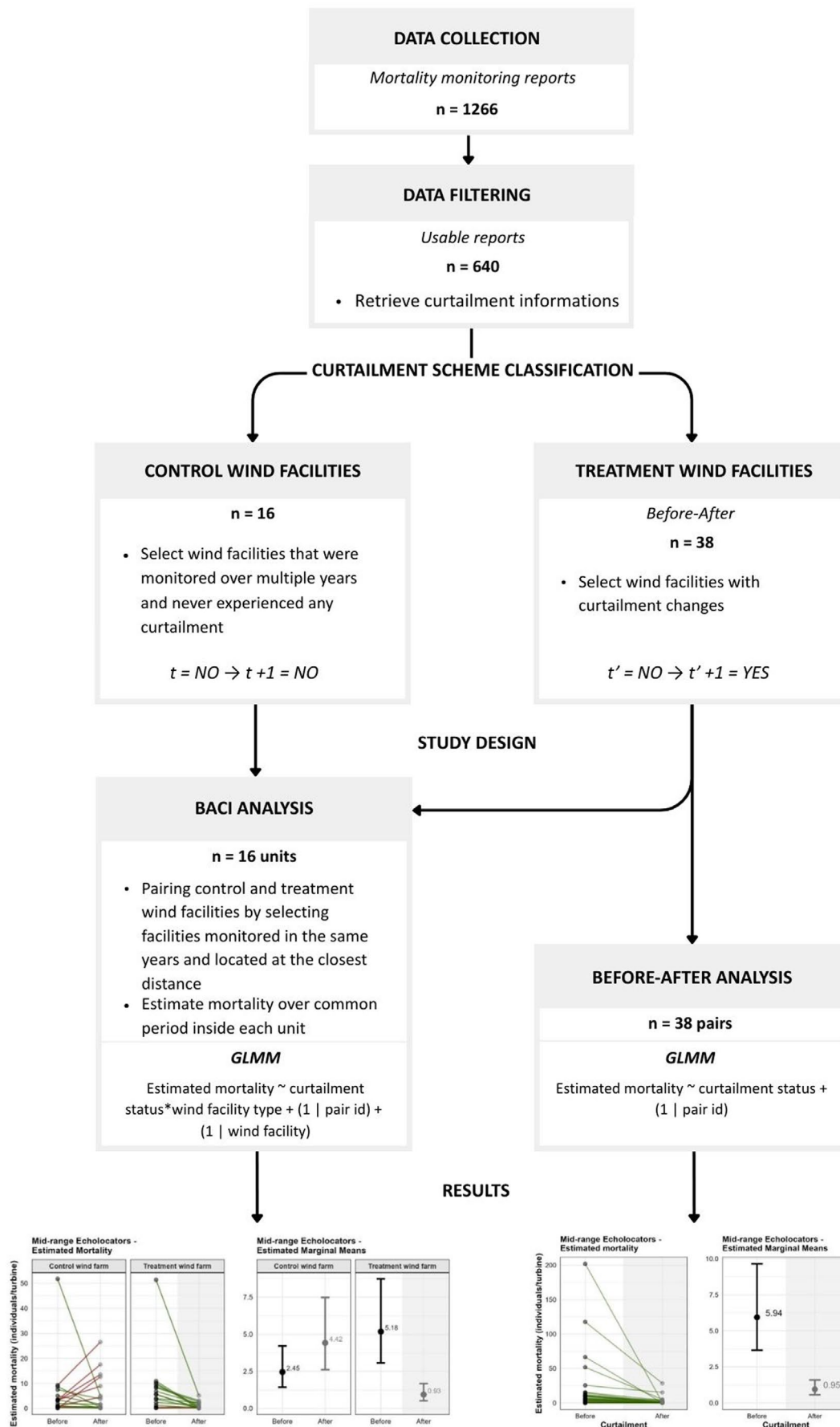


FIGURE 1 Workflow of BACI and before-after analyses.

turbine rotor-swept areas (Rodrigues et al., 2015). Analysing mortality by guild is essential for understanding the differential impacts of wind turbines on bat communities, as it enables targeted mitigation strategies and a nuanced assessment of curtailment effectiveness across functional guilds.

The species identified in selected sites for the BACI and before-after experiments were assigned to functional guilds as follows: (i) **Short-Range Echolocators (SRE)**: *Barbastella barbastellus*, (ii) **Mid-Range Echolocators (MRE)**: *Pipistrellus pygmaeus*, *P. pipistrellus*, *P. nathusii*, *P. kuhlii* and (iii) **Long-Range Echolocators (LRE)**: *Cnephaeus serotinus*, *Nyctalus leisleri*, *N. noctula*, *Vespertilio murinus*. However, SRE were ultimately excluded from comparative analyses, as only a single mortality event was recorded within this functional guild across all sites meeting the study criteria.

Among the bird carcass observed at studied wind facilities, we selected species that conduct their migrations almost exclusively at night, with the aim of assessing whether curtailment measures implemented to protect bats could also effectively reduce collision-related mortality for these species. This classification was based on a comprehensive review of reference databases and scientific literature describing avian migration and activity patterns (Dupuy & Sallé, 2022; Tobias et al., 2022). Only species whose pre- and post-nuptial migrations occur predominantly or entirely at night were included in this analysis, as these species are most likely to benefit from nocturnal curtailment measures. The following species were classified as nocturnal migrants in this study: *Acrocephalus scirpaceus*, *Anas crecca*, *Anas platyrhynchos*, *Ardea cinerea*, *Asio otus*, *Cuculus canorus*, *Coturnix coturnix*, *Erithacus rubecula*, *Ficedula hypoleuca*, *Hippolais polyglotta*, *Muscicapa striata*, *Phoenicurus ochruros*, *Phylloscopus collybita*, *Regulus ignicapilla*, *Regulus regulus*, *Regulus* sp., *Saxicola rubetra*, *Streptopelia turtur*, *Sylvia borin*, *Tyto alba* and *Turdus philomelos*.

2.3 | Mortality estimation

Mortality estimates were generated using the GenEst package (Dalthorp et al., 2018) and the Evidence of Absence (eoa3) package (Dalthorp et al., 2017; Huso et al., 2015) in the R programming environment (R Core Team, 2024). GenEst is a generalized mortality estimator that adjusts the number of detected carcasses based on observer detection probability, carcass persistence between searches, the probability that a carcass falls outside the search area, and the timing of searches. Developed by the US Geological Survey, GenEst is widely regarded as one of the most robust estimators available, as demonstrated in comparative studies (Rabie et al., 2021; Ravache et al., 2024; Thurber et al., 2022). It is particularly well-suited for accounting for variations in survey intervals and persistence test visits (Ravache et al., 2024). Evidence of Absence, also developed by the USGS, employs a Bayesian approach based on similar parameters to estimate plausible mortality even when zero carcasses were observed (Dalthorp et al., 2017). This method is especially useful when carcass counts are zero or very low, as GenEst

estimates may become unstable or uninformative in such cases (Rabie et al., 2021).

GenEst was used to estimate mortality numbers when more than two carcasses were observed during a survey for a given wind facility, while Evidence of Absence was applied when zero or one carcass was detected. A search effectiveness model was fitted using the pkm function. Since the French standardized monitoring protocol only requires a single carcass search during search effectiveness experiments, the parameter k (i.e. the probability of detecting a carcass in a subsequent search if it was missed in the first) was arbitrary fixed at 0.67 ($k_{\text{Fixed}} = 0.67$), because carcasses not found on the first search may become more difficult to find due to their decomposition. Carcass persistence models were fitted with a Weibull family, or an exponential family when the model did not converge. As the probability of carcasses falling within the mandatory survey radius was unknown and impossible to estimate with the raw data collected from the reports, the Density Weighted Proportion (DWP) was set to 0.7, assuming that 70% of collision fatalities fell within the search area, which is in the range of previous studies (Smallwood, 2013). Given that this study aims to compare estimates from different sites and before/after curtailment, this fixed DWP correction factor has minimal impact on these relative comparisons.

To assess mortality across different species groups, estimates were generated separately for each group. The calcSplits function in GenEst was used to partition total mortality among guilds. As no equivalent function exists in eoa3, Evidence of Absence estimates were adjusted by the observed mortality proportion for each guild over the entire dataset. For example, if LRE accounted for 5% of observed mortality, the Evidence of Absence estimate for that guild was multiplied by 0.05 to derive a guild-specific mortality estimate. A total of 5000 mortality estimates were generated for each wind facility. The median mortality estimate was retained as the response variable in subsequent models. More frequent surveys, higher search effectiveness and longer carcass persistence result in more consistent estimates across iterations. Uncertainty in these estimates was quantified using the coefficient of variation (CV), calculated as the ratio of the standard deviation to the mean. This approach standardizes variability relative to the magnitude of the estimates, ensuring that uncertainty is interpreted in a relative rather than absolute context. Mortality estimates were calculated at the wind facility level and then standardized per turbine by dividing the total estimated mortality by the number of turbines monitored.

2.4 | Before-after control-impact analyses

We used a before-after control-impact (BACI) design to assess the effect of turbine curtailment on bat mortality at wind facilities. From the various reports collected, we identified wind facilities that had been monitored once before and once after the implementation of a curtailment strategy. Each 'treatment' site (with curtailment) was

paired with a 'control' site that had also been monitored over two different years but without curtailment in either period. If the curtailment protocol was not properly implemented for all or part of the monitoring period, the affected wind facility was excluded from the analyses. Control sites were selected such that mortality monitoring was conducted during the same years as at treatment sites, while also minimizing the overall geographic distance between paired treatment and control sites. For each BACI unit (treatment before - treatment after - control before - control after), bat mortality

estimates were derived from the same period of the year. In total, 16 BACI units met the selection criteria and were included in the BACI analysis. Within this dataset, the curtailment scheme used an average cut-in speed of 5.5 ± 0.7 m/s (range: 4–6.35 m/s), combined with a temperature threshold of $12.6 \pm 1.9^\circ\text{C}$ (range: 9–17°C; Figure 2). Turbines were programmed to feather their blades (pitching into the wind) when temperature exceeded the curtailment threshold and wind speed was below the threshold, resulting in minimal rotation without full stoppage.

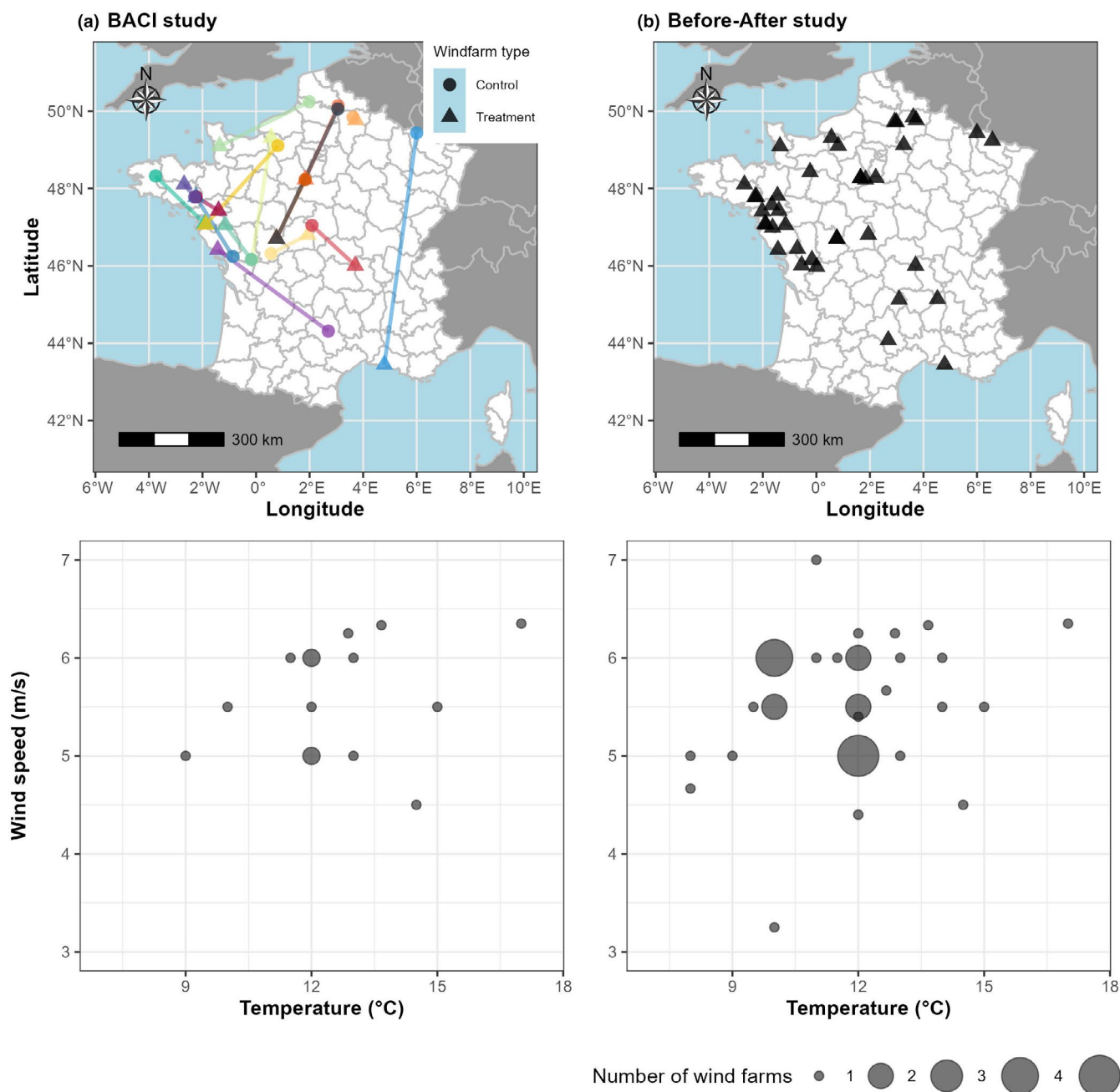


FIGURE 2 Top row: Spatial distribution of wind facilities included in mortality estimation. (a) Geographic locations of paired wind facilities (control and reference) used in the before–after control–impact (BACI) study design ($n = 16$). Control facilities are indicated by circles, and reference facilities by triangles. Paired facilities are connected by lines and share the same colour. (b) Locations of all wind facilities where mortality was estimated both before and after the implementation of curtailment measures, used in the before–after analyses ($n = 38$). Bottom row: Temperature and wind-speed threshold applied at curtailed wind facilities in the BACI (left) and before–after (right) analyses.

2.5 | Before–after analyses

To further investigate the effect of curtailment, we expanded the analysis using a before–after approach focusing exclusively on the guilds where the BACI analysis had identified a significant effect. By removing the requirement for paired control sites, this approach enabled us to include twice as many wind facilities in the analysis. Although inherently less robust than a BACI design (Christie et al., 2020), this strategy substantially increased the spatial coverage and overall generality of the study. This broader analysis included mortality estimates from 38 wind facilities that had been monitored both before and after the implementation of curtailment, without the pairing with control sites. In the before–after analyses, curtailment was triggered when wind speed fell below 5.5 ± 0.7 m/s (range: 3.25–7 m/s) and temperature exceeded $11.7 \pm 1.9^\circ\text{C}$ (range: 8–17°C; Figure 2). For each of these 38 wind facilities, we compared the mortality rates estimated before and after curtailment over the same temporal window. By aggregating these data, we calculated the overall average reduction in mortality due to curtailment, providing a more comprehensive assessment of its effectiveness across a larger sample of wind facilities.

2.6 | Statistical analyses

All models were fitted as generalized linear mixed-effects models (GLMMs) using the *glmmTMB* package in R. We specified a Tweedie distribution with a log-link function to account for the high frequency of zeros and positive skew in mortality estimates (Dunn & Smyth, 2008). Median mortality estimates served as the response variable in all analyses. In order to account for the mortality estimation uncertainty, we incorporated weights into the models, inversely proportional to their coefficient of variation (1/CV). This weighting scheme assigns greater influence to mortality estimates with lower relative uncertainty (i.e. where the standard deviation is small relative to the mean). This weighting approach was chosen to account for the high correlation between bat mortality estimates and their variability (Spearman's $\rho = 0.94$). By using 1/CV weights, we balanced the influence of sites with high mortality (and inherently high absolute variability) while avoiding the underrepresentation of such sites, which are critical for evaluating the effectiveness of wind turbine curtailment measures.

For the BACI framework, we included curtailment status (before/after) and site type (treatment/control) as fixed effects. An interaction term between curtailment status and site type was added to test whether the change in mortality from before to after curtailment differed significantly between treated and control sites. Random intercepts for wind facility and matched pair were included to control for site-specific variability and the paired structure of the data.

The BACI model was specified as:

$$\log(\mu_{ijk}) = \beta_0 + \beta_1 \times \text{curtailment_status}_k + \beta_2 \times \text{park_type}_i + \beta_3 \times (\text{curtailment_status}_k \times \text{park_type}_i) + u_j + v_i$$

where as follows μ_{ijk} is the mean of the Tweedie distribution for the median mortality estimate ME_{ijk} of wind facility i , within BACI unit j and period k ; β_0 is the intercept; β_1 is the fixed effect of curtailment status (before/after); β_2 is the fixed effect of facility type (treatment/control); β_3 is the interaction effect between curtailment status and facility type; $u_j \sim N(0, \sigma_u^2)$ is the random effect of the BACI unit (treatment before–treatment after–control before–control after); $v_i \sim N(0, \sigma_v^2)$ is the random effect of the wind facility; $ME_{ijk} \sim \text{Tweedie}(p, \mu_{ijk}, \phi)$ follows a Tweedie distribution with mean μ_{ijk} .

For the before–after framework, the model included curtailment status (before/after) as the sole fixed effect. Random intercept for the wind facility was retained to account for variability within and between sites.

The before–after model was specified as:

$$\log(\mu_{ijk}) = \beta_0 + \beta_1 \times \text{curtailment_status}_k + v_i$$

where μ_{ijk} is the mean of the Tweedie distribution for the median mortality estimate ME_{ijk} of wind facility i and period k ; β_0 is the intercept; β_1 is the fixed effect of curtailment status (before/after); $v_i \sim N(0, \sigma_v^2)$ is the random effect of the wind facility; $ME_{ijk} \sim \text{Tweedie}(p, \mu_{ijk}, \phi)$ follows a Tweedie distribution with mean μ_{ijk} .

Residuals and R-squared of the fitted models were checked with the *performance* package. Statistical significance was assessed at the 5% level ($\alpha = 0.05$). Predicted mortality estimates for treatment and control group, before and after curtailment, were obtained using the *emmeans* package. This package calculates least-squares means (also known as marginal means) on the log scale, adjusted for the model's fixed and random effects, while accounting for the inverse coefficient of variation (1/CV) weights. These marginal means were then back-transformed to the original response scale. The difference ratio before and after curtailment was calculated using the contrast function from *emmeans* package. The percentage difference was calculated as $1 - \left(\frac{1}{\text{ratio}}\right) \times 100$, where the ratio represents the before-to-after mortality on the log scale. 95% confidence intervals for these percentages were derived by back-transforming the log-scale confidence intervals of the ratios, accounting for the asymmetry inherent to log-transformed data.

Although the models do not include explanatory variables—since the before–after and BACI designs inherently control for other conditions by comparing the same sites before and after the intervention—we provide descriptive statistics for key site characteristics. These include the proportion of forest area, built area, aquatic area, open natural areas and agricultural area within a 1000 m buffer around the turbines, as well as altitude, distance from the nearest coast, facility age, rotor area, ground clearance and total turbine height. These characteristics are classified into three groups: Control facilities, Treatment facilities in the BACI analyses, and additional Treatment facilities from the before–after analyses.

3 | RESULTS

3.1 | BACI analyses

The BACI analyses included 30 distinct wind facilities in the analysis, with a total of 60 site-years of mortality monitoring (Figure 2). Specifically, 15 treatment-control pairs were established: each treatment site was paired with a control site. In addition, a 16th BACI unit was created because two wind facilities were monitored for 2 years as a control (before curtailment) and 1 year as a treatment (after curtailment implementation) and served both as control and treatment pairs. The average distance between paired treatment and control wind facilities was 235 km (Figure 2). Monitoring period and duration for each pair are presented in Appendix S1.

According to the results of the BACI GLMM model (see Appendix S2), the predicted number of LRE fatalities per turbine over the monitored period at treatment turbines decreased from 0.83 estimated mortality per turbine (before) to 0.13 (after), representing an 84% reduction (95% CI: [74%, 90%]), while control turbines showed no significant difference between the two periods (Figure 3, Appendix S2). Among the treatment sites, only 3 out of 16 exhibited an increase in predicted mortality after curtailment implementation. These 3 sites exhibited mortality rates among the lowest recorded in the dataset both before and after the intervention (<0.3 estimated mortality per turbine). The interaction term (Before $\times$ Treatment) was significant ($\beta=1.83$, $p<0.01$), indicating that the difference in mortality at treated wind facilities before and after curtailment implementation was significantly greater than at control sites.

For MRE, the interaction term was significant ($\beta=2.30$, $p<0.01$). Predicted fatalities at treatment turbines dropped from 5.18 (before) to 0.93 (after), an 82% average reduction (95% CI: [73%, 88%]), compared to an 80% increase (95% CI: [29%, 151%]) at control turbines (from 2.45 to 4.42, Figure 3, Appendix S3). Only two treated sites exhibited an increase in mortality, with the largest observed increase rising from 0.2 to 0.6 predicted individuals per turbine.

For nocturnal migratory birds, predicted mortality at treated sites decreased after curtailment, from 1.73 to 0.51 (Figure 3, Appendix S3). However, a reduction was also observed at control wind facilities (from 0.99 to 0.46), and the interaction term was not statistically significant ($\beta=0.45$, $p=0.27$).

3.2 | Before–after analyses

Before–after GLMM analyses, conducted on 38 before–after wind facility pairs (Figure 2), revealed a significant correlation between

curtailment and reduced bat mortality (Figure 4, Appendix S4). For long-range echolocators (LRE), the predicted number of mortalities per turbines decreased from 0.41 (before) to 0.07 (after, Figure 4, Appendix S5), representing an 83% average reduction in mortality (95% CI: [76%, 88%], $\beta=2.20$, $p<0.001$, Appendix S4). Similarly, mid-range echolocators (MRE) exhibited an 84% reduction in mortality (95% CI: [79%, 88%]), with predicted mortality dropping from 5.94 (before) to 0.95 (after) ($\beta=1.84$, $p<0.001$). The high explanatory power of the models (marginal R^2 : 0.27–0.26; conditional R^2 : 0.85–0.91 for LRE and MRE, respectively) indicates that curtailment was a strong predictor of mortality reduction across both bat guilds.

3.3 | Facilities characteristics

Site characteristics, including land cover proportions within a 1000 m buffer, altitude, distance from the nearest coast, facility age, rotor area, ground clearance and total turbine height, are presented for Control facilities, Treatment facilities in the BACI analyses, and additional Treatment facilities from the before–after analyses in Appendix S6.

4 | DISCUSSION

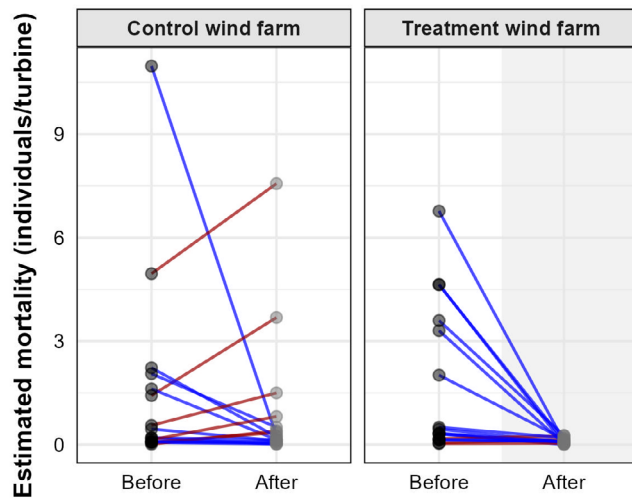
Our work presents the first large-scale curtailment effectiveness test in Europe, using standardized mortality monitoring and estimation coupled to a before–after control–impact framework, ensuring both scientific rigour and practical applicability.

4.1 | Groups mortality estimates

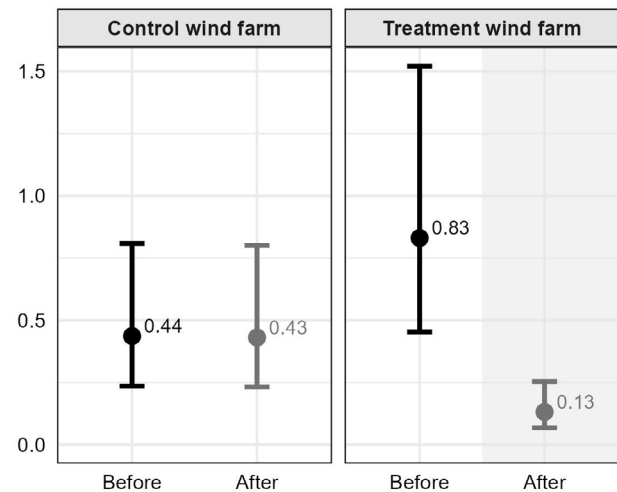
Mid-range echolocators (MRE) exhibited the highest predicted mortality rates, while long-range echolocators (LRE) showed mortality estimates roughly 10-fold lower. However, the lower mortality of LRE compared to MRE does not necessarily reflect lower vulnerability. Instead, it may mirror population size disparities in France, MRE being ten to hundred times more abundant than LRE species (Kerbirou et al., 2015). Thus, raw mortality figures alone do not directly translate to population-level impacts. (Roemer et al., 2017). Mortality estimates for each species group were calculated over standardized, site-pair-specific time windows to ensure comparability between wind facilities, but these periods do not cover the entire annual mortality; thus, the reported values should not be interpreted as absolute mortality rates for either curtailed or non-curtailed turbines.

FIGURE 3 Results from the BACI analyses. Left column: Median mortality estimates (in number of individuals per turbine) for long-range (top), mid-range echolocating bats (middle) and nocturnal migratory birds (bottom) at treated sites (with curtailment, right panel) and paired control sites (without curtailment, left panel) during 2 years of monitoring conducted over the same period within each 4 site-year pairs. Blue lines indicate a decrease in estimated mortality between years, red lines indicate an increase. Right column: Estimated marginal mean of mortality (mean and 95% confidence intervals) from the BACI GLMM for each group (reference and control sites) across the study period. In both columns, grey background represents the curtailed period.

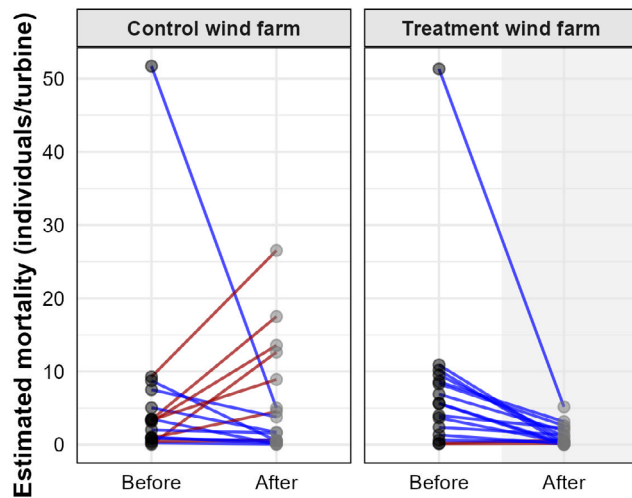
Long-range Echolocators - Estimated Mortality



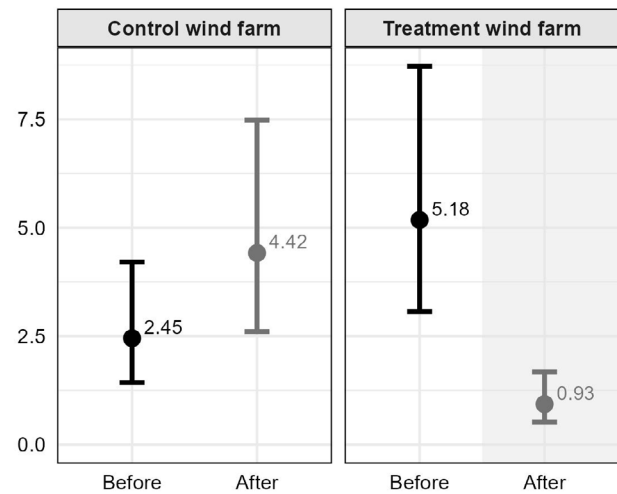
Long-range Echolocators - Estimated Marginal Means



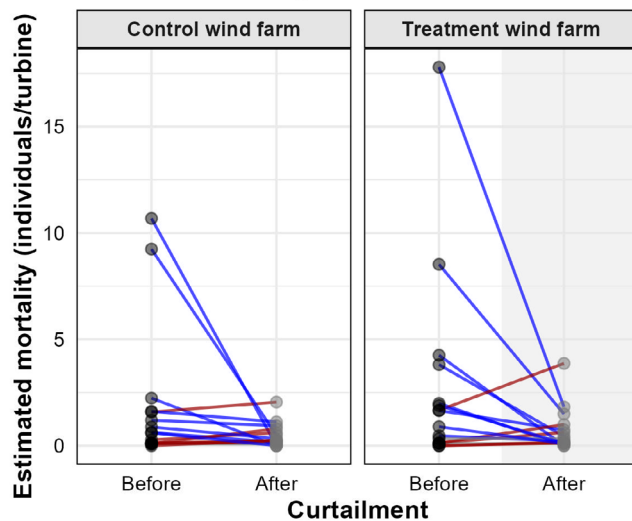
Mid-range Echolocators - Estimated Mortality



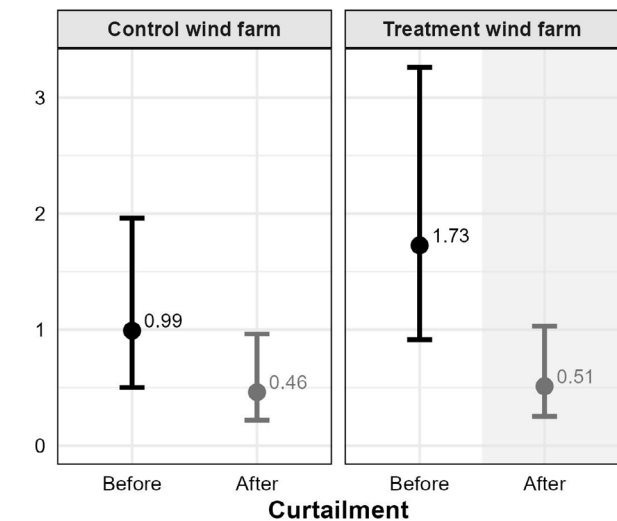
Mid-range Echolocators - Estimated Marginal Means



Nocturnal migratory birds - Estimated Mortality



Nocturnal migratory birds - Estimated Marginal Means



Curtailment

Curtailment

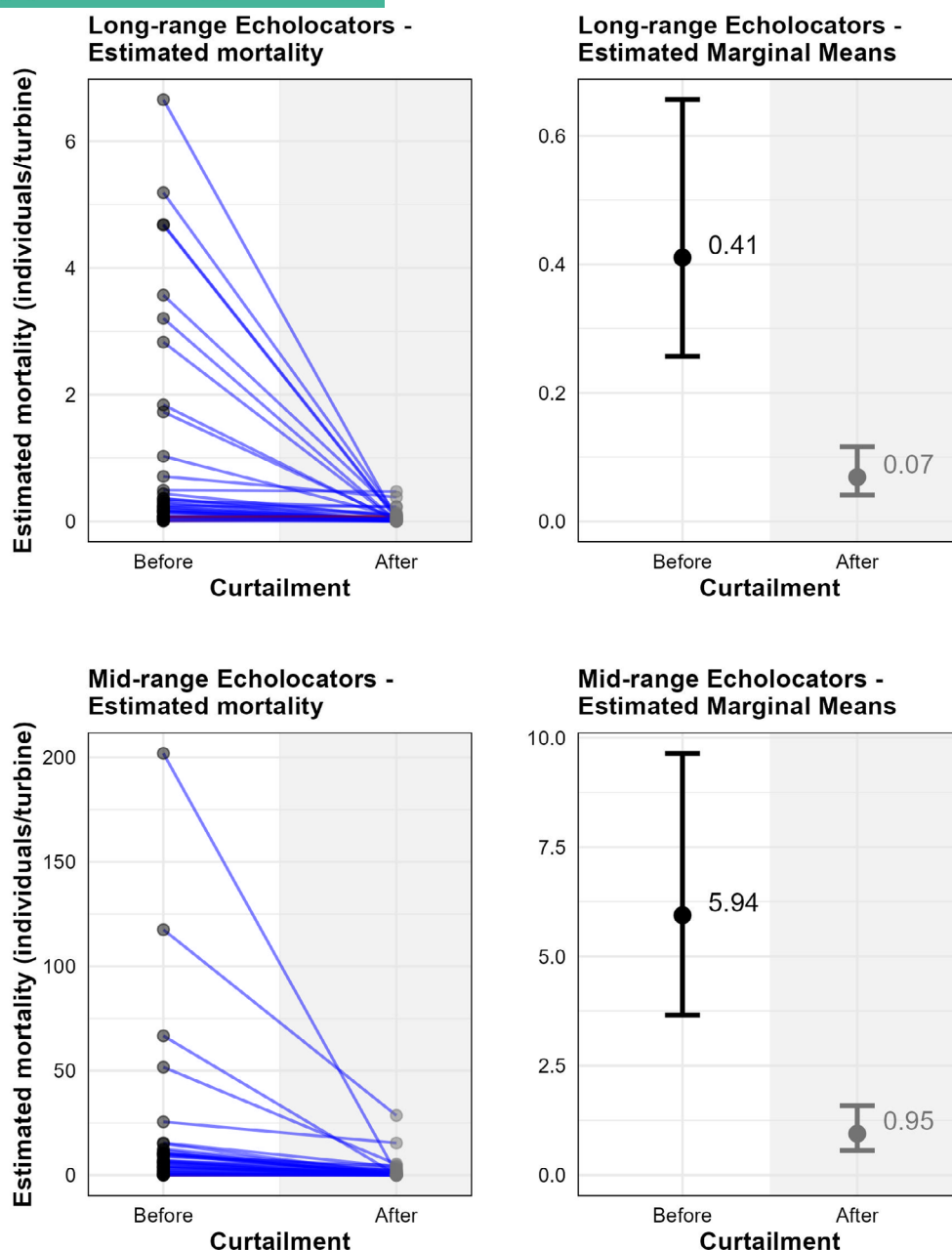


FIGURE 4 Results from the before–after analyses. Left column: Median mortality estimates (in number of individuals per turbine) for long-range (top) and mid-range (bottom) echolocating bats at sites where curtailment was applied. Blue lines indicate a decrease in estimated mortality between years; red lines indicate an increase. Right column: Estimated marginal mean of mortality (mean and 95% confidence intervals) from the before–after GLMM before and after curtailment. In both columns, grey background represents the curtailed period.

4.2 | Effectiveness of curtailment to reduce mortality

Results from the BACI analysis showed that the predicted mortality reductions for LRE and MRE bats at curtailed wind facilities exceeded those in control sites. For LRE, treatment turbines experienced an 84% reduction on average, while mortality remained stable on control sites. Similarly, MRE mortality at treatment turbines dropped by 82%, while it tended to increase at controls without a significant difference. The BACI design confirmed that

the observed mortality reduction is specifically attributable to curtailment, isolating its effect from natural variability through control sites. The before–after analysis, conducted on a larger sample of 38 wind facilities monitored before and after curtailment implementation, corroborates and strengthens the BACI findings. The BA results mirrored the BACI findings, with average decreases of 83% (LRE) and 84% (MRE), as the BACI data were a subset of the BA dataset. Given that the BACI design previously demonstrated that these reductions are directly attributable to the curtailment measures, the BA results can thus be interpreted

as evidence of curtailment effectiveness at a broader scale for these two bat functional guilds.

We also evaluated whether curtailment measures—primarily designed to reduce bat mortality—might confer incidental protection to nocturnal migratory bird species, given their overlapping activity periods. The BACI analysis revealed that current bat-targeted curtailment protocols do not reduce mortality for nocturnal migratory birds. One plausible explanation is that the meteorological thresholds used to trigger curtailment for bats do not align with the migration conditions of nocturnal birds. While some radar-based studies have demonstrated that warm weather conditions correlate with increased nocturnal migration intensity in birds (Schekler et al., 2024)—a pattern that also enhances bat activity (Barré et al., 2023)—a European study revealed that the number of bird passages was positively associated with stronger tailwind (Nilsson et al., 2019), a factor that does not align with the environmental cues driving bat activity. Increasing wind speed not only influences migration intensity but also alters the flight altitudes of nocturnal migrants, increasing collision risks with human infrastructure under specific wind directions (Hamer et al., 2021). These distinct behavioural responses to wind conditions likely contribute to the inefficacy of bat-optimized curtailment measures in protecting nocturnal migratory birds. This emphasizes the need for species-specific additional mitigation strategies to address avian collision risks at wind facilities.

Although curtailment markedly reduces bat fatalities, residual mortality may still have population-level consequences. Since bats exhibit low fecundity and slow population growth, even small increases in adult mortality can adversely affect population viability and conservation status (Frick et al., 2017; Friedenberg & Frick, 2021; Péron, 2013). Consequently, mitigation effectiveness should be evaluated not only in terms of % of mortality reduction but also in terms of whether residual mortality (i.e. number of fatalities relatively to population size and annual growth rate) remains demographically sustainable. This highlights the need for precautionary curtailment thresholds and population viability assessments to ensure that mitigation measures are compatible with long-term conservation objectives.

4.3 | Comparison to previous studies

Our results indicate an even greater reduction in bat mortality following curtailment implementation than previously documented. For instance, Whitby et al. (2024), employing a control treatment design across six wind facilities over a 10-year period, reported a 62% average reduction in bat mortality (95% CI: 54%–69%) using a curtailment scheme based solely on a 5 m/s wind speed threshold—a value comparable to the 5.5 m/s average threshold applied in our study. Similarly, in a meta-analysis of 36 surveys across 17 wind facilities, Adams et al. (2021) found a 63% decrease in mortality under curtailment, using wind-speed-only thresholds ranging from 4.0 to 7.0 m/s. The only other European BACI study, to our knowledge, was conducted by Măntoiu et al. (2020). Their work, focused on a

single wind facility, found a 78% reduction in mortality when setting a cut-in speed of 6.5 m/s during the high-risk period from July 15 to September 15 on the 10 most impacting turbines, a result closer to our study. The greater reduction in mortality we observed may be attributed to the localized definition of curtailment thresholds. By setting cut-in wind speeds and temperature thresholds based on bat activity recorded at nacelle height, this approach accounts for natural variability in bat responses to meteorological conditions and the specific requirements of local species, potentially enhancing the effectiveness of mitigation measures. While the relationship between recorded activity and collision risk remains debated (Behr et al., 2023; Peterson et al., 2025; Solick et al., 2020; Voigt, Scherer, & Runkel, 2022), our findings demonstrate that using acoustic activity to inform curtailment thresholds effectively reduces bat mortality. However, further research is needed to elucidate the mechanistic links between activity levels and collision risk. Advanced algorithms using real-time acoustic activity data or predictive models of bat activity could further refine curtailment protocols, potentially reducing fatalities beyond the levels achieved by current threshold-based methods.

4.4 | Impact on energy production

Previous studies showed that increasing the cut-in speed enhances bat protection and reduces mortality (Adams et al., 2021; Whitby et al., 2024), but it also increases energy production losses. By locally adapting these thresholds, it is possible to optimize the balance between effective protection and minimal operational impact, avoiding unnecessary over-mitigation when risks are lower. While our study lacked data to quantify the energy production losses associated with curtailment, the targeted nature of the studied mitigation strategy—restricted to specific periods of the year, nighttime only, and under combined wind speed and temperature thresholds—may significantly limit operational downtime. For instance, Martin et al. (2017) demonstrated that incorporating temperature into mitigation protocols during high-risk periods decreased energy losses by 18%, resulting in an approximative 3% energy loss over the curtailed period.

4.5 | Study strengths and generalizability of findings

Our study, which includes a large and diverse sample of wind facilities, addresses a critical gap in the transferability of curtailment effectiveness across varied ecological and operational contexts. The study encompassed wind turbines distributed across the Atlantic, Continental and Mediterranean biogeographic regions, capturing the diversity of bat communities found in France. Turbines, monitored over 5 years, spanned broad gradients of landscape context and turbine characteristics, including substantial variation in age and dimensions (see Appendix S6). Such extensive ecological, technical

and temporal coverage offers a rare opportunity to disentangle the drivers of bat mortality and assess their consistency across contrasting environmental, operational and regulatory conditions. Importantly, the use of a before–after control-impact (BACI) design ensures that observed mortality reductions are attributable to curtailment rather than confounding temporal or environmental factors, providing a more robust causal inference than simple before–after comparisons. As the largest study of its kind in Europe, it offers a more generalizable assessment of curtailment impacts, reducing the risk of context-specific biases that can arise from single-site or small-scale investigations. This breadth, combined with the rigour of the BACI framework, strengthens confidence in applying these findings to other wind energy facilities, where local conditions may differ but underlying patterns of bat-turbine interactions remain consistent.

AUTHOR CONTRIBUTIONS

Andréas Ravache, Christian Kerbiriou and Brice Normand conceived the ideas, designed the methodology and secured fundings; Brice Normand and Christian Kerbiriou supervised the study; Camille-Amélie Sand, Clara Mailhol and Andréas Ravache curated the data; Andréas Ravache, Clara Mailhol, Camille-Amélie Sand, Elise Sivault, Fabien Verniest, Cyrielle Ballester, Kévin Barré, Aurélien Besnard and Christian Kerbiriou analysed the data; Clara Mailhol and Andréas Ravache created the visualizations; Andréas Ravache led the writing of the manuscript; all authors contributed to writing, review and editing and validated the results; all authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from data. InDoRES repository for before–after control-impact analyses: <https://doi.org/10.48579/PRO/BKCHBQ> (Ravache, 2026a) and before–after analyses: <https://doi.org/10.48579/PRO/GA0MZZ> (Ravache, 2026b).

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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: Monitoring period and duration of each 4 site-years pairs used in BACI analyses.

Appendix S2: Results from the GLMM BACI analysis (log scale). The interaction term, testing the difference in mortality trends between treatment and control sites, is shown in bold.

Appendix S3: Number of bat carcasses predicted by GLMM per control and treatment wind facilities, before and after curtailment, for each bat guild.

Appendix S4: Results from the GLMM Before-After analysis (log scale). The fixed effect for curtailment status (before vs. after), testing the change in mortality following implementation, is shown in bold.

Appendix S5: Number of bat carcasses predicted by GLMM before and after curtailment, for each bat guild.

Appendix S6: Histograms showing the distribution of land cover proportions (forest, built, aquatic, open natural, and agricultural areas within a 1000m buffer), altitude, distance from the nearest coast, facility age, rotor area, ground clearance, and total turbine height. Colours represent facility groups: Blue=Control facilities, Green=Treatment sites in the BACI analyses, Orange=Additional treatment sites in the Before-After analyses.

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