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Research article

Habitat and site age drive carcass persistence at wind energy facilities: Evidence from a large-scale analysis

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ABSTRACT

Accurately estimating wind turbines' direct impact on biodiversity remains challenging, as many carcasses are scavenged or displaced before detection. This bias is often assessed by placing carcasses around turbines, then integrated into fatality estimators. Given the limited number of carcasses used in studies, identifying key factors affecting persistence is essential to select relevant variables to account for. The development of robust predictive models could ultimately replace this approach. To this end, we aggregated over 10,000 carcass persistence records from France and used parametric survival models to evaluate the effects of habitat, weather, wind facilities, and carcass characteristics. Our results showed that the exponential distribution poorly fits carcass persistence over time, despite being assumed by most fatality estimators. Median persistence time was only 1.91 days. Survival models revealed significant effects of habitat and wind facilities variables: persistence increased with hedgerows length and urban area extent, but decreased with facilities age and the extent of forests, aquatic, and open natural areas. Birds persisted significantly longer than rodents. Meteorological variables had no effect, but carcasses persisted significantly longer in summer, followed by spring, and shortest in autumn. Despite these significant effects, the low explanatory power of our model suggests that carcass detection probability and removal by scavengers is poorly predicted by these variables alone. These results highlight that modeling alone cannot reliably predict persistence and cannot replace field-based trials. Instead, local persistence estimates should be integrated into robust fatality estimators allowing the appropriate distribution function to be selected.

1. Introduction

The rapid expansion of wind energy worldwide, growing by 10-20% per year, constitutes a pivotal strategy to address the increasing energy demand while minimizing greenhouse gas emissions (IRENA, 2023; Kumar et al., 2016). However, despite its well-documented environmental and socio-economic advantages, wind energy production is not without ecological drawbacks, leading to a complex green-green dilemma (Gasparatos et al., 2017; Voigt et al., 2019, 2024). Indeed, the installation and operation of wind turbines have demonstrated pronounced direct and indirect effects, particularly studied and marked for bats and birds, including loss of habitat functionality (Barré et al., 2018; Zimmerling and Francis, 2016), local displacement (Leroux et al., 2022), and direct mortality due to collisions with turbine blades (Nilsson et al., 2023; Smallwood, 2007, 2013). Direct mortality of bats and birds can have a significant, yet understudied, impact on populations (Duriez et al., 2023; Frick et al., 2017). Accurately estimating these impacts is critically important as it enables the comparison between studies, identification of the most affected species, determination of mortality hotspots, and the implementation of effective mitigation strategies. Furthermore, precise fatality estimates can influence policy decisions and support the development of deterrent technologies that reduce

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fatalities (Zeng et al., 2025).

Fatalities of birds and bats is generally estimated through post-construction mortality monitoring at wind facilities, during which an observer conducts repeated visits within a certain radius around the turbines over a specified period (Arnett et al., 2008; Smallwood, 2007; USFWS, 2012). Yet, estimating bird and bat fatalities caused by wind turbines remains a challenging task, as the observed carcasses under the turbines represents only a fraction of the actual fatalities they cause (Smallwood, 2007). Several factors can influence the proportion of carcasses found during searches. Firstly, the detection of carcasses by observers can be imperfect, leading to only a portion of the present carcasses being reported (Philibert et al., 1993), hereafter referred to as "*searcher efficiency*". Secondly, it is likely that a dead individual may have been scavenged or displaced by a predator, or consumed by detritivores between searches (Wobeser and Wobeser, 1992). This probability of disappearance increases with time; thus, the longer the interval between searches, the higher the likelihood that the carcass will have disappeared. The period during which a carcass remains detectable will henceforth be termed "*carcass persistence*". The topography or vegetation can also, in some cases, prevent a portion of the area under the turbines from being surveyed due to low visibility or inaccessibility. Finally, despite the density of carcasses decreasing with distance from the turbine, not all carcasses fall within the search area, and the probability of finding them depends on the turbine height and the weight of the individual (Arnett et al., 2008; Hull and Muir, 2010; Maurer et al., 2020).

Searcher efficiency and carcass persistence are often estimated through two dedicated experiments conducted at the monitoring site during fatality surveys. The first experiment typically involves randomly placing carcasses around the turbines to estimate their rate of disappearance, and the second involves randomly placing decoys in the search area to test the observers' detection abilities (Bispo et al., 2013; Costantini et al., 2017). The relative density of carcasses around a turbine can be modeled using carcass location data (distance and azimuth). The proportion of carcasses falling outside the searched area can be calculated from these based on the configuration of unsearched area beneath each turbine (Dalthorp et al., 2024; Hull and Muir, 2010; Huso and Dalthorp, 2014). Following the rise of wind energy development and the increasing awareness of its environmental impacts, several estimators emerged, providing fatality estimates corrected for these sources of bias (Dalthorp et al., 2018; Huso, 2011; Korner-Nievergelt et al., 2011; Shoenfeld, 2004). These formulas differ in bias, accuracy, and sensitivity to input parameters (Maurer et al., 2020; Rabie et al., 2021; Ravache et al., 2024).

While searcher efficiency, primarily dependent on the size of the carcass and the vegetation around it, it is relatively easy to estimate and can be significantly improved by using search dogs (Barrientos et al., 2018; Smallwood et al., 2020). Carcass persistence varies greatly between sites and time periods and remains challenging to estimate accurately. Several hypotheses have been proposed to explain this variability. One major factor is carcass removal by scavengers or decomposers, which induces considerable variation in persistence probability over time and between sites (Paula et al., 2015; Rosa et al., 2019). The habitats surrounding the wind turbines play a crucial role in determining the animal communities present in the area, which in turn can influence the types of scavengers that may consume or move the carcasses (Kostecke et al., 2001) and the seasons in which they are most impactful, e.g., when feeding young. Additionally, seasons may affect vegetation density and the likelihood of scavengers locating carcasses, as well as the availability of alternative food sources, thus influencing scavengers' behavior (Bernardino et al., 2022; Villegas-Patraca et al., 2012). Meteorological conditions could also play a role by altering the carcass's attractiveness over time and influence the speed of decomposition by insects and bacteria (DeVault et al., 2004; Shean et al., 1993).

The size of the carcass is also assumed to impact scavengers' ability to fully consume the prey in a single event, to dismember it making it difficult to determine the initial number of carcasses or to remove it from the search area entirely (Barrientos et al., 2018; Bernardino et al., 2022). Empirical studies provide variable results on this factor (Paula et al., 2015). Studies also show contrasting results regarding the effect of the species or type of carcass used in persistence trials (Barrientos et al., 2018; Villegas-Patraca et al., 2012).

Finally, if fatality events occur repeatedly around wind turbines, scavengers may learn to associate these locations with food availability over time, a phenomenon known as associative learning (Shettleworth, 2010). We could therefore expect a negative correlation between carcass persistence and the age of the wind facility. This hypothesis was previously proposed by Kerns et al. (2005), but it was based solely on a comparison between two wind facilities, and it has since never been tested in carcass persistence studies, to the best of our knowledge. The lack of specific research on this topic suggests a gap in the scientific literature regarding long-term scavenger behavior at wind facilities. This point is particularly important when a decrease in carcass observations is noted within a wind facility (Davy et al., 2021). It is crucial to determine whether this decline results from scavenger habituation, leading to reduced carcass persistence and detection, or from an actual decrease in fatality events caused by the avoidance of local bird and bat populations or their decline within the area.

Studies testing the effect of all the previously mentioned factors show considerable variation in their methods and results, complicating their comparison. Additionally, some studies combine data from wind facilities with other human infrastructure such as roads or power lines, whose more linear structure and associated semi-natural habitat, may not lead to similar habituation by scavengers (Barrientos et al., 2018). Moreover, studies on carcass persistence rates along roadsides based on opportunistically found carcasses cannot be rigorously compared due to the lack of information on carcass arrival times (Henry et al., 2021; Santos et al., 2016). Finally, many studies rely on small sample sizes, which raises questions about the generalizability of the obtained results.

In countries with rapidly growing wind energy production, national protocols have been developed to provide guidelines on field methodologies for estimating fatalities while addressing and correcting for carcass persistence and other sources of biases (APA, 2010; MTERD, 2020; MTES, 2018; SNH, 2009; USFWS, 2012). However, there is no consensus on which factors affecting persistence should be included in estimators, nor on which estimator should be used. In France, the implementation of a national protocol since 2018 has enabled the deployment of standardized fatality monitoring and the collection of extensive carcass persistence data around wind facilities (MTES, 2018). Persistence experiments conducted in accordance with these guidelines could allow for a detailed study of persistence, moving beyond case-by-case analysis, to an understanding of the factors affecting carcass persistence in the context of wind energy and in turn to a better design of these experiments. This statistical approach may result in a ranking of the relative importance of variables that, when accounted for, may result in more broadly applicable and reliable fatality estimates. Despite national protocols in several countries, persistence experiments from mandatory post-construction surveys are never aggregated, making broad scale analysis challenging. This study aggregates persistence data from fatality monitoring reports conducted in France using the national standardized protocol, in order to identify the most salient and consistent factors affecting carcass persistence. We used a statistical approach based on parametric survival models to evaluate the influence of habitat and meteorological variables at different spatiotemporal scales, as well as variables specific to carcasses and wind facilities on persistence.

2. Material and methods

2.1. Persistence surveys

Fatality monitoring around onshore wind facilitiesin France is governed by a national environmental monitoring protocol established in 2018 (MTES, 2018). To account for disappearance between consecutive searches, two carcass persistence experiments per monitoring campaign are conducted at different times of the year. According to the national protocol, between 3 and 5 carcasses per turbine, mostly consisting of chicks or mice, are usually dispersed in the surveyed area and their persistence is tracked with repeated visits: once the day after placement and then twice weekly, either until they disappear or for a maximum of 14 days if they remain. These data are then recorded in a fatality monitoring report submitted to the Regional Directorates for the Environment, Planning, and Housing (DREAL), the governmental bodies responsible for implementing environmental and urban planning policies at the regional level.

2.2. Data collection

Fatality monitoring reports conducted as part of post-implementation impact studies of wind facilities were collected from the DREAL in nine different regions of mainland France. Additional data from persistence experiments, carried out as part of fatality monitoring, were also gathered from environmental consultancy firms. A small subset of the data (n = 266) was collected using camera traps in 2021 (n = 73) and 2022 (n = 193), providing a precise estimate of carcass removal time and enabled the identification of the scavengers responsible for removal. Only the data collected after the beginning of the year 2019, corresponding to the homogenization of fatality monitoring and persistence experiments protocols, were included in this study. When available and when the wind facility and turbine number could be identified, the coordinates and date of commissioning of each turbine were retrieved from the French government website (https://www.georisques.gouv.fr/donnees/bases-de-donnees/eolien-terrestre).

In total, we collected the persistence time of 39,107 carcasses, reported from 900 reports conducted at 607 different wind facilities between 2019 and 2023. When the turbine at which the experiment was conducted was not indicated, the coordinates could not be retrieved from the database (e.g. the name provided in the report did not match any of those in the government website), or the explaining variables could not be retrieved, these data were excluded from the analyses. After filtering carcass persistence data according to these criteria, the analysis included 11,576 carcasses collected from 348 reports conducted across 260 different wind facilities between 2019 and 2023. The persistence rate of the filtered data followed a distribution very similar to that of the initial dataset, ensuring that the data to which the model was applied were representative of the original dataset. The mean number of carcasses per report was 33 ± 32 (SD). Monitored facilities offer a good spatial coverage of the national wind facilities distribution (Fig. 1).

2.3. Variables influencing carcass persistence

To test which variables and to what extent they might impact carcass persistence around wind turbines in our dataset, we selected a set of variables that, according to the scientific literature, could affect carcass degradation or removal. Thus, we investigated the effect of the following variables.

- **Habitats:** Distance and area of surrounding habitats classified as *urban*, *open natural*, *agricultural*, *forest*, *hedge*, *road* or *water body*. Indeed, habitats surrounding the wind turbines, are likely to affect the occurrence and movement of scavenger species (Kostecke et al., 2001; Lambertucci et al., 2009; Mata et al., 2017; Pelletier-Guittier

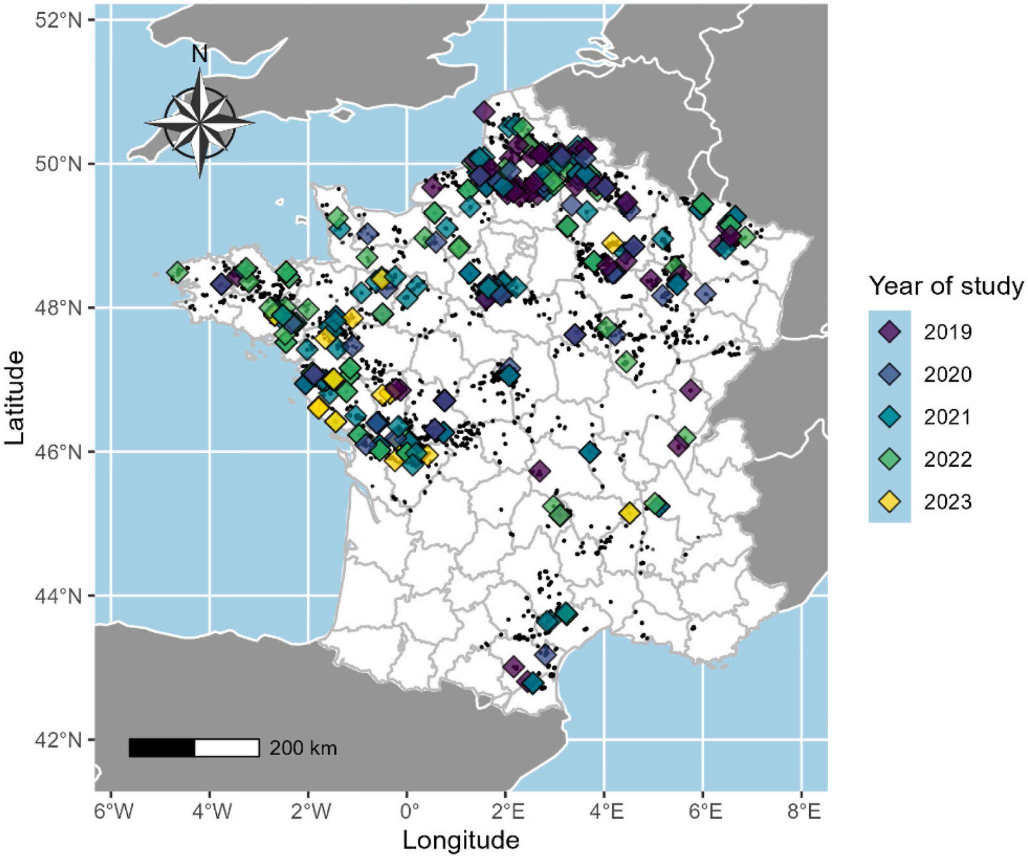

Fig. 1. Distribution map of wind facilities where at least one carcass persistence test was conducted as part of fatality monitoring, with the results used in the analysis of factors affecting persistence. Colored diamonds indicate the location of wind *facilities* where tests were conducted, with colors representing the year of the test. Small black dots show the location of all wind *facilities* in mainland France included in the government database.

et al., 2020). As a wide range of scavenger species was expected, selecting a single biologically appropriate spatial scale was not feasible. Consequently, we implemented a data-driven approach, evaluating multiple buffer sizes (125, 250, 500, 1000, 2000, 3000, and 5000 m) to assess which scale most effectively captured variation in carcass persistence. Additionally, hedge length was extracted in the same buffers from a dedicated french national database (https://geoservices.ign.fr/bdhaie). Data were extracted from the 2021 version OSO layer (https://www.theia-land.fr/en/blog/product/land-cover-map/), a 10-m land use raster dataset based on the analysis of satellite imagery from the Copernicus Program (Thierion et al., 2022).

- **Meteorological variables** (*temperature* in °C, *rainfall* in mm, and *humidity* in %), were expected to affect carcass desiccation, with increased desiccation leading to reduced attractiveness for scavengers (DeVault et al., 2004; Shean et al., 1993). Meteorological variables were averaged over periods of 1 to 10 days after the day of carcass placement in order to select the temporal scale best explaining the carcass removal rates. Daily means (temperature, humidity) or total (precipitations) of meteorological data were extracted at a 0.1° spatial resolution using the weather database from E-OBS (https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php).
- **Season** (*spring*/*summer*/*autumn*/*winter*) in which trials were carried out, susceptible to affect scavengers' activity patterns (Bravo et al., 2023; De Pelsmaeker et al., 2024; Villegas-Patraca et al., 2012). Winter was defined from the winter solstice in late December to the spring equinox in late March, spring from the spring equinox to the summer solstice in late June, summer from the summer solstice to the autumn equinox in late September, and autumn from the autumn equinox to the winter solstice. In the final dataset, 3850 carcasses were monitored in spring, 4907 in summer, and 2819 in autumn;
- **Carcass type** (*rodent* or *bird*) used in carcass persistence trials, previously shown to impact persistence rate (Barrientos et al., 2018). The final dataset contained 6504 birds and 5075 rodents;
- **Carcass weight:** tested in a separate model. Heavier carcasses have been shown to persist at higher rates (Barrientos et al., 2018),
- **Wind facilities age:** the time elapsed since the wind facilities commissioning until the date of the persistence experiment. We hypothesize that the repeated occurrence of mortality events at wind facilities creates predictable anthropogenic food subsidy for scavengers, which may lead to a reduction in carcass persistence over time (Kerns et al., 2005).

2.4. Statistical analyses

The workflow used to estimate the effect of covariates on persistence probability is summarized in Fig. 2.

2.4.1. Choice of family distribution for fitting persistence

In the context of fatality monitoring at wind facilities, carcass persistence is typically estimated through repeated surveys to determine whether the carcasses placed during the persistence experiment remain detectable or have been removed. Consequently, the exact date of carcass disappearance is unknown, but it is known to occur within a given time interval, referred to as interval-censored data (Leung et al., 1997). Additionally, persistence experiments can end before the carcass disappearance event, resulting in right-censored data (Leung et al., 1997). The interval-censored and right-censored nature of persistence data necessitates the use of appropriate models, known as survival models (Kalbfleisch and Prentice, 2011; Leung et al., 1997; Moore, 2016). To describe the probability of carcass persistence over time, we employed parametric survival models that account for both these types of censoring using the "survreg" function from the "survival" package in R. Parametric models require the specification of the underlying statistical distribution, which is determined by one or more parameters (Moore, 2016). To determine the best-fitting distribution for describing our dataset, we fit a null model with each of the following distribution families: exponential, Weibull, log-logistic, log-normal, logistic, and Gaussian, and selected the model with the lowest Akaike Information Criterion (AIC). The log-normal distribution provided the model with the lowest AIC. In addition, the adequacy of the model fit was confirmed by visual inspection through overlaying the model's predicted survival curve with an empirical Kaplan-Meier curve (Supplementary S1). The exponential distribution proved to be the least suitable for describing carcass persistence in our dataset. Specifically, the observed disappearance rates were initially higher during the first few days and then decreased significantly after day 5, deviating from the assumption of a constant rate inherent to the exponential distribution (Supplementary S1). Therefore, we retained the log-normal distribution for further modeling.

2.4.2. Selection of spatial and temporal scales and relative effects of each variable

Prior to building the full model, preliminary analyses were conducted to determine the appropriate spatial and temporal scale to be considered. Although spatial scale selection should ideally rely on species-specific ecological hypotheses, the interspecific variability of identified scavengers and temporal fluctuations in their home ranges led us to determine the optimal spatial scale using an AIC-based statistical approach. Several models were adjusted using habitat proportions at distances of 125, 250, 500, 1000, 2000, 3000, or 5000 m buffer around the turbines where carcasses were set. All habitat variables were analyzed using the same buffer size to determine the effect of habitat on carcass persistence. In addition, we developed separate models using the nearest distance from the turbine to each habitat as an alternative to the proportion of habitat within a buffer. To avoid including highly correlated variables, the proportion and distance to agricultural habitat—the most represented habitat around the sampled turbines—were excluded from the models, as the combined habitat variables account for nearly 100% of the buffer areas when agricultural habitat proportion are considered. Habitat variables (buffer size, distance) included in the final model were selected based on the model with the lowest AIC. The selection of the optimal temporal scale for studying the effect of meteorological variables (averaged over periods of 1 to 10 days following carcass placement) was performed by fitting separate models for temperature, rainfall, and humidity at each of the 10 temporal intervals. For each variable, the temporal scale with the lowest AIC was retained as the best-fitting model.

2.4.3. Modelling

Once spatial scales of habitat variables and temporal scales of meteorological variables were selected, a full model integrating all these variables along with carcass type, season and age of the wind facility was fit using the "survreg" function from the package "survival" (Therneau, 2024). To compare the relative effects of each continuous variable, they were centered to their mean and scaled to have a standard deviation of one. This standardization process ensures comparability between variables by placing them on a common scale, preventing those with larger ranges from disproportionately influencing the model's results. The correlation between continuous variables was assessed using a Spearman correlation test, and it never exceeded an absolute value of 0.5. To mitigate potential issues of model overparameterization, we conducted preliminary analyses to evaluate the informational contribution of interactions between variables (i.e. interactions between season and numeric variables, as well as between carcass type and other numeric variables). Finally, these interaction effects were not retained due to a lack of significant effect and to avoid overparameterization. We used the Nagelkerke R^2 (Nagelkerke, 1991) to evaluate the goodness-of-fit of our parametric survival model.

Persistence probabilities over time were predicted using a survival regression model fit with scaled variables. For each variable, predictions

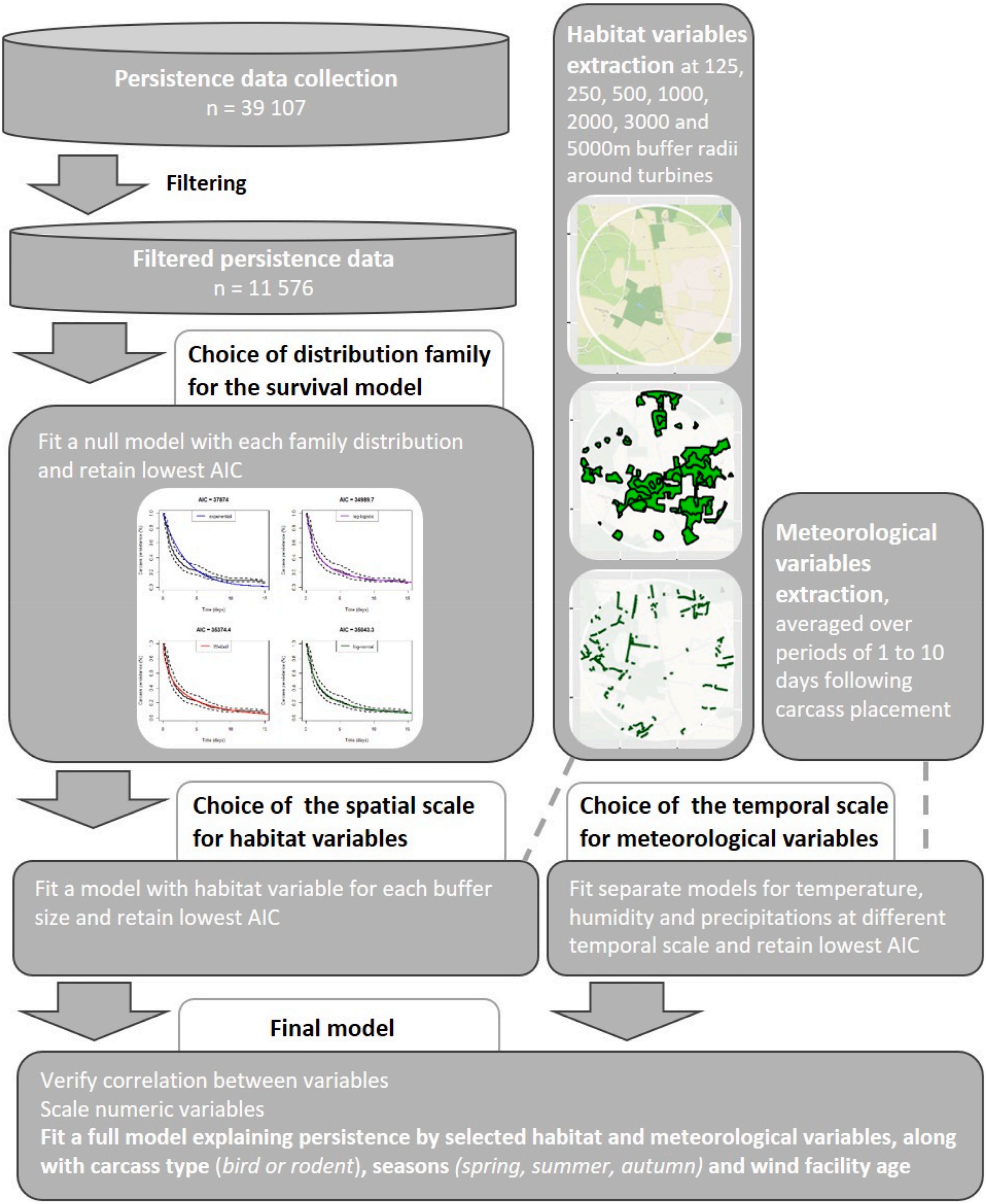

Fig. 2. Workflow used to estimate the effect of covariates on carcass persistence probability. Each step summarizes data processing and modeling procedures applied to aggregated trial data from wind facilities.

were made across 5 quantiles (0.1, 0.3, 0.5, 0.7, 0.9) of the selected explaining variable while keeping other variables at their mean. The predicted values were rescaled back to their original units using the scaling parameters (mean and standard deviation) from the dataset to ensure interpretability. Predicted mean survival times were computed on the original scale for categorical variables using the package “emmeans” (Lenth and Piaskowski, 2017).

2.4.4. Carcass weight

Since carcass weight data were mostly unavailable in the reports, this variable was tested in a separate survival model fit on a subset of the data, comprising 2595 carcass persistence records for which weight information was available. Given the potential for body mass to influence carcass persistence, we aimed to assess whether the observed differences between birds and rodents could be attributed to variations in carcass weight. To do so, we fit a parametric survival model using a similar family distribution as the main model. The model included carcass type (bird vs. rodent) as a categorical predictor, body mass as a continuous predictor, and their interaction term. Since the model contained only one continuous variable, carcass weight was not scaled in the model to allow interpretation on the original scale (grams).

2.4.5. Scavenger guild

To assess whether scavenger type (mammals or birds) showed a preference for specific carcass types (rodents or chicks), a Chi-square test of independence was performed on the observed frequencies of carcass removal.

3. Results

3.1. Global estimation of persistence

3.1.1. Family distribution for fitting persistence

The estimated scale parameter of the log-normal model was 1.35 ($p < 0.001$), indicating deviation from the constant hazard assumption of the exponential model (Kalbfleisch and Prentice, 2011). A scale value greater than 1 in a log-normal model implies a non-monotonic hazard function, with the hazard rate increasing to a peak before decreasing, consistent with a process that is not constant over time. Visual inspection of the survival curves showed that carcass disappearance occurred more rapidly during the initial days than predicted under an exponential distribution (Supplementary material S1).

3.1.2. Persistence probability over time

The survival model estimating carcass persistence over time from the entire dataset yielded the following results (Fig. 3): After one day, 65% of carcasses remained (95% CI: [0.55, 0.76]). After 14 days, only 7.1% of carcasses persisted (95% CI: [0.05, 0.09]). The median persistence time, which represents the time by which half of the carcasses have disappeared, was 1.91 days (95% CI: [1.24, 2.71]).

3.2. Factors influencing global persistence

3.2.1. Spatial and temporal scales selected

Among the models tested to determine the appropriate buffer size for habitat variables, the 1000-m buffer around the turbines resulted in the lowest AIC value compare to other buffer sizes or to the distance to each habitat. Through the process of selecting the appropriate temporal scale for meteorological variables, the following scales were retained based on the lowest AIC values: temperature averaged over the 3 days following carcass placement, precipitation averaged over the 4 days following carcass placement, and humidity on the placement day. The AIC values for each of these models are summarized in Supplementary Material S2.

3.2.2. Variables influencing carcass persistence

Within the 1000 m buffer around the wind turbines where persistence experiments were conducted, the total length of hedgerows and the area covered by urban zones were significantly and positively correlated with an increased carcass persistence rate over time (Fig. 4). In contrast, a higher proportion of natural open spaces, forests or water bodies in the surroundings were negatively correlated with persistence rate. Total length of roads and rails paths and meteorological variables were not significantly correlated with persistence rate in the model. Seasonal differences in persistence were predicted by the model, persistence being higher during summer compared to spring, and higher in spring compared to autumn. Persistence was significantly lower in older wind facilities, and rodents disappeared significantly faster than birds during persistence experiments. The estimates and confidence intervals from the model supporting these findings are summarized in Supplementary Material S3.

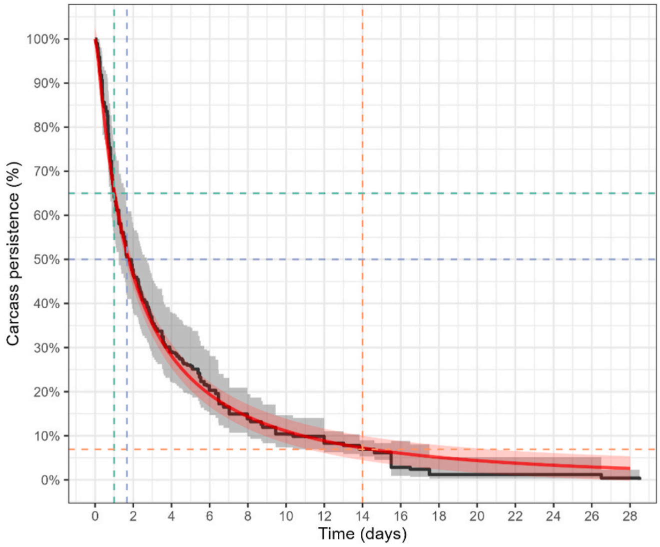

Fig. 3. Survival curve showing the probability of carcass persistence over time. The black curve is a Kaplan-Meier curve, representing the empirical probability of persistence. The red curve represents the prediction of the null survival model adjusted with a log-normal distribution family. The shaded areas represent the 95% confidence intervals for these two curves. The green dashed line represents the probability of persistence after one day, the orange dashed line represents the probability of persistence after 14 days (the recommended duration for persistence trials), and the blue dashed line represents the median persistence probability (i.e., the time at which 50% of the carcasses disappeared on average).

Predicted survival curves describing the influence of variables on persistence probability over time are presented in Supplementary material S4. Additionally, median persistence times for each significant variable and for different values of the explanatory variables are presented in Supplementary material S5. As an example, the model predicts that during summer, 50% of bird carcasses will have disappeared after 2.42 days in a 1-year-old facility, compared to 2.18 days in a facility that has been operational for 12 years, with all other variables held constant. Similarly, the model predicts that during autumn, 50% of rodent carcasses will have disappeared after 0.96 days when the total hedge length within a 1000-m radius is 387 m, while this time increases to 1.97 days when the hedge length reaches 21,110 m. Under the same conditions, our model predicts that a bird carcass would have persisted for 1.37 and 2.8 days, respectively.

Overall, the survival model describing persistence, which includes 12 variables (10 numeric and 2 categorical) and has an R^2 value of 0.11, suggests a modest ability to explain the variability in persistence. Histograms showing the median carcass persistence at each site, stratified by carcass type and season, are provided in the Supplementary Material S6 to illustrate the persistence variability among wind facilities.

The separate survival model fit on the subset of 2595 carcasses

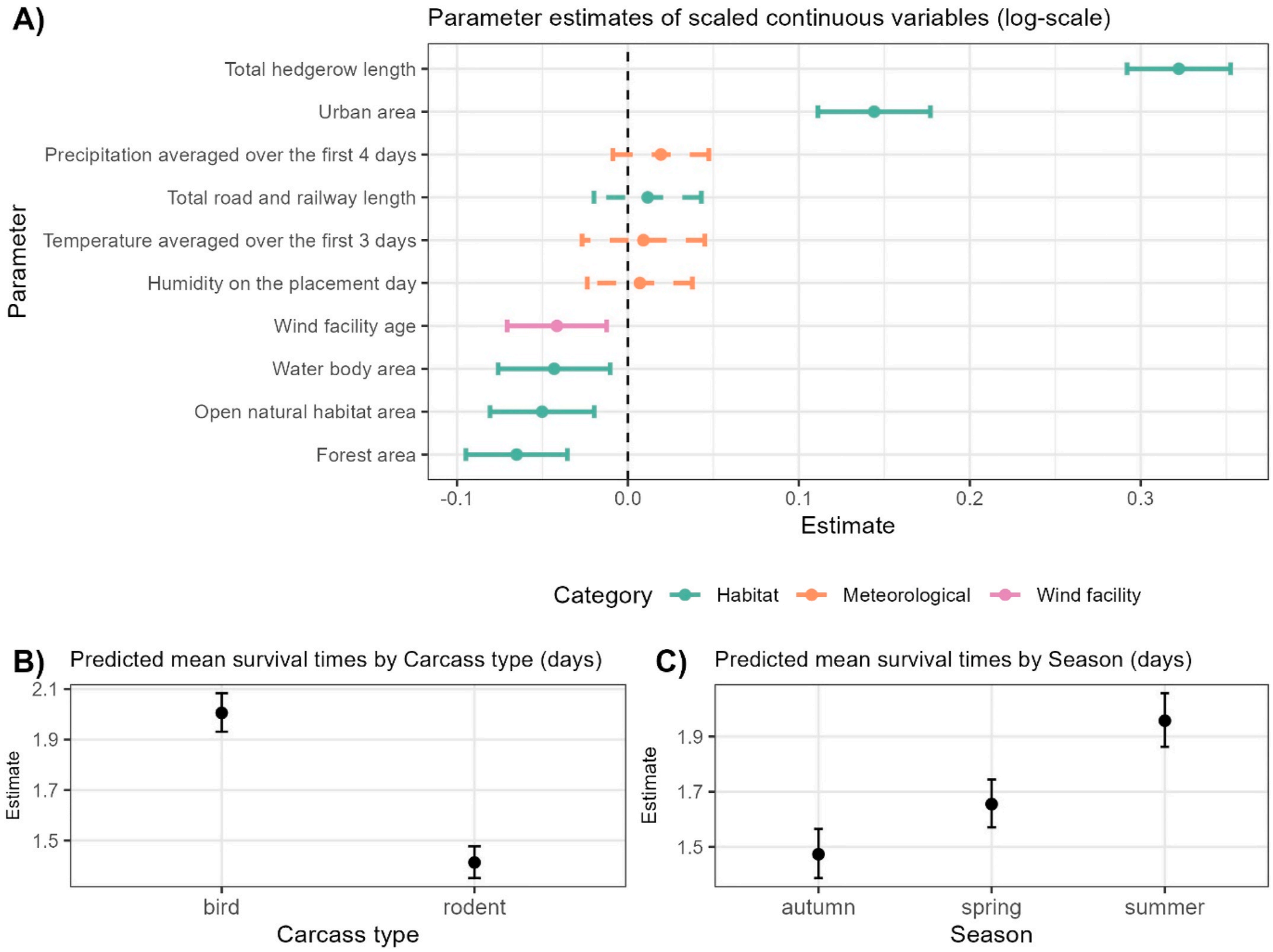

Fig. 4. Estimated model coefficients and predicted mean survival times from a parametric survival model fit to scaled data with a log-normal distribution family. **A)** Parameter estimates with confidence intervals from the full model. Dots represent standardized coefficients for each continuous variable (scaled to mean = 0, SD = 1) on the log scale. Error bars indicate 95% confidence intervals. The vertical dashed line at zero indicates no effect; if the confidence interval of a variable's estimate crosses this line, the effect of the variable is not statistically significant. **B)** Predicted mean survival times in days (dots), back-transformed on the original scale, for the significant effect of carcass type on persistence duration. Error bars indicate the 95% confidence intervals. **C)** Predicted mean survival times in days (dots), back-transformed on the original scale, for the significant effect of season on persistence duration. Error bars indicate the 95% confidence intervals.

revealed a significant negative effect of body mass on persistence time (coefficient = −0.001, 95% CI: [−0.002, −0.001]), indicating that heavier carcasses persisted for shorter durations. Similarly to the global model, carcass type also had a significant effect, with rodents exhibiting shorter persistence times compared to birds (coefficient = −0.90, 95% CI: [−1.16, −0.65]). The interaction between body mass and carcass type was not significant (coefficient = 0.006, 95% CI: [−0.004, 0.016]), suggesting that the effect of body mass on persistence did not differ significantly between birds and rodents.

3.3. Camera traps

Among the 266 carcasses monitored using camera traps, 187 disappeared before the end of the 14-day study period. Of these, 169 removal events were precisely identified within an interval of less than 1 h, while the remaining 18 could not be accurately determined due to camera malfunctions or poor lighting conditions. Among the precisely identified events, 70 removals occurred during the day, and 99 occurred at night.

Among the 266 carcasses monitored using camera traps, 187 disappeared before the end of the 14-day study period, with 169 removal events precisely identified within less than 1 h (70 during the day and 99 at night), while 18 events remained unclear due to camera malfunctions or poor lighting. In 45 cases, the scavenger responsible could not be identified. Excluding unidentified scavengers, 65% of carcass removals were attributed to mammals (red foxes, *Vulpes vulpes*: 37; domestic cats, *Felis catus*: 26; pine martens, *Martes*: 9; , *Canis lupus familiaris*: 5; European badgers, *Meles meles*: 2; unidentified mustelids: 2; brown rats, *Rattus norvegicus*: 2; pine martens, *Martes martes*: 2; European hedgehog, *Erinaceus europaeus*: 1; domestic dog, *Canis lupus familiaris*: 1), 29% to birds (carrion crows, *Corvus corone*: 20; common buzzards, *Buteo buteo*: 18; Eurasian magpie, *Pica pica*: 1; black kite, *Milvus migrans*: 1; cattle egret, *Ardea ibis*: 1), and 3% to humans (including farming activity). The remaining carcasses were decomposed by necrophagous insects, rendering them nearly undetectable. Mammalian scavengers consumed 28 mammal and 31 bird carcasses, while avian scavengers consumed 16 mammal and 10 bird carcasses. The Chi-square test of independence ($\chi^2 = 0.925$, p = 0.336) revealed no significant difference in the proportions of carcass type consumption between scavenger types.

4. Discussion

4.1. Temporal patterns of carcass persistence

The results of this study demonstrate that the exponential distribution is inadequate for describing carcass persistence in our dataset, indicating that carcass disappearance rates vary over time rather than remaining constant. Yet, many estimators used to assess persistence in national protocols for estimating fatalities at wind facilities assume that carcass removal follows an exponential distribution (Erickson et al., 2000; Shoenfeld, 2004). Consequently, these formulas are not appropriate for estimating mortality based on these data, reinforcing the need for more recent estimators like the GenEst estimator (Dalthorp et al., 2018) or Evidence of Absence (Dalthorp et al., 2017). These recently developed estimators allow users to select the survival distribution that best fits carcass persistence data, providing greater flexibility and accuracy in mortality estimation. This adaptability is particularly valuable for addressing variability in persistence rates and ensuring more reliable results.

This study on carcass persistence rates, which gathered an extensive dataset of 11,576 carcasses from 260 French wind facilities, indicates that 35% of carcasses were scavenged or displaced from the search area within a day, and 50% after 1.91 days. Since more than 83% of carcasses had disappeared within one week, which is the average interval between fatality surveys in many countries, and more than 50% after two days, these results highlight the importance of incorporating this correction factor into mortality estimates, because observed carcasses may represent a very low fraction of real fatalities. The rapid initial disappearance after placement underscores the importance of checking persistence shortly after placement, as recommended by the French protocol. A second mandatory check the second day would provide a more accurate description of carcass disappearance during the early stages of the study. After the initial period, visits at intervals longer than daily are justified due to the reduced number of carcass disappearance events (as remaining carcasses become rarer) and the slower rate of carcass removal observed in the subsequent days. By the 14th day, only 7% of the carcasses remained, with little change thereafter, suggesting that a 14-day monitoring period is sufficient to estimate persistence, provided that appropriate survival models are applied to account for the right-censored and interval-censored nature of the persistence data. The rapid removal of carcasses in our study suggests that a shorter interval between fatality surveys would reduce uncertainty of persistence estimates in France and countries with similar removal rates. Despite a large and geographically diverse dataset representing a wide range of habitats across France, the results of this study may not be directly transferable to other regions or countries due to potential differences in scavenger communities and environmental conditions. Comparatively, a study conducted within the same geographic region, in Portugal, found a longer median persistence of bird carcasses at 3.5 days, with a 26% probability of removal after one day (Bernardino et al., 2022). Another Portuguese study using birds and mice showed median persistence times of 2.25 days in rainy conditions and 8.36 days without precipitation (Paula et al., 2015). In Japan, a study on bird carcass persistence around wind turbines estimated a median persistence of 1.2 days in winter, with this duration significantly increasing during other seasons due to higher food availability for scavengers (Kitano et al., 2020). Finally, a review of raptor carcass persistence originated from the USA, Canada, UK, Japan, South Africa and Australia reported a median persistence of 420 days (Wilson et al., 2022). The differences observed among studies can be attributed to several factors, such as the use of carcasses of varying types and sizes or climate differences that may influence resource availability and the scavenger species present at the site (DeVault et al., 2004; Paula et al., 2015). However, given the variability in persistence estimation methodologies across studies and the very low values observed in our extensive dataset, our results suggest that average carcass persistence may be lower than previously assumed.

4.2. Factors influencing persistence rate

4.2.1. Habitat variables

The shorter persistence of carcasses in natural areas characterized by a higher proportion of open natural, forests and aquatic habitat compared to urbanized regions may be explained by variations in scavenger abundance and diversity, as previous studies show that human disturbance significantly influences both scavenger diversity and abundance (Gerke et al., 2022; Sebastián-González et al., 2019) and that scavenger diversity is positively correlated with carcass disappearance speed (Wenting et al., 2022). Natural habitats areas are assumed to have more diverse and abundant scavenger communities, leading to faster carcass removal (Santos et al., 2016; Sebastián-González et al., 2019; Wenting et al., 2022). Additionally, the lower persistence observed in open natural habitats could also be due to the increased detectability of carcasses by scavengers, particularly birds (raptors, corvid), in contrast to more enclosed environments where carcasses are less easily detected, as suggested by previous studies highlighting a better carcass detection by generalist predators in open habitats (Tobajas et al., 2022). On the other hand, the higher persistence rates associated with higher hedgerow density in our study suggest that increased landscape heterogeneity in agricultural areas may reduce pressure from generalist scavengers by limiting detection of carcasses, as supported by previous studies linking lower hedgerow density with increased corvid abundance and predation (Bravo et al., 2023). Road density was expected to influence carcass persistence, as roads may limit the movement of certain species and function as artificial home range boundaries (Mata et al., 2017). However, our model did not confirm this hypothesis.

4.2.2. Meteorological variables and seasons

Meteorological variables such as precipitation, temperature and humidity did not significantly affect carcass persistence in our study, despite showing significant effect in other studies (Paula et al., 2015). However, persistence differed significantly between seasons, with the longest persistence observed in summer, followed by spring and autumn. These results are in line with previous studies showing a seasonal effect on carcass persistence (Bernardino et al., 2011, 2022; Borner et al., 2017), but contrasts with (Barrientos et al., 2018) which found no significant relationship. Although temperature was not a significant predictor and did not differ significantly between seasons, the observed seasonal differences may still be partly driven by temperature, as some of its variance may be captured by the season factor in the model. This could partially explain longer persistence in summer, as temperature accelerates carcasses decomposition (Englmeier et al., 2023), which gradually reduces the nutritional value of carrion, while microbial toxins accumulate over time, eventually making it inedible for vertebrates (Janzen, 2006). Similar results were obtained in a previous study, showing that higher temperatures limited carcass availability due to increased insect activity, which accelerated decomposition and potentially reduced olfactory cues for vertebrate scavengers (DeVault et al., 2004). Additionally, seasons may also influence vegetation density, thus the probability of scavengers to locate carcasses, and influence their scavenging behavior (Bernardino et al., 2022; Prosser et al., 2008; Villegas-Patraca et al., 2012).

4.2.3. Carcass type and body mass

Our model revealed that birds persisted significantly longer than rodents during persistence experiments. Complementary analyses conducted on a subsample of data also revealed that carcass persistence decreases with increasing body mass. However, bird carcasses, heavier on average in this dataset (birds: mean = 22g, SD = 7g, rodents: mean = 70g, SD = 96g), persisted longer than rodent carcasses, suggesting that carcass type had a stronger influence on persistence than body mass alone. These findings contrast with a review that aggregated persistence data collected worldwide from various anthropogenic facilities and found that mammals persisted at higher rates than birds, and that heavier carcasses tended to persist longer (Barrientos et al., 2018). Several other studies have found no significant difference in persistence rates between birds and rodents (Henry et al., 2021; Kreuser et al., 2022; Paula et al., 2015). The relationship between carcass weight and persistence has been attributed in some studies to smaller carcasses often being fully removed, whereas larger carcasses are more likely to remain partially consumed at the site (Ponce et al., 2010). However, it is possible that the size range of carcasses tested in this study (7 to 400 g) does not pose a significant obstacle to removal by local scavenger species such as foxes or feral cats, the two main scavengers identified in this study. Instead, larger carcasses may be more quickly detected and thus disappear more rapidly. In line with this, Paula et al. (2015) showed that carcass persistence was primarily explained by scavenger category rather than by carcass type, as observed through camera-trap monitoring. In this study, we did not find any preference of scavenger type for rodents or birds, but this may be explained by the very limited dataset size from camera traps. Finally, differences in carcass persistence between birds and rodents could be explained by faster body decomposition in rodents, while bird feathers may remain detectable for longer periods.

The differences in carcass persistence observed during trials raise important questions regarding the representativeness of the chosen carcass size and taxa for estimating the persistence of bird and bat fatalities associated with wind turbines. If persistence rates are influenced by weight, size, and, as demonstrated by previous studies, the origin of the carcasses (e.g., domestic versus wild; Urquhart et al., 2015), it is critical to evaluate whether the persistence values used in estimation models are adequately reflective of natural environmental contexts. This highlights the need for further refinement in experimental design to ensure accurate estimate of persistence and fatalities. However, it seems impractical to test every parameter and their interactions in the framework of mandatory surveys performed at the wind facility scale.

4.2.4. Wind facility age

Few previous studies investigated the relationship between carcass persistence and the amount of time since the wind park was built. In our study, we observed a decrease in carcass persistence correlated with the age of the wind facility, supporting the hypothesis that the frequent presence of carcasses associated with wind facility fatalities may lead to scavenger habituation and quicker carcass removal, as proposed by Kerns et al. (2005). De Pelsmaeker et al. (2024) tested the scavenger habituation hypothesis by randomly placing cervid carcasses at either unique locations or predictably at fixed locations at regular intervals over 8 years in a German forest National Park. They found no effect on carcass visitations by any of the species studied, which fails to validate the habituation hypothesis. In contrast, Clarke et al. (2020) suggested that ravens frequently and quickly scavenging near windows may be due to an existing recognition of these sites as predictable food sources, indicating a quickly learned response to carcass presence due to window-collision.

A decrease in fatality observations at wind facilities over the years might simply reflect a reduction in carcass persistence from one year to the next. This reinforces the need to reevaluate annually persistence rates and include them in fatality estimation modelling, in order to disentangle the effect link to changes in scavengers' behavioral response from changes link to fatality events. It could be done as part of ongoing mortality monitoring, or by including the age of the wind facility into the parameters used for estimating persistence.

4.2.5. Explanatory power of the model

In survival models, the presence of censoring and the time-to-event nature of the outcome complicate direct variance decomposition, often resulting in low R^2 values (Choodari-Oskooei et al., 2012). Despite including a comprehensive set of variables potentially influencing persistence—such as carcass traits, wind facility attributes, surrounding habitat, and meteorological conditions across spatial and temporal scales—the Nagelkerke R^2 measure of our model was 0.11. This indicates that, while these variables have significant effects, they account for little of the observed variability in carcass persistence rates. This is in line with Bernardino et al. (2022), investigating the ecological and methodological drivers of persistence of bird at power lines, which found an R^2 of 0.22. Similarly, Devault et al. (2017) found an R^2 of 0.165 in their best-fit binary logistic regression model predicting complete bird carcass disappearance. The low explanatory power of our model could be attributed to the inherently stochastic nature of carcass removal events, which are influenced by the occasional presence of scavengers, the availability of alternative food resources, and the random chance of a scavenger encountering a carcass. Such variability and unpredictability in carcass persistence suggest that this parameter should be estimated locally, and that modeling carcass persistence would not yield reliable results for accurately inferring mortality.

Since our survival model treated carcass persistence data as independent observations, it did not account for the nested structure of our dataset, where carcasses are grouped within wind facilities. This oversight may lead to underestimated standard errors and prevents partitioning of variance between measured site-specific covariates (e.g., local habitat, meteorological conditions) and unmeasured park-level factors (e.g., local scavenger community or background resource availability). Future analyses could benefit from nested survival models to explicitly quantify this unobserved site-level heterogeneity, thereby improving explanatory power by isolating the contributions of known predictors from residual variability. However, such nested approach would not enhance predictive accuracy for unsampled sites since the random effects would capture untransferable park-specific conditions, and thus would not address the fundamental challenge of predicting persistence at new sites.

4.2.6. Data challenges and standardization need

The process of collecting and gathering data from various reports presented significant challenges. A considerable portion (about a third) of the collected data proved to be unusable for this study due to insufficient survey frequency, missing information, or untraceable coordinates, often resulting from the lack of a unique identifier for the studied wind facilities. Moreover, essential methodological details, such as sampling intervals, number of replicates, and type of carcass used, were frequently absent in these reports, severely limiting the ability to conduct statistical analyses. These challenges underscore the urgent need for a standardized, comprehensive database capable of systematically collecting fatality survey data. Additionally, clear protocols are essentials to guide the collection of information in the field and ensure its inclusion in fatality monitoring reports. This would not only enable accurate inferences about fatalities at specific sites but also support broader scientific research. Such research is essential for informing the global planning and development of wind energy, ensuring that its ecological impacts are thoroughly understood and mitigated. Adopting the FAIR principles (Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016) would further enhance the utility and accessibility of this data for large-scale studies, ultimately improving our ability to assess and mitigate the ecological effects of wind energy development.

5. Conclusion

This study underscores the high variability in carcass persistence rates at wind facilities, with rapid disappearance in the first few days, followed by a slower decline. The inadequacy of the exponential distribution to describe persistence data highlights the limitations of commonly used estimators based on this assumption. Using estimators like GenEst (Dalthorp et al., 2018) or Evidence of Absence (Dalthorp et al., 2017), which allow for more flexible survival distributions, would thus be better suited. Hedgerows length and urban areas were found to increase carcass persistence, while persistence decreased with wind facility age, likely due to scavenger habituation, as well as with the extent of forest, aquatic and open natural habitats. Despite incorporating a broad range of explanatory variables, the model's low explanatory power suggests that these factors, while significant, do not fully explain the observed variability in carcass persistence around wind facilities.

The findings highlight the need to improve persistence estimation methods and refine experimental designs by including key variables such as wind facility age and carcass type. Annual reevaluations of persistence are recommended to account for changes in scavenger behavior and improve the accuracy of fatality estimates. Finally, the lack of standardized data and reporting protocols significantly limits large-scale analyses, reinforcing the importance of establishing comprehensive, consistent databases to better inform ecological mitigation efforts.

CRediT authorship contribution statement

Andreas Ravache: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Manuela Huso:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Kévin Barré:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Brice Normand:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Alejandro Sotillo:** Writing – original draft, Methodology, Formal analysis. **Aurélien Besnard:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Christian Kerbiriou:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

At the time of submission one of the authors, Brice Normand, was an employee of Ouest Am’, an environmental consultancy involved in wind turbine impact assessment studies. Authors thus declare a direct conflict of interest according to Journal of Environmental Management ethics. Authors take complete responsibility for the integrity of the data and the accuracy of their analysis.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.128906.

Data availability

The data that has been used is confidential.

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