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Red kite (*Milvus milvus*) collision risk is higher at wind turbines with larger rotors and lower clearance, evidenced by GPS tracking

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ABSTRACT

Wind turbines are important for achieving renewable energy goals, but present a considerable threat to wildlife, especially birds and bats. This study reports 41 confirmed collisions of GPS-tracked Red Kites (*Milvus milvus*) with wind turbines across Europe (2017–2024). We compared environmental and turbine-specific factors during collisions and non-collision movements within 500 m of turbines. Collisions occurred year-round, with the highest mean number of collisions per day during spring and autumn migration. Rotor clearance and diameter were significant predictors of collision risk: turbines with greater clearance exhibited lower probabilities of collision, likely due to reduced overlap with typical Red Kite flight altitudes. Based on our model, a 25.5 m increase in rotor diameter was associated with a fivefold increase in collision probability; mitigating this risk would require increasing rotor clearance by approximately 19.3 m. Variation in collision probability was greater between wind parks than between individual birds. No significant effects were found for cloud cover, precipitation, wind speed, or turbine density within 500 m. Our findings suggest that turbines with rotor diameters ≤90 m and clearances ≥60 m may pose a lower relative threat to Red Kites.

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Increasing rotor diameters without adjusting height restrictions reduces clearance and increases the risk of collisions. These results highlight the need for turbine designs minimizing overlap with bird flight heights and underscore the importance of legislative adjustments to height restrictions.

1. Introduction

Wind turbines play an important role in the global movement towards renewable energy, reducing greenhouse gas emissions and mitigating the effects of rapidly occurring climate changes (Gielen et al., 2019). In Europe, many wind farms are currently operating and more are demanded for the near future (European Commission, 2021; Global Wind Energy Council, 2022). Such growth in wind energy infrastructure has raised concerns about its environmental impact, particularly in regard to collisions with wildlife (Smallwood, 2013).

Birds and bats are particularly vulnerable to collisions with wind turbines (Smallwood et al., 2007; Thaxter et al., 2017). Specifically, large broad-winged species of birds (such as eagles, vultures, and storks) in soaring flight frequently harvest the same wind conditions (thermals and orographic wind currents) that render certain areas optimal for wind farms, thereby spawning conflicts between raptors and turbines (De Lucas et al., 2008; Sandhu et al., 2022). However, medium and small-sized birds collide with wind turbines as well (May et al., 2021; Duriez et al., 2022).

Wind farms may affect bird species in two ways: directly via collisions with the wind turbines or indirectly via habitat loss as a result of avoidance of wind turbines and related infrastructure, disturbance, and destruction/fragmentation of suitable habitats (Marques et al., 2014; Watson et al., 2018). Several bird species exhibit avoidance behavior and displacement from wind farm areas, leading to reduced breeding success (Dahl et al., 2012; Fernández-Bellon et al., 2018; Santos et al., 2021; Santos et al., 2022). Wind turbines in breeding areas correlate with increased collision risk, because the movements of breeding birds are concentrated around their nests, increasing the probability of collisions (Murgatroyd et al., 2021; Morant et al., 2024). Therefore, environmental assessments often apply so-called conservation buffers, i.e., distance restrictions between turbines and nesting grounds before the installation of new wind turbines.

Wind turbine characteristics seem to influence the collision risk of birds (Schaub et al., 2024), although it can be difficult to isolate the impact of individual features as they are frequently interrelated (Aschwanden et al., 2024). Wind turbine dimensions appear to be an important factor, with larger and taller turbines posing a greater collision risk, although conclusions on this matter vary across studies (De Lucas et al., 2008; Everaert, 2014). Wind farm placement can also influence collision risk, with turbines placed along ridge lines, or other areas that concentrate bird movements being associated with higher collision risk (Marques et al., 2019; Estellés-Domingo and López-López, 2024). Elevated turbine density has likewise been linked with increased collision risk (Schaub, 2012; De Lucas et al., 2008; Morant et al., 2024). Over the past years, the wind energy industry is trending towards larger wind turbines, with higher per-turbine energy production (Enevoldsen and Xydis, 2019). This may reduce negative effects on soaring birds, as this can result in fewer turbines required to produce the same energy, larger spacing between them, and higher rotor clearance (i. e. the distance between ground level and the tip of the rotor blade in its lowest position), hereby reducing the overlap of usual bird flight paths and rotor-swept zones (Shimada, 2021; Therkildsen et al., 2021).

Several studies have examined bird interactions with wind turbines, using methods like carcass searches and Global Positioning Systems (GPS) telemetry to assess collision risk (Smallwood and Thelander, 2008; May et al., 2019; Murgatroyd et al., 2021; Duriez et al., 2022; Vignali et al., 2022; Murgatroyd and Amar, 2025). However, gaps remain, as data recorded during collisions under real-life circumstances is lacking, complicating mitigation efforts (Schaub, 2012; Korner-Nievergelt et al., 2013; Everaert, 2014; Marques et al., 2014; Aschwanden et al., 2024; Morant et al., 2024).

The Red Kite *Milvus milvus* is a medium-sized raptor of the western Palearctic (Aebischer and Sergio, 2020). It is a suitable model species to study possible conflicts of raptors with wind turbines due to its soaring flight behavior, migration (Literák et al., 2022), large-scale prospecting patterns (Orgeret et al., 2023), and extensive use of open habitats, which often coincide with locations of wind farms. This synanthropic species is sensitive to environmental changes and human activities, making it an ideal indicator for assessing the ecological impacts of wind turbines on raptor populations (Rasran and Mammen, 2017). Our study aims to investigate the effect of wind turbine characteristics and weather on collisions with turbines by providing detailed descriptions of 41 Red Kites collisions that were tagged with GPS loggers. We aim to explore differences in weather conditions and turbine characteristics between collision and non-collision events of the same individuals approaching the wind turbines. We expect turbine density, rotor diameter, and rotor clearance to significantly differ between collision and non-collision events. We expect larger rotor diameters to increase the relative collision probability, whereas we expect greater rotor clearance to decrease it (Aschwanden et al., 2024; Schaub et al., 2024). Based on a simulation study, we also anticipate that higher wind turbine density increases the relative probability of collisions (Schaub, 2012).

2. Methods

2.1. Telemetry data

In this study, we utilized GPS telemetry data recorded from 41 tagged Red Kites (Supplementary material 1), representing all cases of a large data set of 2943 Red Kites where we attributed the deaths to collisions with wind turbines. Red Kites in the data set were tagged between 2013 and 2023 and are part of the LIFE EUROKITE project or collaboration partners shared them. The temporal resolution of the GPS locations ranged from one data point per 1 h to one data point per second, depending on the device settings, part of the day, and remaining battery life. We set the GPS logging frequency higher during the day than at night, with adjustments based on the length of daylight to conserve logger battery life. This approach explains the seasonal variation in the number of recorded locations, as it is roughly proportional to daylight duration across months (Supplementary material 1). We fitted tags as backpack-type "harnesses" (Kenward, 1985) on the back of the Red Kites using Teflon ribbon spanning 9–11 mm in width. For each tagged bird, we kept the tag weight relative to the body mass at tagging within the limits of local regulations (typically below 3 % of the body weight for soaring birds) (Kenward, 1985; Bodey et al., 2018). We sourced transmitters from various suppliers (Supplementary material 1). Of all the birds, we tagged 32 as nestlings and 9 as adults. We tagged 40 of them at or around the nest during spring and summer, and one bird during winter in Spain.

We classified collision certainty with wind turbines based on the LIFE EUROKITE Assessment Protocol (LEAP) method (Panter et al., 2025), defining three levels: certain (25 cases), probable (9 cases), and possible (7 cases) (Supplementary material 1).

2.2. Data collection and processing

To explore potential differences in the circumstances when birds collided with wind turbines versus when they did not, we used all GPS locations from the 41 studied birds before collisions and standardized the dataset to one position per hour, allowing for a tolerance of 15 minutes. We accomplished this using the 'track_resample' function from the amt package in R (Signer et al., 2019). When the birds had a gap in data collection, we used all available data without applying dead-reckoning or interpolation. Following this method, we obtained 269,803 GPS positions (details summarizing the monthly distribution of recorded data can be found in Supplementary material 1). In the next step, we calculated the ground speed of birds' movement by dividing the geodesic distance and time difference between consecutive locations and filtered out points with ground speed lower than 3 km/h to avoid including stationary points (e.g. roosting, nesting). This resulted in 51,376 GPS positions.

From these standardized GPS locations, we selected points within a 500 m buffer of wind turbines, resulting in 1895 non-collision data points. The majority of non-collision events occurred in the summer months (details summarizing the monthly distribution of non-collision data can be found in Supplementary material 1). However, for 487 locations (42 % from Spain and Italy), we lacked information about wind turbine characteristics; therefore, for the statistical evaluation of the relative probability of collision mentioned below, we used only the dataset of 1408 non-collision events. We used these non-collision data as a baseline to test against collision data (histograms of collected data can be found in Supplementary material 1). For the collision data, we analyzed 41 cases and identified 32 as clear (specific turbine involved) and 9 as unclear (due to long GPS data collection intervals or data gaps). For the unclear cases, we assigned the closest wind turbine. We annotated these locations with weather data, and we calculated the number of wind turbines within a 500 m radius, rotor diameter, and free area under the rotor.

We obtained weather data for the GPS positions via the ENV-data track annotation service on Movebank (Dodge et al., 2013) using the ECMWF ERA5 reanalysis database, with a temporal and spatial resolution of 1 h and 0.25°, respectively. We used bilinear interpolation for wind components and applied the nearest-neighbour method for precipitation and total cloud cover. We sourced information about the exact location of wind turbines from OpenStreetMap, wind farm operating companies, and the TB Raab database.

Finally, we gathered age at collision in calendar years, class at collision (1CY – post-fledgling birds in their first calendar year, floater – birds in their second calendar year or older before first breeding, and breeding – birds after their first breeding attempt), and part of the year of collision/non-collision (spring migration – SM, summer period – S, autumn migration – AM, winter – W) for all collision and non-collision events. We obtained breeding information from field observations. When field data were unavailable, we used the NestTool package in R (Oppel et al., 2024) to predict breeding probability. We classified predicted probability greater than 0.5 as breeding for birds in a third calendar year (3CY) or older.

We determined the part of the year manually for each bird by visualizing their movements individually. After visualizing the movement data, we defined summer and winter periods as the time between migrations. Migration started when a bird left its summer or winter grounds and ended when it reached the corresponding winter or summer grounds and ceased moving further south or north. For resident birds (n = 3), where we observed no distinct shift between summer and winter sites, we assigned the seasons arbitrarily: summer as the period from 20 March to 22 September, and winter from 23 September to 19 March. To compare the relative collision probability across different periods, we calculated the mean number of collisions per day by dividing the number of collisions in each period by its average duration. We assessed the durations of the seasonal periods based on telemetry data from the 41 birds investigated in this study. The summer period averaged 201 days (range: 89–268 days), autumn migration and spring migration periods averaged 19 and 14 days, respectively (range: 4–73 days; 4–48 days), and the winter period averaged 131 days (range: 66–254 days). We also calculated the distance from collision points to the birds' nests, to explore the collision location from the birds' nesting site. For 1CY and floater birds, we measured this distance to their natal nests, while for breeding birds, we measured it to their breeding nests.

2.3. Statistical analysis

We conducted all statistical analyses in RStudio version 2023.09.1 (Posit Team, 2023) using R version 4.3.2 (R Core Team, 2023). We employed Bayesian modeling using the 'brms' package (Bürkner, 2018). We constructed generalized linear mixed models (GLMMs) with a binomial response variable, assuming a Bernoulli distribution (collision = 1, no collision = 0), to investigate the factors behind birds' relative probability of collisions with wind turbines. The predictor variables included wind turbine density within a 500 m radius, rotor clearance (clearance below the rotor), rotor diameter, wind speed, precipitation, and cloud cover. We scaled all continuous predictor variables (using the scale function) to ensure the comparability of coefficients. Before model fitting, we assessed multicollinearity by computing a correlation matrix. We detected a moderate correlation between rotor diameter and rotor clearance ($r = 0.64$), but variance inflation factors (VIF < 3) indicated no strong multicollinearity, so we retained both variables in the model. We included random intercepts for individual bird ID and wind park ID to account for variability in multiple measurements of birds and wind parks, respectively. We grouped wind turbines into wind parks using a 2 km clustering radius.

We assigned weakly informative priors to regularize parameter estimates, with normally distributed priors for fixed effects (mean = 0, variance = 5) and Half Cauchy distributions for random intercepts (mean = 0, variance = 2.5) (Gelman et al., 2008). We ran four chains, each with 15,000 iterations, including 3000 warm-up iterations (trace plots can be found in Supplementary material 2). To improve sampling efficiency and avoid divergent transitions, we set adapt_delta = 0.95 and max_treedepth = 15. All parameters achieved effective sample sizes (ESS) greater than 1000, and R-hat values were lower than 1.01, indicating model convergence. We performed model diagnostics via the DHARMa package (Hartig, 2022) and DHARMa.helpers (Rodríguez-Sánchez, 2024) (results provided in Supplementary material 2).

Because non-collision events were not evenly represented for each bird, we decided to assess the robustness of our results to sample size by conducting leave-group-out cross-validation, following the approach used by Mortlock et al. (2025). In each iteration, we randomly removed 20 % of the individuals (eight birds) and re-ran the model. We repeated this process ten times and compared the posterior distributions of fixed and random effects to those of the main model to evaluate whether the model results were sensitive to sampling imbalance (results in Supplementary material 2).

3. Results

We analyzed wind turbine collisions involving 41 Red Kites tagged with GPS-GSM telemetry transmitters (Fig. 1). Most collisions (78 %) occurred in Germany, Spain, and Austria (Fig. 1). These individuals recorded on average 20 non-collision events per year, ranging from 1 to 241. Collisions occurred at wind turbines with a median rotor diameter of 82 m (30–158 m), whereas non-collision events were associated with a median of 90 m (14–162 m). The rotor clearance was lower during collisions (median: 45 m; range: 15–97 m) compared to non-collisions (median: 60 m; range: 16.5–98.5 m). Wind turbine density within 500 m was slightly higher at collision sites (median: 4 turbines; 1–9) than at non-collision locations (median: 3; 1–14). Weather conditions during collisions showed a median wind speed of 4.46 m/s (0.74–9.34 m/s), compared to 4.23 m/s (0.07–13.45 m/s) during non-collisions. Cloud cover was slightly lower for collisions (median: 0.58; range: 0.00–1.00) than non-collisions (median: 0.70; range: 0.00–1.00), while precipitation was minimal in both cases (median: 0.00 mm; range: 0.00–1.56 mm for collisions, 0.00–5.04 mm for non-collisions). The

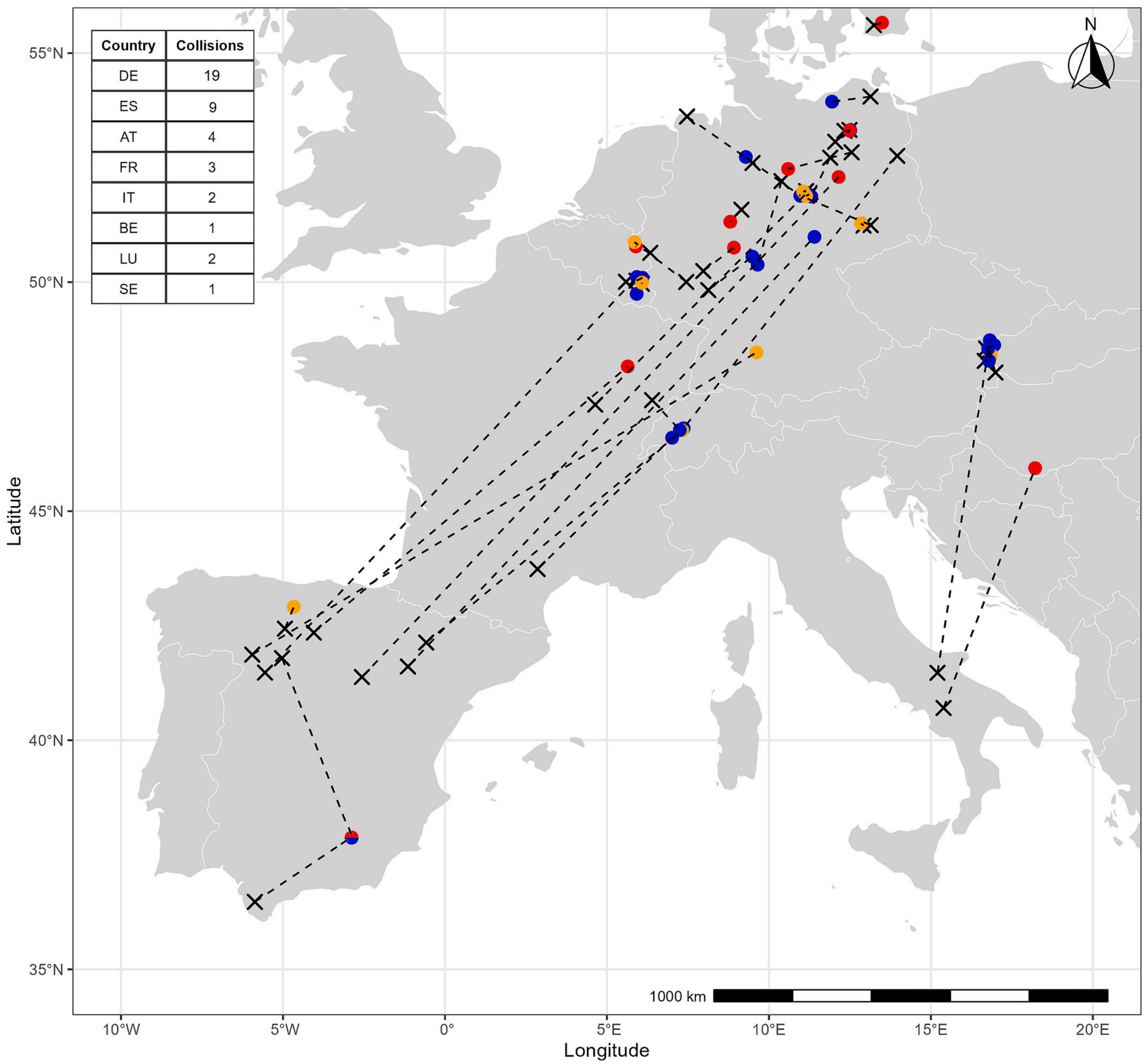

Fig. 1. Map displaying the locations of nests (points) and collision places (crosses). Red, blue, and orange points represent the nests of 1CY birds, floaters, and breeding birds, respectively (for breeding birds it represents their last breeding place). The dashed lines show the distance between each nest and the collision place. The table in the top left corner summarizes the number of collisions per country. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

median distance from the nest was 97 km for collision events (1.5–1646 km) and 11 km for non-collision events (0.6–943 km). A detailed overview of metrics for each bird can be found in Supplementary materials 1.

Although most collisions occurred during the summer and winter periods, the highest mean number of collisions per day was observed during spring and autumn migration periods (Table S2, Supplementary materials 1). Specifically, the mean number of collisions was 0.12 collisions per day in summer, 0.07 in winter, 0.28 for the spring migration, and 0.21 for autumn migration.

Our Bayesian model revealed strong effects of rotor clearance and rotor diameter on the relative collision probability of the studied birds. Rotor clearance had a negative effect on collision probability (Table 1), indicating that collisions happened at wind turbines with less clearance (Fig. 2). Similarly, rotor diameter was an important predictor of collisions, with larger rotors increasing the likelihood of collisions (Table 1, Fig. 2). Parameter estimates for the number of wind turbines within a 500 m radius, cloud cover, wind speed, and precipitation all included 0 in their 95 % credible interval (Table 1). The random effect estimate for wind park was larger (estimate = 1.52) than the random effect estimate for individuals (Table 1), suggesting that collisions were more influenced by wind park differences than individual bird differences.

Cross-validation showed that fixed-effect estimates remained stable across all runs, with rotor clearance and diameter consistently retaining their impacts in every CV fold. Although minor deviations in parameter estimates were observed, the overall results show that the model is robust and not unduly sensitive to data imbalance among individuals (Supplementary materials 2).

Table 1
Model estimates of Bayesian model. Number of turbines–number of wind turbines within a 500-m radius. The table includes estimates for each parameter along with the standard error (Est. Error), the 95 % credibility interval (CrI), the potential scale reduction factor (Rhat), and the effective sample sizes for both the bulk (Bulk_ESS) and tail (Tail_ESS) of the posterior distribution. All variables were scaled.

	Parameter	Estimate	Est. Error	95 % CrI		Rhat	Bulk_ESS	Tail_ESS
Random effect	Bird_ID	1.52	0.60	0.41	2.84	1	9181	9331
	Windpark_ID	2.45	0.96	0.85	4.57	1	4946	8308
Fixed effect	Intercept	−4.52	1.1	−7.11	−2.84	1	6230	11,849
	Cloud cover	−0.32	0.25	−0.84	0.16	1	50,771	34,421
	Number of turbines	0.34	0.26	−0.16	0.88	1	35,043	27,390
	Rotor clearance	**−1.53**	**0.47**	**−2.6**	**−0.78**	**1**	**9160**	**13,757**
	Wind speed	−0.28	0.29	−0.92	0.24	1	21,486	22,025
	Rotor diameter	**1.65**	**0.48**	**0.88**	**2.77**	**1**	**8779**	**13,031**
	Precipitation	−0.3	0.34	−1.06	0.27	1	59,089	31,773

R^2 - 0.38, (CrI: 0.20, 0.55).
Significant results (95% credible interval not including zero) are highlighted in bold.

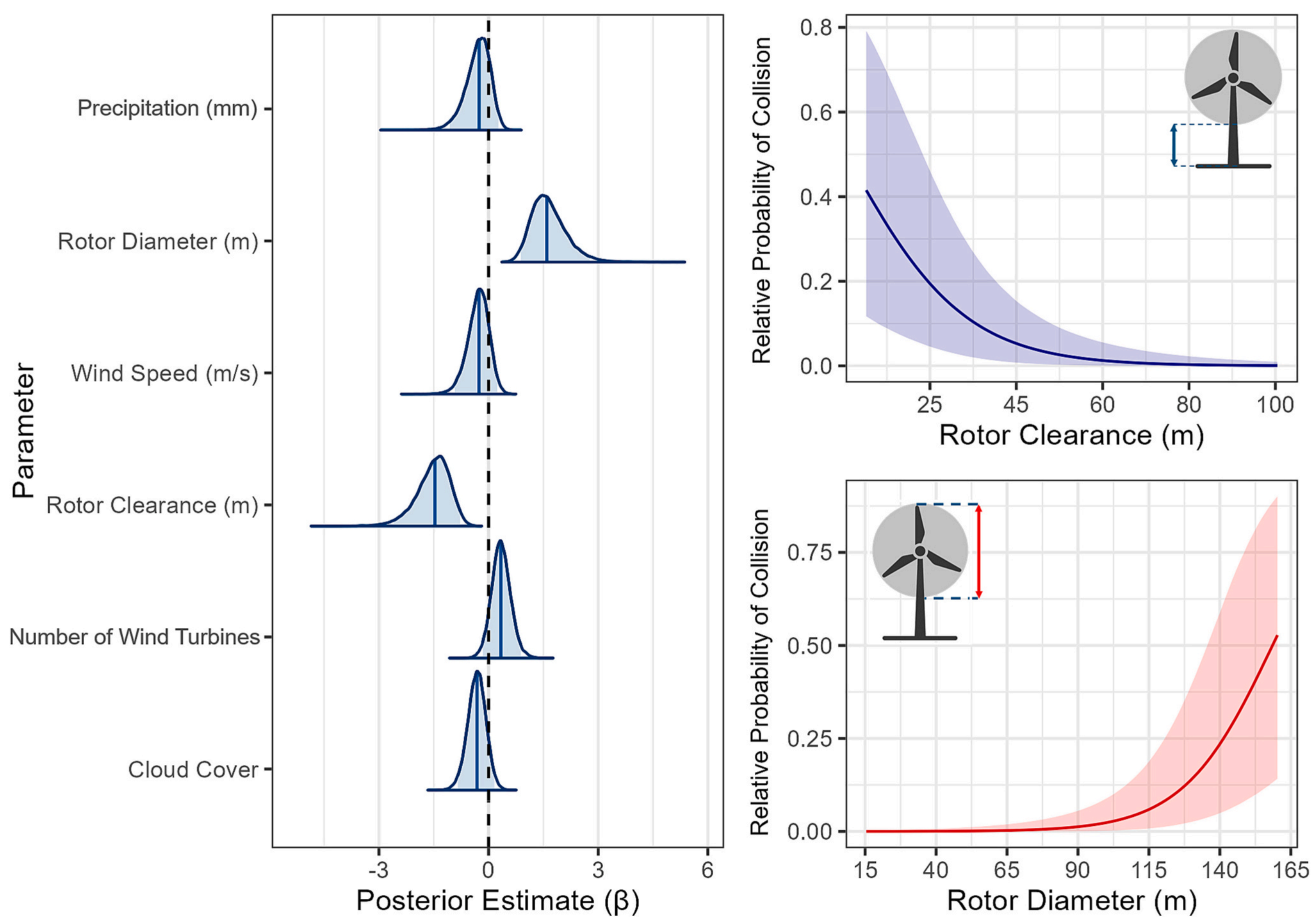

Fig. 2. Left: posterior distributions of the scaled fixed effects in the model, showing the estimated effects of each predictor on collision probability. The density plots represent the uncertainty around the parameter estimates, with values centered around zero indicating weak or no effect. Right: effect plots for significant variables, illustrating the relationship between rotor clearance (top) and rotor diameter (bottom) with the probability of collision. Shaded areas represent 95 % credible intervals.

4. Discussion

Our results show clear associations between wind turbine characteristics and relative collision probability in the studied Red Kites. Collisions were more likely at turbines with larger rotor diameters and lower clearance between the rotor and the ground, as demonstrated by our Bayesian model (Fig. 2). In contrast, the number of wind turbines, and weather variables such as wind speed, cloud cover, and precipitation showed weak effects with high uncertainty (Table 1). These findings remained consistent across all cross-validation runs, confirming their robustness despite individual variation in the dataset. By analysing 41 confirmed Red Kite mortalities based on GPS telemetry data from across Europe, this study provides valuable new insights into the still poorly understood issue of raptor collisions at wind turbines.

4.1. Wind turbine characteristics

We found strong support that rotor clearance influences the relative collision probability. Turbines with greater clearance exhibited a lower probability of collision, likely due to reduced overlap with Red Kite flight paths, which generally occur at altitudes between 5 and 60 m (Pfeiffer and Meyburg, 2022; Aschwanden et al., 2024). This aligns with findings that species flying predominantly at lower altitudes, such as Red Kites, benefit from higher rotor clearance (Schaub et al., 2024). Guidelines from the Federal Nature Conservation Act, in Germany (BNatSchG, 2009), emphasize the importance of rotor clearance for species like marsh harriers and eagle owls, with a suggested minimum rotor clearance of 50 to 80 m depending on the terrain. Our results reinforce the importance of designing turbines to minimize overlap with bird flight height to reduce collision risk. However, while higher rotor clearance is beneficial for many species, its effectiveness depends on species-specific flight behaviours, which vary across regions and migratory pathways (De Lucas et al., 2008; Péron et al., 2017; McClure et al., 2021; Schaub et al., 2024). For example, for species that typically fly at higher altitudes, such as eagles or vultures, taller turbines may increase collision risk by shifting the rotor-swept zone into their usual flight range (Devault et al., 2005; Tikkanen et al., 2018). Placing wind turbines in areas of recursive movement, such as between foraging and nesting or roosting sites, may increase collision risk due to the higher frequency of bird activity and repeated crossings through these zones (Rasran et al., 2017). Therefore, wind farm planning should integrate species-specific movement data to optimize turbine design and placement for both local and migrating wildlife (Marques et al., 2014; Dohm et al., 2019; Péron et al., 2017; Thaxter et al., 2017).

Regarding rotor diameter, our Bayesian model provides strong posterior support for an association between larger rotor diameters and increased collision probability for Red Kites. Larger turbines, with diameters up to 160 m, expand the volume of airspace affected by rotor blades, increasing the challenge for birds to avoid them (Marques et al., 2014; Shimada, 2021). However, larger turbines have also been shown to reduce the overall number of turbines required for the same energy output, potentially mitigating collision risk by decreasing turbine density and increasing rotor clearance (Thaxter et al., 2017; Enevoldsen and Xydis, 2019; Therkildsen et al., 2021). Based on our model, theoretically, a 25.5-meter increase in rotor diameter (equivalent to one standard deviation in our dataset) is associated with a 5-fold increase in the odds of a collision. To offset this elevated risk through turbine design, rotor clearance would need to increase by approximately 19.3 m. Achieving the same risk reduction through turbine density alone would require the removal of nearly nine turbines within a 500-m radius—a magnitude well beyond the observed density in our data (mean = 3.3 turbines per 500 m). This further supports the idea that combining larger rotor diameters with increased turbine clearance could help balance collision risk reduction with energy optimization. Nevertheless, while this trade-off suggests that careful wind farm planning helps minimize risk, effective mitigation strategies should not only focus on turbine design but also take a population approach and optimize wind farm permitting processes accordingly (Murgatroyd and Amar, 2025).

While a large rotor-free area is generally associated with higher wind speeds and increased energy yields (Barthelmie et al., 2020), regional planning constraints, landscape regulations, and military restrictions often impose height limitations on turbine construction (FA Wind, 2021). Although technical advancements allow for rotor clearances exceeding 100 m in modern turbines, the combination of increasing rotor diameters and unchanged height restrictions could reduce rotor clearance, potentially undermining species protection objectives. This underscores the urgent need for legislative adjustments regarding height restrictions.

The effect of wind turbine density within a 500-meter radius on collision probability for the 41 Red Kites in this study remains uncertain. While the estimated effect size suggests a possible trend of increased collision probability with higher turbine density, the wide credible intervals indicate substantial uncertainty. Previous studies of other species, such as White-Tailed Eagles (*Haliaeetus albicilla*) and Griffon Vultures (*Gyps fulvus*), reported that higher turbine density has been linked to increased collision risk (Heuck et al., 2019a; Morant et al., 2024). However, given the uncertainty in our estimates, we cannot support a similar effect for Red Kites in our study. The large variation explained by the windpark_ID random effect suggests that some parks were considerably more collision-prone than others, although the current analysis does not allow inference about the underlying mechanism.

4.2. Weather conditions

Our results suggest that weather conditions played a secondary role in influencing collision probability. Our Bayesian models indicate that wind speed, cloud cover, and precipitation had posterior distributions overlapping zero, suggesting little evidence for a consistent effect on collision probability. Poor visibility, caused by fog or rain, has been proposed to impair a bird's ability to detect turbine blades, potentially increasing collision risk (Marques et al., 2014). Interestingly, the posterior distribution of cloud cover suggests that higher cloud cover may be associated with a lower probability of collisions in the studied birds, though the posterior uncertainty remains high. A possible explanation can be attributed to the blurring effect of white wind turbine blades against the bright sky, especially while turning, making them difficult to spot in time (May et al., 2020). This can be particularly true for raptors with downward-focused vision adapted for spotting prey on the ground in open areas, as their small binocular fields limit their ability to detect obstacles in their flight path (O'Rourke et al., 2010; Martin et al., 2012). Although we observed no direct effect of wind speed on collisions, previous research has highlighted its connection to the altitude of birds' flight (Heuck et al., 2019b; Pfeiffer and Meyburg, 2022; Aschwanden et al., 2024). Furthermore, wind direction has been shown to influence avoidance of wind turbines in closely related Black Kites (*Milvus migrans*), that showed increased avoidance when pushed by wind towards the direction of the wind turbine (Santos et al., 2022).

Despite the weak effects of weather variables in our model, the lack of strong weather-related effects in our study may reflect the hourly resolution of our weather data, which could overlook short-term weather variations (e.g., sudden fog, strong wind gust, or heavy rain). Future research incorporating higher-resolution meteorological data could provide more precise insights into these dynamics.

4.3. Seasonal patterns

Despite higher interaction with wind turbines during the summer period, results show that collision probability per day peaks during migration. These patterns align with existing research indicating elevated mortality risk for Red Kites and other raptors during migration, potentially due to decreased familiarity with environments on their migration paths (Klaassen et al., 2014; Oppel et al., 2015; Thaxter et al., 2017). Seasonal differences in flight behavior between annual cycles (i.e. breeding, wintering, migration) may also influence collision probability (Marques et al., 2014; Pfeiffer and Meyburg, 2022).

Non-collision events were reduced in winter, although wind turbines are also present in major Red Kite wintering countries such as Spain, France, and Italy (WindEurope, 2018). While fewer GPS locations were recorded during this period (see Fig. S1 in Supplementary material 1), the proportion of non-collision events relative to total GPS positions also declined (see Fig. S3 in Supplementary material 1). This indicates that the seasonal reduction in non-collision detections is not merely due to reduced tracking effort but likely reflects an ecological pattern, possibly driven by decreased winter activity or migration to areas with fewer wind turbines.

The distance between collision sites and either the breeding or natal nest varies widely. For breeding birds that collided, the shortest distance to their breeding site was 2.6 km, and the longest was 1421 km. For non-breeding birds, the shortest distance to their natal nest was 1.5 km, with a maximum of 1418 km. This indicates that risk is not restricted to a specific range around the nests or a phase of the annual cycle.

Unfortunately, we were not able to assess the effect of distance and season on collision probability in our model due to missing wind turbine parameters in key wintering areas. We believe that incorporating these data, along with information from birds that did not collide with wind turbines, in future studies will provide valuable insights into collision risk throughout the annual cycle (Marques et al., 2014). A comprehensive analysis of the broader LIFE EUROKITE dataset could offer a more complete understanding of these spatial and temporal dynamics.

4.4. Limitations

While this study provides valuable insights into Red Kite collisions with wind turbines, it is important to note the main limitations of this study, which are the small sample size of collisions and imbalance in the dataset, with only 41 collision events versus 1408 non-collision observations. The lack of wind power characteristics in important wintering areas of Red Kites may limit the interpretation of our model for populations in Italy and Spain. Furthermore, as the study aimed to compare the circumstances surrounding the collision and non-collision events rather than to quantify absolute collision risk, our model does not incorporate factors such as the time spent near wind turbines, or potential learned avoidance. Additionally, the 1-hour resolution of weather data may not capture fine-scale weather conditions during collision events. Despite these limitations, the model performed well. The findings remain valuable for understanding collision risk, given that despite only 41 collisions, this is the largest existing data set of GPS-tracked collisions in a single species.

5. Conclusion

In conclusion, our results indicate that factors such as rotor clearance and rotor diameter play a significant role in determining collision likelihood, with collision probability increasing with lower clearance and higher diameter. Collisions happened throughout the whole year, with higher mean collisions per day during migration. Furthermore, our real-life Red Kite data provide support for the model predictions published in recent studies (Aschwanden et al., 2024; Schaub et al., 2024), underlying the need to consider spatio-temporal distribution and behavioural patterns in the planning of new wind turbine infrastructure. Building larger and, more importantly, taller wind turbines can decrease the risk of collision for Red Kites and mitigate the ratio between collisions per generated energy, potentially leading to a functional compromise between nature conservation and green energy production (Shimada, 2021), although for some species this may increase risk by shifting the rotor-swept zone into their typical flight altitudes. Therefore, implementing species-specific data into wind farm planning is crucial for the conservation of local wildlife.

Future studies should focus on further statistical analysis and modeling to understand how wind park characteristics, their location, and birds' annual cycle correlate with avoidance behavior and collisions. This approach should incorporate additional explanatory variables, such as landscape features, topography, and bird-specific data like age and sex. Addressing these aspects could considerably enhance our understanding and guide the design of wind farms to mitigate risk to Red Kites and other vulnerable raptor species.

CRediT authorship contribution statement

Jan Škrábal: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Maximilian Raab:** Writing – review & editing, Methodology. **Rainhard Raab:** Writing – review & editing, Conceptualization. **Martin U. Grüebler:** Writing – review & editing, Methodology. **Urs G. Kormann:** Writing – review & editing, Methodology. **Patrick Scherler:** Writing – review & editing, Methodology. **Petra Sumasgutner:** Writing – review & editing. **Susanne Åkesson:** Writing – review & editing. **Ana Bermejo:** Resources. **Nayden Chakarov:** Resources. **Wolfgang Fiedler:** Writing – review & editing, Resources. **Alfonso Godino:** Resources. **László Haraszthy:** Resources. **Katharina Klein:** Resources, Conceptualization. **Martin Kolbe:** Writing – review & editing, Resources. **Ivan Literák:** Writing – review & editing, Resources. **Kerstin Mammen:** Writing – review & editing. **Ubbo Mammen:** Resources. **Jean-Yves Paquet:** Resources. **Thomas Pfeiffer:** Resources. **Javier De La Puente:** Resources. **Alexander Resetaritz:** Resources. **Stef van Rijn:** Resources. **Luisa Scholze:** Data curation. **Péter Spakovszky:** Resources. **Eike Steinborn:** Resources. **Jörg Westphal:** Resources. **Manuel Wojta:** Data curation. **Rainer Raab:** Writing – review & editing, Supervision, Funding acquisition, Data curation.

Ethics approval and consent to participate

The tracking study of Red Kites was undertaken under permits issued by the relevant authorities in Austria (MIL2-J-0812/012, GFL2-J-107/014, BHBRN-2019-314986/5-PS), the Czech Republic (S-JMK 188552/2014 OŽP/Kuč, S-JMK 32177/2015 OŽP/Kuč, S-JMK 30634/2016 OŽP/Ško, S-JMK 177265/2017/OŽP/Ško), Germany (BW: RPS35-9185-99/381, 55-7/8852.11; HE: RPKS-23-19 c 16/3-2020/1, JW-1151; some of the tagging of juvenile Red Kites in HE took place within the framework of a cooperation under the animal testing permit number G 8/2018 of the Conservation Ecology Group at the Phillips-Universität Marburg and under the species protection exemptions for ringing and extended tagging by the Helgoland Ringing Centre (Institute of Avian Research, IAR) and the State Ornithological Institute of Hesse; MV: 72213-2012/20, 661.35.5.2.000-02/22, VG-22-051, 44.30-2022-148-Gru, 66.1-55.40.30-1-150; NI: H41L.22202/VB(H41L)_2022(Windt), 33.19-42502-04-21/3648; NRW: 81.02.04.2020.A188; ST: LAU 43.14-22480-75/2021, 43.13-22480-19/2018, 43.13-22480-21/2021 and 1/32 De), Luxembourg (N/Réf 90832 CD/tw; N/Réf 93179 CD/gp; N/Réf 95445 CD/ne; N/Réf 102316), the Netherlands (IvD-light, 23 April 2009 (University of Groningen)), Portugal (875/2023/ CAPT (ICNF)), Spain (INAGA 500201/24/2019/1147 & INAGA 500201/24/2019/11844 (Institute of Environmental Management of the Government of Aragon), EP/CYL/346/2019 & EP/CYL/66/2020 (Dirección General de Patrimonio y Política Forestal de la Junta de Castilla y León), 10/131599.9/19 & 10/168601.9/20 (Dirección General de Biodiversidad y Recursos Naturales de la Consejería de Medio Ambiente, Vivienda y Agricultura de la Comunidad de Madrid), VS/MLCE/avp_21_205 (Dirección General de Medio Natural y Biodiversidad), AUES/CYL/213/2021 & AUES/CYL/214/2022 (Dirección General de Patrimonio y Política Forestal de la Junta de Castilla y León), 10/126043.9/21 & 10/185882.9/22 (Dirección General de Biodiversidad y Recursos Naturales de la Consejería de Medio Ambiente, Comunidad de Madrid)), Sweden (ethical permit from Malmö-Lunds Djurförsöksetiska Nämnd 5.8.18-06518/2020, M74-20; Ringers Licence no. 440 to SÅ from the Swedish Environmental Protection Agency and the Swedish Ringing Office) and Switzerland (Ringing and tagging were permitted in Switzerland by the Amt für Lebensmittelsicherheit und Veterinärwesen (LSVW) of the Canton of Fribourg (Permit No. 2017_29_FR) and the Federal Office for the Environment (FOEN)). We performed all methods following the relevant guidelines and regulations concerning study animals. We confirm that the study is reported in accordance with ARRIVE guidelines (https://arriveguidelines.org/).

Declaration of competing interest

This publication was produced as part of the LIFE EUROKITE project, which is funded by the European Commission's LIFE Nature program (60%), grid operators (15.8%), nature conservation NGOs (9.2%), authorities (8.8%) and renewable energy companies (6.2%). As the LIFE EUROKITE project is based on international cooperation of scientists, NGO, authorities and companies, many people of different background contributed to this study in different ways. Based on the legal setup of the LIFE project, co-financers only provide funding but have no say in the content of scientific contributions. Contributors from private companies and NGOs were largely responsible for tagging birds and providing data to the project, while data evaluation, interpretation and writing of the manuscript was performed by the TB Raab GmbH in cooperation with authors working for independent research institutions. Martin Bergmann, who works for iTerra energy GmbH, conducted a mandated quality assurance review to ensure scientific standards.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111482.

Data availability

The data will be made available after the acceptance of the article. It will be deposited on an openly available repository, e.g. Dryad.

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