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Bird Survival in Wind Farms by Monte-Carlo Simulation Modelling Based on Wide-Ranging Flight Tracking Data of Multiple Birds During Different Seasons

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Simple Summary

Wind farms are growing fast, but their real impact on birds is still debated. We tracked eight Common Buzzards with high-precision Global Positioning System over several years in Northeast Bulgaria, where more than 200 wind turbines have operated for over 15 years. Using these flight-height data, we ran Monte-Carlo simulations based on the Band collision risk model to estimate how often Common Buzzards might collide with turbines of different sizes. We then checked our predictions against 18 years of systematic carcass searches under 114 turbines. Both the simulations and the field data point to a relatively low collision probability for Common Buzzards, and this probability varies with season: it is lowest during migration, when birds fly higher, and highest in winter and breeding, when they stay low. Our findings show that realistic flight-height distributions and seasonal behaviour must be included in Environmental Impact Assessments. Our results also suggest that Common Buzzards may quickly habituate to wind farms, although continued monitoring is essential.

Abstract

Wind energy development is a key component in the transition to sustainable clean energy. Collision probability depends on turbine dimensions and species-specific behaviour, and understanding these relationships is essential for effective Environmental Impact Assessment (EIA). We applied a simulation approach based on flight-height distributions of a medium-sized diurnal raptor, the Common Buzzard (*Buteo buteo*). Long-term Global Positioning System (GPS) tracking data from an area with over 200 operating wind turbines in Northeastern Bulgaria were combined with Monte Carlo simulations of the Band collision risk model, and the predictions were validated against 18 years of systematic carcass searches under 114 turbines. Importantly, collision probability of the Common Buzzard was season-dependent, being greater during breeding and wintering, when flights occurred at lower altitudes, and lower during migration, when birds flew higher. Both the simulations and the field data supported an overall relatively low collision probability, indicating a high avoidance rate in this species. These findings suggest that wind energy planning should account for seasonal variation in flight behaviour and community composition, while long-term monitoring remains essential to ensure that cumulative impacts are adequately assessed.

Keywords: GPS tracking; energy transition; Environmental Impact Assessment; cumulative effect; flight behaviour; wind turbine

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1. Introduction

The dynamic changes in climate systems on the planet are obvious. One of the most efficient tools to mitigate these changes is the transition of energy production to renewable sources such as wind power. According to official information from the European Union, the installed wind power capacity by 2030 must be 510 GW [1]. This is more than twofold compared to 2022 [2]. While broad-scale analyses have not yet demonstrated global population declines attributable to wind power, there is growing evidence of negative impacts at local and regional scales, particularly for large raptors [3–5], but future expansion needs careful planning and effective Environmental Impact Assessment (EIA) tools.

The main impact is the collision of birds in some species sensitive to wind turbines and in badly sited wind farms. Several raptors and Old-World vultures appear to be especially vulnerable to collision with wind turbines [3,6–13]. Previous studies have documented high collision risks for upland raptors such as Hen Harriers (*Circus cyaneus*) and Golden Eagles (*Aquila chrysaetos*) in Scotland and the UK [6,7,11], for Griffon Vultures (*Gyps fulvus*) in Spain [9,10], and for White-tailed Eagles (*Haliaeetus albicilla*) in Norway [13]. More general assessments have summarized the broad-scale impacts of wind farms on birds in Europe and North America [3,8,12]. Habitat-related analyses show that turbine placement in or near key foraging areas strongly increases collision risk [14]. In addition, large soaring raptors often overlap with areas of high wind energy potential, leading to a systematic conflict between conservation and energy development [15–18]. Model-based approaches have demonstrated that Golden Eagles and other raptors select habitats and flight paths in ways that can significantly increase risk if turbines are not properly sited [19–21].

At least some other 'soaring bird' species do not appear to be similarly vulnerable. For example, while Old World vultures and their taxonomic relatives may have some difficulty in avoiding collisions [7,8,11,12,22,23], this difficulty does not seem to apply to New World vultures, as they are disproportionately unlikely to be killed at wind farms despite their frequent occurrence [3,24–27]. Another unrelated but predominantly scavenging species, the Common Raven (*Corvus corax*), is frequently recorded at wind farms but is rarely found as a victim of turbine collision [24,25]. Such species-specific differences underline that predictors of collision risk, such as flight type and seasonal movement strategies, must be taken into account [4]. This additional increase in selective pressure in the altered environment may impact local bird populations [28,29].

Mitigation measures are used to reduce the collision risk of birds with wind turbines in many regions of the world, including Northeastern Bulgaria. The most efficient are careful EIA-based selection of turbine locations and shutdown on demand during periods with increased collision risk [30]. More recent studies have highlighted that both turbine technical specifications and site-level factors strongly affect the probability of collision [21,31–34]. For example, rotor size and hub height determine the volume of airspace intersected, while maximum tip height and spacing influence the extent of overlap with flight paths [32,33,35]. Larger turbines may reduce overall collision numbers if fewer are installed, but they can also increase exposure for large soaring raptors flying at typical rotor heights [5].

There are two principal methods to evaluate collision probability. The first is direct carcass searches, and the second is simulation of collision probability using mathematical models. Carcass searches are limited by local land coverage and accessibility to the turbines. The models are often based on assumptions and cannot always be confirmed by direct evidence from real mortality, since long-term monitoring data are often lacking [31,36]. The rapid need to develop more wind energy projects requires information on the effects of turbine dimensions on collision risk for a range of bird species, especially species important for ecosystems and human life.

The best approach is to use carcass search results to validate collision risk estimated by models of flight behaviour, mainly with respect to flight height distributions [36,37]. The study of flight height is limited by the accuracy of altitude measurements and requires long-term data to account for variations related to changes in species ecology across the annual cycle. In this study, we used tracking data collected over several years to investigate the flight height distributions of eight Common Buzzards across migratory, breeding, and wintering periods in areas with operational wind turbines. The Common Buzzard is a model species of a medium-sized diurnal raptor (Accipitriformes). This ecological group of species is particularly exposed to potential collisions with wind turbines [38]. The low mortality rate found in our carcass monitoring for 18 years in the study area excludes a significant impact at the current moment [39,40]. Despite this, as raptors are long-lived, their populations are particularly sensitive to increased mortality [29,38].

Our study approach was based on a stochastic Monte Carlo adaptation of the Band collision risk model [5,19,41]. We considered the overlap of the wind turbines' rotor height ranges with the birds' flight height distributions as well as wind speed, operational periods, and turbine-specific technical parameters such as rotor diameter and rotation speed. Furthermore, we considered the increase in the rated power of wind turbines with larger rotor diameters to determine whether survival chances for Common Buzzards depend on many small turbines versus fewer large ones. Finally, we assessed the consistency of results between theoretical Monte Carlo simulations and real mortality of Common Buzzards found after 18 years of systematic carcass monitoring.

In this study, we hypothesized that collision risk for Common Buzzards would be season dependent. Specifically, we predicted that the probability of collisions would be higher during the breeding and wintering periods, when birds often fly at lower altitudes within the rotor-swept zone, and lower during migratory periods, when birds typically fly higher and are less exposed to turbine blades.

2. Materials and Methods

2.1. Study Area

The research was conducted in the Kaliakra region, Dobrich Province, Northeastern Bulgaria, part of the Dobruja Plateau and located within the Continental biogeographic region [20]. The area lies along the Via Pontica migration flyway, one of Europe's most important routes for migratory birds, and includes breeding and wintering grounds for several raptor species of conservation concern. The climate is temperate-continental with maritime influence from the Black Sea; summers are hot, winters mild, and mean annual precipitation is ~450–500 mm [42]. Vegetation is dominated by steppe grasslands and arable farmland (wheat, maize, sunflower), with scattered shrublands and small woodland patches [20].

The study area (Figure 1) and its surroundings contain 114 operational wind turbines distributed across approximately 249 km^2 (≈24,900 ha). Inter-turbine distances vary from ~115 m to ~11.8 km, reflecting multiple projects and layouts. Turbine models vary in hub height and rotor diameter, influencing the vertical extent of the rotor-swept zone. Most turbines are sited in open agricultural landscapes and on elevated plateaus to maximize wind exposure. The main technical specifications of the wind turbines in the study area are summarized in Table 1, and these parameters were used to define the vertical extent of the rotor-swept zone in the collision-risk modelling.

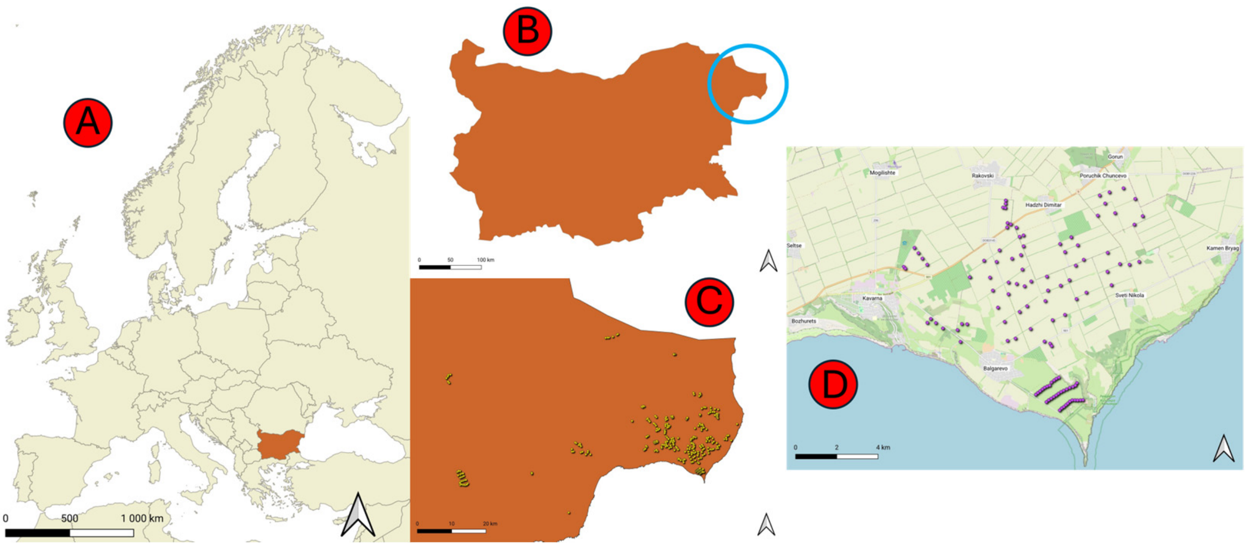

Figure 1. Location and spatial context of the study area in Northeastern Bulgaria. (**A**) Map of Europe showing the location of Bulgaria. (**B**) Map of Bulgaria with the study area in the Northeast highlighted. (**C**) Distribution of wind farms in the northeastern region of Bulgaria. (**D**) Detailed map of the study area with the locations of individual wind turbines.

Table 1. Basic technical specifications of the wind turbines operating in the study area.

Model	Number of Turbines	Rotor Diameter (m)	Hub Height (m)
Mitsubishi MWT-1000A	35	61.4	69
Vestas V90	73	90.0	105
HSW 250 T	6	28.5	50

Habitats in the area provide suitable foraging grounds for Common Buzzards due to abundant prey, including small mammals such as common vole (*Microtus arvalis*) and wood mouse (*Apodemus sylvaticus*) [43], and reptiles such as the European green lizard (*Lacerta viridis*) [44], as well as the availability of perching and nesting sites.

2.2. Study Species

The Common Buzzard is a widespread, medium-sized diurnal raptor across Europe and parts of Asia. It is listed as Least Concern on the IUCN Red List [45], with a global population estimated at 3.6–6.0 million mature individuals, including ~2.0–3.7 million breeding pairs in Europe and ~12,000–18,000 breeding pairs in Bulgaria. The species typically breeds in forests, woodland edges, and agricultural mosaics, nesting in trees but occasionally also on cliffs or artificial structures [46]. Within our study area, suitable nesting conditions are present in small forest patches and shelterbelts, and several active nests have been confirmed, generally located at distances > 500 m from wind turbines. The number of breeding pairs varies between years in response to fluctuations in prey abundance, particularly of small mammals, which strongly influences Common Buzzards density and breeding success [47].

In Central and Western Europe populations are largely resident, while northern and eastern populations are migratory, moving south across Eastern Europe and the Balkans during autumn and returning north in spring [45]. The study area is situated along the Via Pontica flyway, one of the most important raptor migration corridors in Europe [20], where large numbers of Common Buzzards are recorded annually. Regional counts have documented tens of thousands of migrants at coastal sites [48], and vantage-point surveys in our study area between 2019 and 2023 recorded between 1169 and 4129 individuals per season crossing the area of a single turbine [40].

The diet of the Common Buzzard is opportunistic, including small mammals such as voles and mice [43], reptiles such as the European green lizard (*Lacerta viridis*) [44], as well as birds and carrion, reflecting the species' considerable behavioural flexibility in foraging strategies. Key threats include habitat loss, illegal persecution, collisions with turbines and vehicles, and secondary poisoning from rodenticides [38].

2.3. Study Design and Concepts

We investigated the theoretical survival probability of Common Buzzards passing through a wind farm area in Northeast Bulgaria. The study combined long-term GPS tracking data with systematic visual monitoring of raptor flights and carcass searches under operational turbines. We used seasonal flight-height distributions as inputs to a stochastic Monte Carlo implementation of the Band model [5,41] to estimate collision probability across turbine configurations. The study design is summarized in Figure 2.

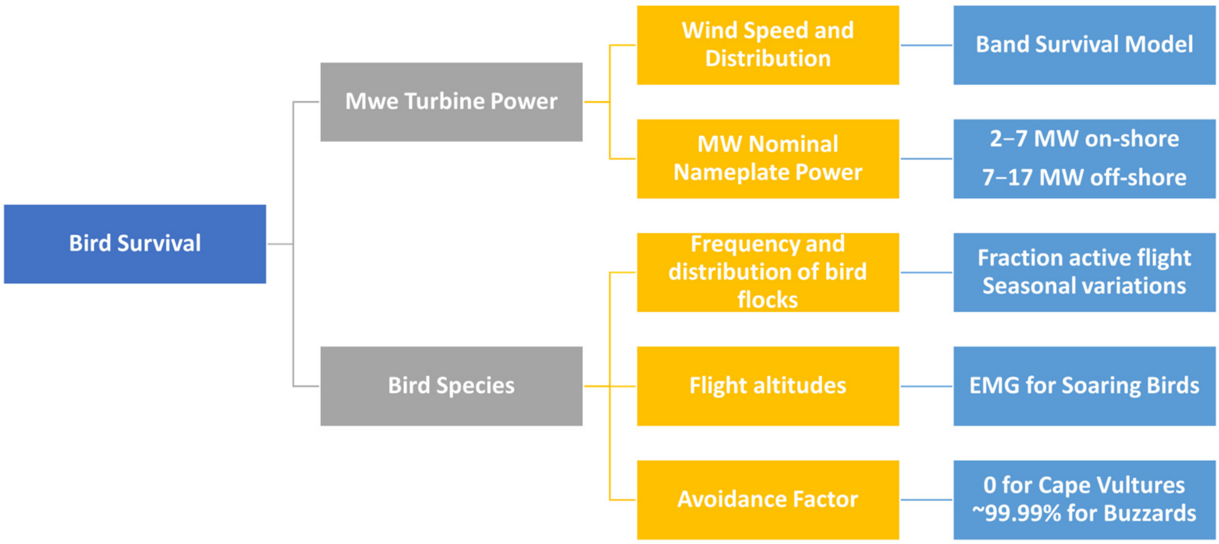

Figure 2. Schematic of study design and data flow.

2.4. Data Collection

2.4.1. GPS Tracking

We used solar-powered GPS/GSM tags (Druid LEGO 2G, weight 18.7 g) deployed on nine B. buteo individuals. Each device recorded location, orthometric and ellipsoid altitude, ground speed, and other telemetry parameters with spatial accuracy of ~5 m. Devices were powered by integrated solar panels, enabling up to 2000 fixes per day. Altitude values from ellipsoid measurements were converted to orthometric heights using the UNAVCO Geoid Height Calculator (EarthScope Consortium, Washington, DC, USA) [18,49]. Only GPS fixes with ground speed >0 were retained for flight-height analysis.

2.4.2. Visual Observations

Standardized daytime vantage-point (VP) surveys followed the Ornithological Monitoring Plan developed for the Saint Nikola Wind Farm [39], which is consistent with international standards for raptor monitoring at wind facilities [14,50]. Fixed observation points were selected to cover turbine clusters and the main raptor flight corridors. At each of the six VP stations, one observer was continuously present, and an additional mobile observer assisted in tracking flocks across the wind farm area. Surveys were conducted during autumn migration (15 August–31 October), wintering (December–February), and spring migration (15 March–15 May) between 2019 and 2023 and the results were included in seasonal public reports [40]. Observations were carried out daily from sunrise to sunset under suitable weather conditions (no fog, heavy precipitation, or strong winds > 10 m/s). Each station was equipped with 10× binoculars, 20–60× spotting scopes, GPS, and compass. Experienced observers recorded, for each bird or flock, species (with age/sex where possible), number, flight direction and behaviour, as well as prevailing weather. Horizontal distance and flight altitude were estimated using calibrated landmarks and GPS-based trials, and flight heights were assigned to predefined 10 m bands (0–10 m, . . ., >500 m) for consistency and integration with the collision-risk model [30]. Routine VP surveys reported in the public monitoring database were conducted only during spring and autumn migration and wintering. Observations were also carried out during the breeding period (June–July), but these were not part of the standardized monitoring programme and were therefore not included in the publicly available reports. Seasonal flight-height patterns for this period were primarily derived from GPS tracking, complemented by these ad hoc field observations (Figure 3).

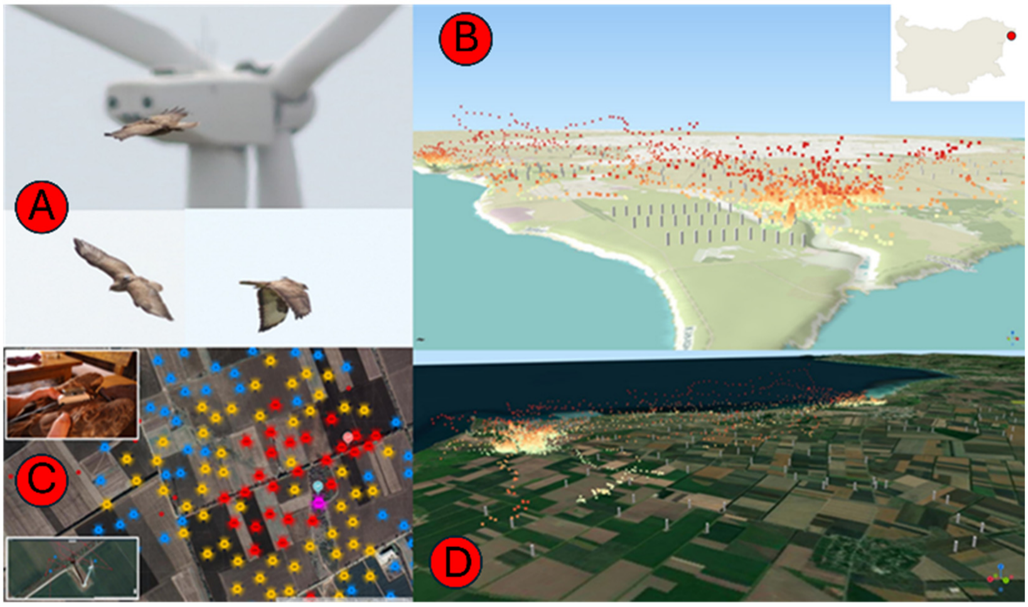

Figure 3. Study area, field methods, and spatial distribution of bird tracking data. (**A**) Common Buzzards flying near a wind turbine within the study area in NE Bulgaria. (**B**) 3D visualization of GPS tracking data showing bird flight altitude and density across the coastal wind farm landscape. (**C**) Clustered GPS locations of a tagged Common Buzzard in the core wind farm area, with inset photo taken during the tagging procedure. (**D**) 3D spatial overview of Common Buzzard movements and wind turbine positions across the agricultural landscape.

The total observation effort amounted to 21,840 h in autumn migration (2019–2023), 25,200 h in wintering, 17,360 h in spring migration, and 17,080 h in the breeding period. At each of the six fixed vantage points, one observer was continuously present, and an additional mobile observer assisted in tracking flocks across the wind farm area, consistent with the Saint Nikola Ornithological Monitoring Plan. A Kruskal–Wallis test showed significant differences in total observation effort among seasons (H = 19.0, df = 3, $p < 0.001$). Post hoc pairwise comparisons indicated that wintering and autumn migration had significantly higher observation effort than spring migration and the breeding period, while spring and breeding did not differ significantly from each other.

2.5. Carcass Searches

Systematic carcass searches followed the Ornithological Monitoring Plan for the Saint Nikola Wind Farm [39], which was adapted from the protocols described by Morrison et al. (2008) [39]. From 2018 to 2023, all 114 operational turbines in the study area were monitored. Searches were carried out in 200 × 200 m plots centred on each turbine, with parallel transects spaced 20 m apart; where vegetation reduced visibility (e.g., unharvested sunflower), transects were narrowed to increase detection probability. During autumn migration (15 August–31 October), wintering (December–February), and spring migration (15 March–15 May), turbines were searched once every seven days, and the results were included in seasonal public reports [40]. Outside these periods, including the breeding season (June–July), searches were performed every 14 days. Each search lasted approximately 30 min per turbine (park-wide 57 h per pass) and was conducted during daylight hours under suitable weather conditions.

This design resulted in total search efforts of 3135 h in autumn migration (2019–2023), 3705 h in wintering, 2565 h in spring migration, and 1140 h in the breeding period. A Kruskal–Wallis test confirmed significant differences in carcass-search effort among seasons (H = 19.0, df = 3, $p < 0.001$). Post hoc pairwise comparisons indicated that wintering and autumn migration had significantly higher effort than the breeding period, while spring and breeding did not differ significantly.

Observers documented every find with photographs, date and time, GPS coordinates, distance and bearing to the nearest turbine, carcass condition (intact, scavenged, or feather spot), and completed a written protocol. Each turbine check was supported by a GPS track. All carcasses were photographed and archived, and carcasses found during the breeding season are reflected in our dataset, even though this period was not covered by the standard seven-day monitoring scheme. Searcher-efficiency and carcass-persistence trials were carried out periodically throughout the study period, most recently in 2022, and the results are publicly available [40].

This monitoring design is consistent with international standards for collision fatality monitoring at wind facilities [32] but was adapted to local conditions in Northeastern Bulgaria, including extensive agricultural landscapes and seasonal changes in vegetation cover.

2.6. Data Processing and Modelling

Flight-height distributions were modelled using the Exponentially Modified Gaussian (EMG) distribution. Seasonal distributions derived from GPS and visual data were bootstrapped to account for inter-individual variation. These distributions were integrated into a stochastic Monte-Carlo implementation of the Band collision risk model [5,41] to estimate collision probability for different turbine configurations. Differences in seasonal flight altitudes were tested using the Kruskal–Wallis test, followed by post hoc pairwise comparisons with Bonferroni correction. All statistical analyses were performed in R version 4.3.2 [51]. In addition to the standardized carcass searches, systematic collision-victim monitoring was organized and performed by the Integrated System for Bird Protection (ISBP) in the Kaliakra SPA territory. These data provided an independent basis for comparison between the collision probabilities predicted by our model and the actual mortality recorded during six years of systematic searches. Mathematical details of the EMG (Figure 4) formulation are provided in the Supplementary Materials (Equations (S1)–(S3)). An illustrative example of the fitted distribution is shown in Supplementary Figure S1, and the SciLab script used for the simulations is available as Supplementary Code S1.

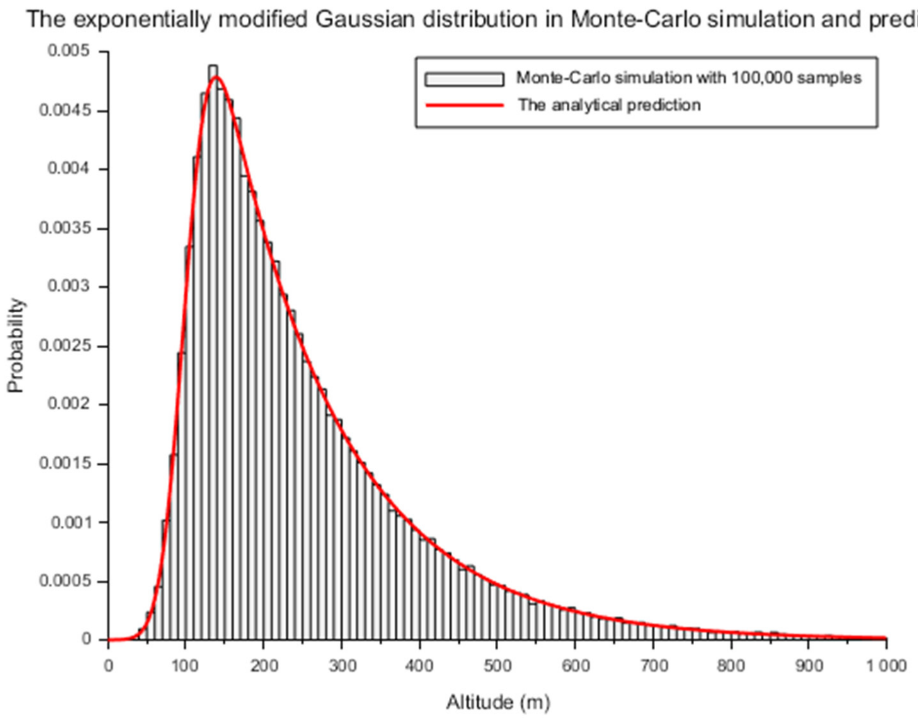

Figure 4. Example of the Exponentially Modified Gaussian EMG in Monte-Carlo simulation and analytical prediction.

3. Results

3.1. Flight Height Distributions

In periods of breeding and wintering, the flight height distributions were clearly unimodal (Figure 5). During the breeding season, Common Buzzards flew at mean altitudes of 68.2 ± 20.4 m (n = 13,047 GPS fixes), while in winter flight height was 68.0 ± 30.3 m (n = 247). In both cases, most flights were concentrated within the rotor-swept zone. By contrast, during migration the distribution shifted upward, with a mean flight altitude of 557.4 ± 372.3 m (n = 10,696), greatly reducing the overlap with turbine rotors. A Kruskal–Wallis test confirmed significant differences in flight altitude among seasons (H = 1138.4, df = 2, $p < 0.001$).

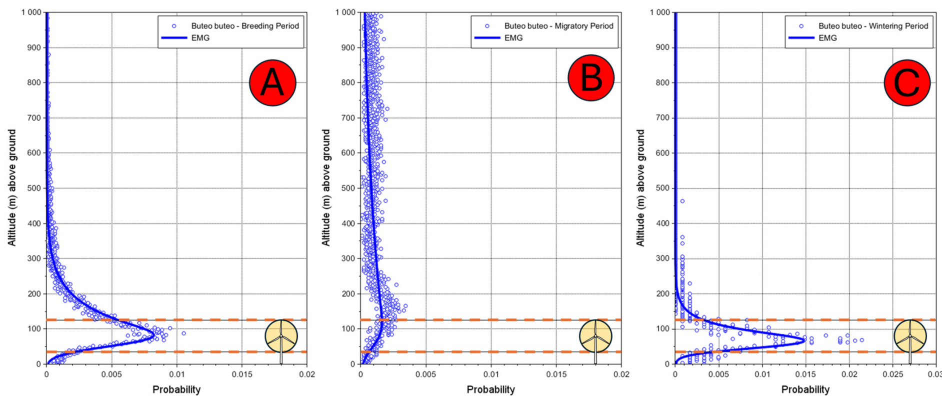

Figure 5. Seasonal variation in flight height distributions of Common Buzzards in relation to wind turbine rotor-swept zones. (**A**) Breeding period: probability distribution of flight altitude above ground with observed data and fitted Exponentially Modified Gaussian (EMG) model. (**B**) Migration period: probability distribution of flight altitude with observed data and fitted EMG model. (**C**) Wintering period: probability distribution of flight altitude with observed data and fitted EMG model. The orange dashed lines represent the lower and upper limits of rotor height for typical turbines in the study area. The rotor icon in the bottom-right corner of each panel visualizes this range.

Seasonal differences in flight altitude were evident (Figure 5, Table 2). During wintering, Common Buzzards flew at low altitudes, with a mean of 68.0 ± 30.3 m (n = 247), reflecting short local flights between perches and feeding sites. In the breeding season, mean altitude was similar (68.2 ± 20.4 m, n = 13,047), but the overall flight activity was higher due to increased food requirements for growing offspring. In contrast, during migration Common Buzzards flew substantially higher, with a mean of 557.4 ± 372.3 m (n = 10,696), as birds undertook long-distance transit flights. A Kruskal–Wallis test confirmed significant differences in flight altitude among seasons (H = 1138.4, df = 2, $p < 0.001$). This seasonal pattern strongly influenced the probability of collision with wind turbines: risk was greatest in winter and breeding, when flights were concentrated within the rotor-swept zone, and lowest during migration, when most flights occurred above rotor height. Collision probability (CP) also varied between turbine models. Monte-Carlo simulations were run for each turbine type using observed flight-height distributions to quantify differences in CP associated with rotor diameter and hub height. An illustrative example of the simulated spatial distribution of bird positions around a turbine is shown in Figure 6.

Table 2. Characteristic data of Common Buzzard GPS tracking in Bulgaria.

Bird Flight Type	Number of GPS	Data Collection Period		EMG * Gaussian Mean and Standard Deviation		EMG * Exponential Decay
	Tracking Positions	From	To	μ (m)	±σ (m)	τ (m)
Breeding	13,047	6 November 2021	29 June 2022	68.2	±20.4	86.2
Migratory	10,696	24 March 2023	20 November 2023	557.4	±372.3	184.3
Wintering	247	18 January 2022	24 January 2022	68.0	±30.3	33.7

Note: "Data collection period" refers to the range of GPS tracking dates used for seasonal analyses. Seasonal assignments (Breeding, Wintering, Migratory) follow the species' known annual cycle and were defined based on calendar periods (Breeding: April–June; Wintering: December–February; Migration: March–May and August–October). EMG = Exponentially Modified Gaussian distribution, with μ representing the Gaussian mean, σ the standard deviation, and τ the exponential decay parameter.

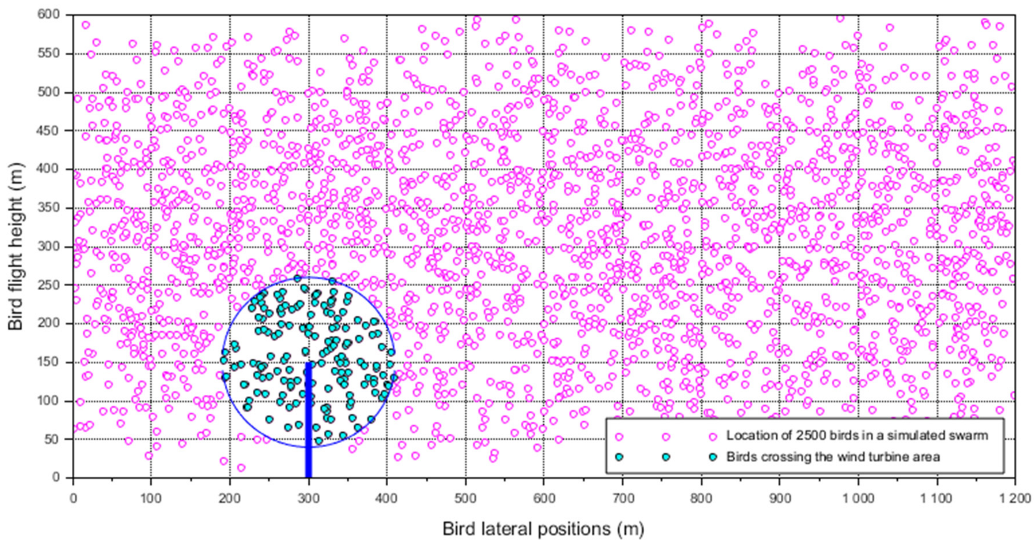

Figure 6. Stochastic model by Monte-Carlo simulations of 2500 birds' distribution in air volume around a wind turbine used in our model.

3.2. Seasonal Variations in Number of Birds at the Risk Zone

For seasonal variation in the collision probability, we have applied data from a permanent Vantage Point (VP) used for monitoring of the birds in the study are in the middle of the area where 114 wind turbines operate in the moment. The data on the number of birds passing through the territory in different seasons, together with the timing, scope, and full details of the visual observation methodology, are available in the long-term monitoring database [40]. According to this data, the number of Common Buzzards passing the area of one single wind turbine with a range around the VP 4 km diameter varies between 1169 and 4129 Common Buzzards. in the period 2019–2023. For our model we have applied an average number of 2355 Common Buzzards passing per year the space of one turbine within an area with diameter 4 km.

Based on the data from permanent VP observations and data from GPS tracking of eight Common Buzzards in the last 3 years we have obtained numbers of Common Buzzards crossing the risky zone per every period of the life cycle of the species.

The model estimated the highest number of passing within the risky zone for wintering period when the number of Common Buzzards at risk are between 76 and 234 for turbines of 2, 6 and 12 MW, respectively. Similar values were estimated for Common Buzzards in the breeding season with variations between 64 and 236 (Figure 7).

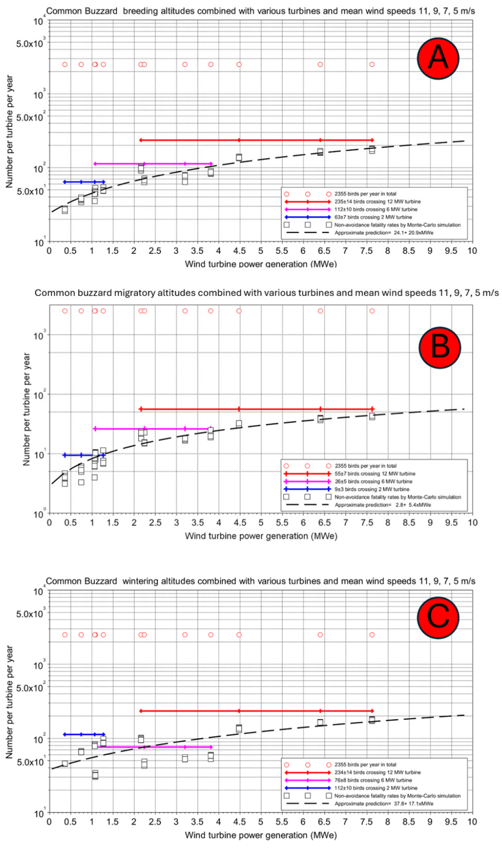

Figure 7. Predicted number of Common Buzzards entering the rotor-swept zone of wind turbines with different rated capacities during (**A**) breeding, (**B**) migration, and (**C**) wintering periods, based on Monte Carlo simulations using seasonal flight-height distributions. Horizontal lines show mean ± SD annual crossings; open squares indicate non-avoidance fatality rates; dashed line represents the approximate prediction curve.

The lowest number of birds at risky zones in the migratory season when 6 to 12 Common Buzzards were in the risky zone of a 2 MW turbine. For bigger turbines with bigger capacity this number increases and reaches 25 and 55 Common Buzzards per season, respectively, for 6 MW and 12 MW turbines (Figures 8–10).

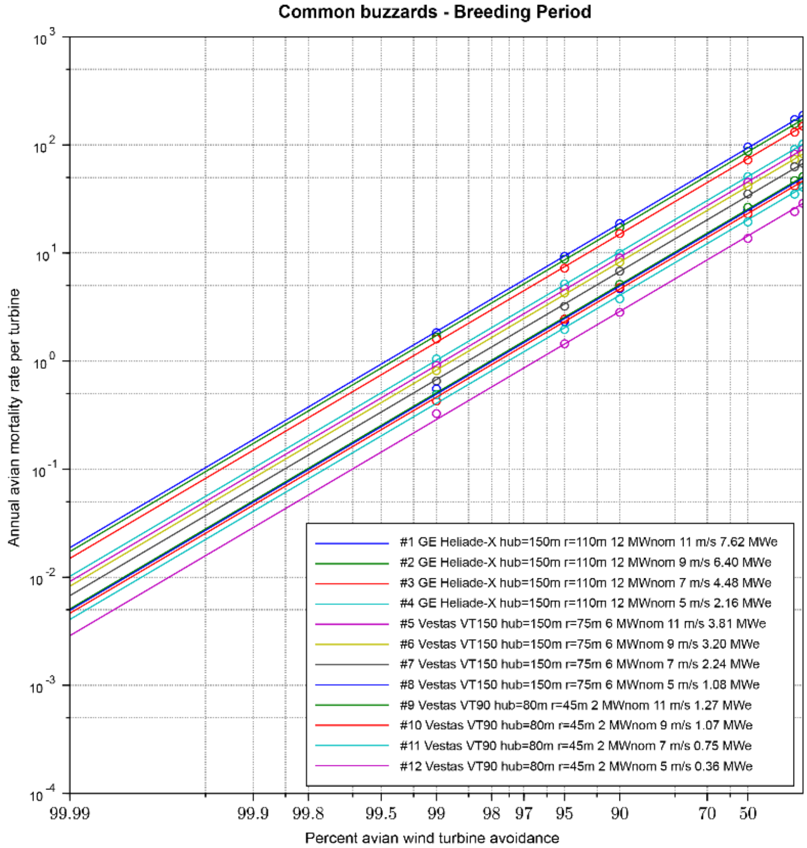

Figure 8. Predicted number of Common Buzzards entering the rotor-swept zone during the breeding season (2, 6 and 12 MW turbines; Monte Carlo estimates; mean ± SD).

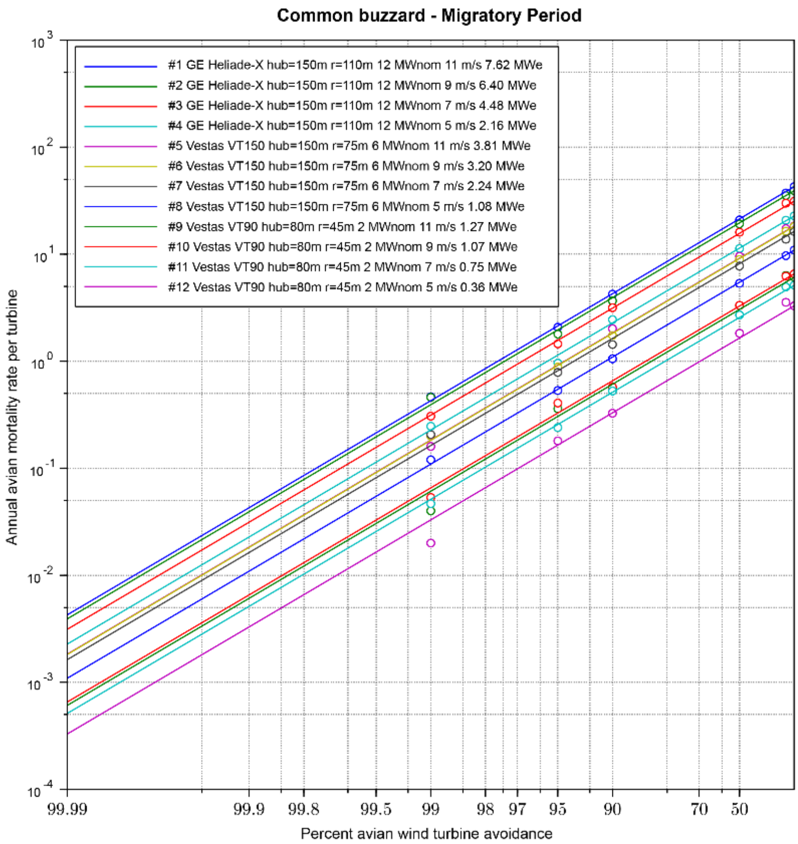

Figure 9. Predicted number of Common Buzzards entering the rotor-swept zone during the migration season (2, 6 and 12 MW turbines; Monte Carlo estimates; mean ± SD).

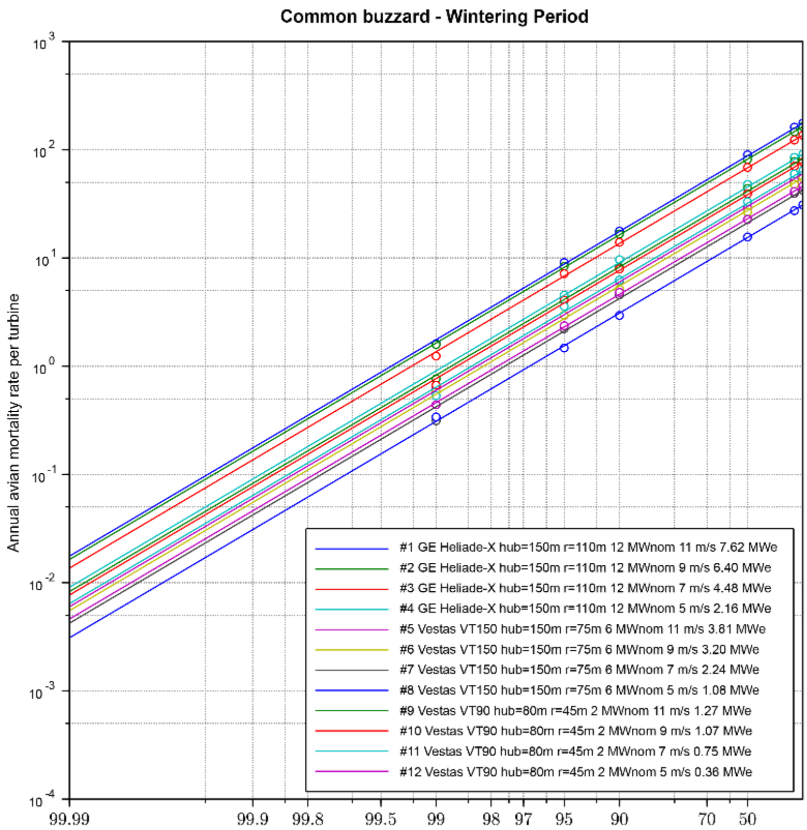

Figure 10. Predicted number of Common Buzzards entering the rotor-swept zone during the wintering season (2, 6 and 12 MW turbines; Monte Carlo estimates; mean ± SD).

Collision probabilities are reported for avoidance levels of 95% and 99%, which are within the range commonly applied for raptors in collision risk modelling [7,27]. These scenarios represent realistic behavioural responses of Common Buzzards and correspond to predicted annual fatalities below 1 bird per turbine (Table 3).

Table 3. Modelled annual collision risk per turbine for Common Buzzards at avoidance levels of 50%, 90%, 95% and 99% across seasons. Values are approximate ranges across turbine configurations.

Season	Avoidance (%)	Min Mortality/Turbine	Max Mortality/Turbine
Wintering	90	2	12
	95	0.3	2.5
	99	0.01	0.25
Migratory	90	1	6
	95	0.1	1.2
	99	0.005	0.1
Breeding	90	1.5	8
	95	0.25	2
	99	0.01	0.15

The field data support the simulation results. The low mortality detected in carcass searches indicates a high avoidance rate in Common Buzzards (Table 4). In our analyses, the species consistently appeared among those with the lowest predicted collision probabilities (Figures 8–10).

Table 4. Data from systematic collision monitoring in 114 wind turbines in the study territory in the period 2018–2023.

Period of Annual Cycle	Number of Collision Victims	Number Per Year in 114 Turbines	Number Per Year Per Turbine
Breeding period	3	0.5	0.004386
Migratory period	2	0.3	0.002632
Wintering period	5	0.8	0.007018
Total 2018–2023	10	1.6	0.014035

4. Discussion

We found that collision probability for Common Buzzards in the studied wind farm area was relatively low, with clear seasonal variation: the highest estimated risk occurred during wintering and breeding periods, when flights were more frequently within the rotor-swept zone, and the lowest during migration, when birds flew at higher altitudes. These modelled probabilities closely matched carcass search results from 114 turbines over multiple years, indicating a high avoidance rate in this species.

These findings contrast with the high vulnerability reported for Hen Harriers (*Circus cyaneus*) and Golden Eagles (*Aquila chrysaetos*) in Scotland [6,7,11], Griffon Vultures (*Gyps fulvus*) in Spain [9,10], and White-tailed Eagles (*Haliaeetus albicilla*) in Norway [13], where mortality rates have been substantially higher. The lower risk observed in our study species may be related to the greater behavioural flexibility and variable flight heights of Common Buzzards compared with these large soaring raptors and vultures.

Our results are consistent with the general pattern reported for Common Buzzards in Brandenburg, Germany, where collision risk was shown to be influenced by proximity to open habitats and specific landscape features [18]. In both cases, Common Buzzards were more exposed when flying low over open farmland, particularly outside migration periods. However, the absolute mortality rates in our study area were lower than those extrapolated in the PROGRESS study [52]. One reason for this difference may be the more dispersed turbine placement in our site, with average inter-turbine distances exceeding 5 km, reducing cumulative risk.

Comparisons with Finnish studies on Golden Eagles (*Aquila chrysaetos*) [19,20] reveal differences in species-specific responses. While Golden Eagles generally avoid turbines and maintain high survival in turbine-free areas, they may experience population-level impacts when mortality increases even slightly, due to their low reproductive rate. Common Buzzards, with higher reproductive potential and greater habitat flexibility, may adapt their flight behaviour seasonally to minimize collision risk, as indicated by our observed migration altitudes. This aligns with broader analyses that identify life-history traits such as flight type and reproductive rate as key predictors of species' sensitivity to wind farms [4,5,35].

Evidence from modelling studies in the UK and Scotland [45,49] shows that spatial planning can significantly reduce collision risk for large raptors by identifying high-use flight paths and avoiding turbine placement in these areas. Similar model-based approaches in Finland and Spain have highlighted how habitat selection by Golden Eagles and subadult White-tailed Eagles can guide safer siting of turbines [21,53], while predictive models for large soaring raptors confirm that local topography and turbine placement strongly influence risk [42]. More recent studies also demonstrate that turbine dimensions, particularly the hub height and rotor diameter, can alter exposure probabilities in ways that must be accounted for in risk assessments [54].

In addition to direct mortality, displacement effects may also play an important role in shaping the impact of wind farms on raptor populations. Several studies have indicated that displacement, through reduced use of habitats near turbines, can sometimes exceed the demographic consequences of collision mortality [4]. We did not find evidence of such effects in Common Buzzards in our study area, but acknowledging their potential importance is necessary for comprehensive impact assessment and for guiding future monitoring programmes.

Our study has several limitations that should be acknowledged. Increasing the number of GPS-tracked Common Buzzards would provide a larger sample size and allow even more precise estimates of seasonal flight-height distributions. GPS altitude measurements, although corrected, remain subject to errors inherent to all GPS devices, which may affect the precision of flight-height estimates. Vantage-point surveys and carcass searches were conducted only during daylight hours, and results may therefore not fully capture potential differences in bird activity and carcass detectability between morning, daytime, and evening periods. Carcass searches are further constrained by detection probability, scavenger removal, and habitat conditions, while collision-risk models rely on assumptions that inevitably simplify bird behaviour and turbine operation. These limitations are common to all studies assessing wind farm impacts on birds and highlight the need for cautious interpretation of absolute risk estimates. From a management perspective, several mitigation measures have been proposed to reduce collision risk. Field trials in Norway demonstrated that painting a single rotor blade in black reduced bird mortality by more than 70% compared with unpainted turbines [34]. Other approaches include the use of bioacoustic deterrents, such as playback of predator and alarm calls combined with visual models, which displaced small birds in short-term trials in Nova Scotia [55]. Future research should aim to expand the sample size of tracked individuals and to include additional species, thereby improving the generality of impact assessments and providing stronger guidance for conservation-oriented planning of wind energy developments.

5. Conclusions

Our study demonstrates that the collision risk for Common Buzzards in the investigated wind farm area is low, with marked seasonal variation driven by flight-height behaviour. The highest potential risk occurs during wintering and breeding seasons, when birds more often enter the rotor-swept zone, while migration periods pose the lowest risk due to higher flight altitudes.

The strong agreement between the modelled probabilities and observed carcass data confirms that integrating high-resolution GPS tracking with systematic mortality monitoring can produce reliable collision risk estimates. This approach enables more precise, species-specific EIA and can inform targeted mitigation, such as seasonal turbine shutdowns that balance renewable energy development with raptor conservation.

Our findings underline the importance of tailoring wind farm planning and mitigation measures to the ecology and seasonal behaviour of focal species, and of validating predictive models with long-term field data.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/birds6030050/s1, Equations (S1)–(S3): EMG formulation and simulation procedure. Figure S1: Example of the Exponentially Modified Gaussian (EMG) in Monte Carlo simulation and analytical prediction. Code S1: SciLab script used for the Monte Carlo simulation.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are stored in a shared Movebank project and are not publicly available due to restrictions related to sensitive species location information.

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