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# Long-Term Decline in Bird Collisions at Operational Wind Farms: Evidence from Systematic Monitoring to Support Sustainable Wind Energy Development (2010–2024)

**Nikolay Yordanov [1,*], Pavel Zehtindjiev [1] and D. Philip Whitfield [2]**

[1] Institute of Biodiversity and Ecosystem Research at the Bulgarian Academy of Sciences, 1000 Sofia, Bulgaria; pavel.zehtindjiev@gmail.com
[2] Natural Research Ltd., Banchory AB31 4BY, Aberdeenshire, UK; phil.whitfield@natural-research.org
* Correspondence: ecopraxis.yordanov@gmail.com

## Abstract

The rapid expansion of wind energy in Southeast Europe has raised concerns about its long-term impacts on bird populations, particularly through collisions with wind turbines. Here, we analyze systematic collision monitoring data collected between 2010 and 2024 within the Integrated System for Protection of Birds in the Kaliakra Protected Area (northeast Bulgaria). Monitoring covered 52 wind turbines until 2017 and 114 turbines from 2018 onwards, using daily carcass searches within standardized 200 × 200 m plots around each turbine. Collision rate was analyzed using effort-normalized statistical models and spatial (GIS-based) analyses to assess temporal trends and habitat context derived from land-cover data. Effort-normalized analyses indicate that collision rate per turbine varied over time and exhibited a pronounced long-term decline, together with clear spatial heterogeneity. Turbines located in open steppe landscapes were associated with consistently higher collision rates compared to turbines situated in other habitat types. These results provide long-term empirical evidence from an operational wind farm area, contributing robust baseline information for cumulative impact assessment and spatial planning. From a sustainability perspective, long-term, effort-standardized collision monitoring represents a critical tool for balancing renewable energy expansion with biodiversity conservation. By providing empirical evidence on how collision occurrence evolves under sustained operational conditions, this study supports adaptive mitigation, cumulative impact assessment, and spatial planning frameworks essential for the sustainable development of wind energy in ecologically sensitive regions.

**Keywords:** wind energy; bird collisions; long-term monitoring; sustainable development; adaptive mitigation; cumulative impact assessment; spatial planning; Southeast Europe

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Academic Editor: Francesco Sottile

Received: 24 December 2025
Revised: 14 January 2026
Accepted: 16 January 2026
Published: 19 January 2026



## 1. Introduction

The transition towards climate-neutral energy systems is a central element of contemporary environmental policy [1] but it also introduces new pressures on biodiversity [2]. Among renewable energy technologies, wind energy has expanded rapidly across Europe [3], including Southeast Europe, where large areas of open agricultural and steppe landscapes are increasingly targeted for wind farm development. While wind energy contributes to climate change mitigation, its deployment may conflict with biodiversity conservation objectives if ecological impacts are insufficiently understood or addressed.

Collisions between birds and wind turbines represent one of the most widely documented direct impacts of wind energy infrastructure on wildlife [4,5]. Existing research has demonstrated that collision occurrence varies across species assemblages, turbine configurations, and landscape settings. In Southeast Europe and adjacent regions, including the Balkans and Turkey, empirical evidence is primarily derived from site-specific collision risk assessments and short-term post-construction monitoring. For example, collision risk analyses conducted at wind farms in Romania [6] have documented bird fatalities based on standardized carcass searches over limited monitoring periods (e.g., Cernavoda I and II wind farms), while studies from Greece [7] report species presence and behavioral interactions with turbines but often record few or no collision events. Similar short-term approaches dominate published collision assessments in Turkey [8] and neighboring regions, where monitoring is typically embedded within environmental impact assessment frameworks. While these studies provide important insights into local collision patterns, their limited temporal scope restricts inference on longer-term dynamics at fully operational wind farms. Consequently, uncertainty remains regarding whether collision victims per turbine represents a stable long-term characteristic or whether it changes over time as bird communities and wind energy infrastructure coexist under prolonged operational conditions [9].

From a theoretical perspective, long-term changes in collision rates at operational wind farms may arise from multiple, not mutually exclusive mechanisms. These include behavioral responses of birds to turbines over time (e.g., avoidance or habituation), shifts in local species composition driven by displacement or broader landscape change, and changes in exposure linked to interannual variability in bird abundance or environmental conditions. In addition, apparent temporal trends in collision victims may partly reflect methodological or operational factors, such as changes in turbine density, spatial configuration, or monitoring effort, rather than biological processes alone [10]. Distinguishing between these alternative explanations remains a key challenge in wind–wildlife research, particularly in regions where evidence is largely derived from short-term or project-based monitoring. Long-term, standardized datasets are therefore essential to evaluate whether observed changes in collision rates represent stable ecological responses, transient dynamics, or cumulative effects emerging over extended operational periods.

Reliable quantification of collision risk is essential for evaluating population-level significance and for conducting cumulative impact assessments, particularly in regions where multiple wind farms operate within ecologically sensitive landscapes. Recent studies have emphasized that cumulative effects of wind energy infrastructure cannot be inferred from single-project assessments alone but require spatially and temporally explicit data that account for the combined influence of multiple installations operating over extended periods. This issue has been increasingly addressed in the literature, including recent syntheses of the environmental impacts of wind farms that highlight the need for long-term monitoring and integrated assessment frameworks [11]. These considerations are especially relevant for Southeast Europe, where rapid expansion of wind energy is projected to overlap with major migration corridors and extensive open habitats used by large soaring birds, raising concerns about cumulative effects that may not be detectable through short-term or project-based studies. In this context, long-term, standardized carcass monitoring provides a unique opportunity to assess temporal and spatial patterns of collision victims under real operational conditions. By combining systematic collision data with spatial (GIS-based) analyses of habitat context, it becomes possible to identify landscape features associated with elevated number of collision victims and to evaluate whether collision probability per turbine changes over time.

The objective of this study is to quantify bird collision victims at an operational wind farm in the Kaliakra Protected Area (northeast Bulgaria) using long-term carcass monitoring data collected between 2010 and 2024. Specifically, we aim to:

(i) Examine whether collision rates per turbine exhibit consistent long-term temporal trends under sustained operational conditions;
(ii) Account for biologically relevant monitoring periods associated with migration and wintering within the long-term collision framework;
(iii) Evaluate the role of landscape context in shaping spatial heterogeneity in collision victims across turbines within a large operational wind farm area.

By providing empirically derived, effort-standardized estimates of collision victims, this study contributes baseline information for cumulative impact assessment and supports evidence-based spatial planning and mitigation of wind energy developments in open landscapes of Southeast Europe.

## 2. Materials and Methods

### *2.1. Bird Collision Monitoring*

Bird collision monitoring was conducted within the framework of the Integrated System for Protection of Birds (ISPB) operating in the Kaliakra Protected Area (northeast Bulgaria). The system applies a unified and standardized protocol for detecting bird collisions at operating wind farms and has been implemented continuously since 2010 [4].

Monitoring was carried out at all wind turbines included in the ISPB [5]. From 2010 to 2017, collision searches covered 52 wind turbines, while from 2018 onwards, following the inclusion of additional wind energy operators, the total number of monitored turbines increased to 114. This configuration remained unchanged until 2024.

Carcass searches were conducted according to a seasonally structured survey schedule reflecting periods of elevated bird activity. During spring migration (15 March–15 May), autumn migration (15 August–31 October), and wintering bird monitoring (December–February), each individual wind turbine was surveyed once per week. Outside these periods, turbines were surveyed once every two weeks. A fixed 200 $\times$ 200 m plot centered on each turbine was systematically searched on foot, ensuring consistent spatial coverage across turbines and years.

Field surveys were carried out by trained observers operating under a unified and standardized protocol. For each survey, observers completed a field protocol documenting the date, start and end time of the search, the turbines inspected, and any collision victims detected. All recorded carcasses were photographed for species verification, and survey routes were documented using GPS tracking based on raw .gpx files downloaded from handheld GPS devices; no dedicated tracking software was used. Observers were equipped with GPS devices to verify survey coverage and effort, and all field records were centrally compiled and quality-checked.

Although the monitoring network expanded after 2018 with the inclusion of additional wind farm operators, all participating teams applied identical survey procedures and documentation requirements. Centralized coordination, standardized training, and verification of survey effort were used to ensure methodological consistency and comparability of records across turbines, seasons, and years.

For each collision victim detected, the following information was recorded: species, sex and age (when identifiable), date of detection, geographic coordinates (GPS), distance and direction from the nearest turbine, condition of the carcass, and relevant environmental or contextual observations. Feathers or other remains were collected when necessary to support identification. Monitoring results were summarized at seasonal and annual scales and reported in regular public reports of the ISPB [5], forming the basis for subsequent analyses of temporal trends, and spatial associations with landscape context.

The monitoring design and search protocol applied in this study are consistent with those previously developed and applied for long-term assessments of bird collision victims at wind farms in the Kaliakra region [12].

### 2.2. Visual Observations

Standardized daytime vantage-point (VP) surveys followed the Ornithological Monitoring plan developed for the Saint Nikola Wind Farm [4], which is consistent with international standards for raptor monitoring at wind facilities [13,14]. 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 [5]. 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 behavior, 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 [15]. 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 program 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. 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. More details about the monitoring program were previously published [12].

Visual observation data were not included in the statistical analyses presented here but are referenced to provide ecological context for bird presence and activity patterns within the study area.

### 2.3. Carcass Removal and Searcher Efficiency Trials

Carcass removal and searcher efficiency trials were conducted to evaluate the performance of the collision monitoring protocol and to assess potential sources of bias related to carcass persistence and detectability. These trials served as methodological validation of the monitoring design rather than as a basis for correcting collision counts used in the main statistical analyses.

https://doi.org/10.3390/su18020992

Controlled experiments using poultry carcasses of known origin were conducted at the Saint Nikola Wind Farm [5]. Initial trials were carried out in autumn 2009, followed by additional experiments in autumn 2010, autumn 2014, and winter 2010/2011. The primary objective of these trials was to assess searcher efficiency and carcass removal rates under local conditions and to evaluate the suitability of the adopted search protocol.

In the autumn 2010 trial, five plots centered on representative turbines (T25, T43, T49, T51, T54) were selected to reflect prevailing crop types and ground cover. Five hen carcasses were randomly placed within each plot on 20 August 2010, with locations recorded using GPS. Searches were conducted the following day along transects spaced at 20 m intervals by a searcher unaware of carcass placement. Immediately after each search, carcass presence or removal was verified, and carcasses were subsequently revisited at regular intervals until complete disappearance (final visit on 6 September 2010).

These trials demonstrated high searcher efficiency (approximately 89.5%) and carcass removal rates comparable to those reported in similar studies [10,16]. Comparable experiments conducted in autumn 2018 and winter 2022, coinciding with the expanded ISPB framework, produced consistent results, supporting the robustness of the monitoring protocol under varying annual and seasonal conditions.

### 2.4. Spatial Data and Habitat Context

Spatial analyses were conducted to evaluate the relationship between bird collision occurrences and landscape context around wind turbines. All turbine locations and collision records were georeferenced using WGS84 (EPSG:4326) coordinates and integrated in a GIS environment.

Land-cover information was derived from CORINE Land Cover (CLC) datasets [17], complemented by high-resolution satellite imagery to refine habitat boundaries in the immediate vicinity of turbines. Habitat categories were aggregated into ecologically meaningful classes relevant to bird movement and collision victims, including:

(i) Open steppe and grasslands;
(ii) Arable agricultural fields;
(iii) Shelterbelts, tree groups, and shrub vegetation;
(iv) Wetlands and water bodies; and
(v) Urbanized or infrastructural areas.

Each wind turbine was assigned a dominant habitat context based on the land-cover composition within the 200 × 200 m monitoring plot. In addition, distances from turbines to selected habitat features (e.g., shelterbelts, wetlands) were calculated to support exploratory spatial analyses.

Collision records were linked to habitat categories at turbine locations, allowing collision frequency and effort-normalized collision victims to be evaluated in relation to landscape context.

The number of turbines within each aggregated habitat class is provided in Table 1.

**Table 1.** Distribution of wind turbines across aggregated habitat classes.

| Aggregated Habitat Class (CLC-Based) | Number of Turbines |
|---|---|
| Non-irrigated arable land | 74 |
| Natural grasslands (62C0) | 34 |
| Vineyards | 4 |
| Transitional woodland–shrub | 1 |
| Pastures | 1 |

All spatial processing and analyses were performed using GIS software (QGIS, version 3.42) [18] and R spatial packages running under R (version 4.4.2) [19], ensuring reproducibility and consistent integration with statistical modeling.

### 2.5. Statistical Analysis

Statistical analyses were designed to quantify bird collision victims while accounting for variation in monitoring effort, turbine numbers, and habitat characteristics. Collision data were analyzed using count-based regression models, appropriate for discrete, non-negative response variables.

Temporal trends in collision victims were evaluated using Poisson generalized linear models (GLMs) with a log link function. To ensure comparability across years with different numbers of monitored turbines (52 turbines until 2017; 114 turbines from 2018 onwards), monitoring effort was explicitly incorporated as an offset term, allowing collision fatality to be expressed on a per-turbine basis and standardized across the full study period.

Model coefficients were interpreted as incidence rate ratios (IRR), describing proportional changes in collision victims associated with temporal progression, or broad habitat categories. Year was treated as a continuous predictor to assess long-term trends under operational conditions.

To evaluate potential departures from linear temporal patterns, generalized additive models (GAMs) were fitted using a smooth function for year. These models were used as a robustness check to explore non-linear dynamics rather than as primary inferential tools.

Habitat-related effects were assessed by extending the GLM framework to include categorical predictors representing dominant land-cover classes associated with turbine locations, derived from GIS-based land cover analyses (Figure 1).

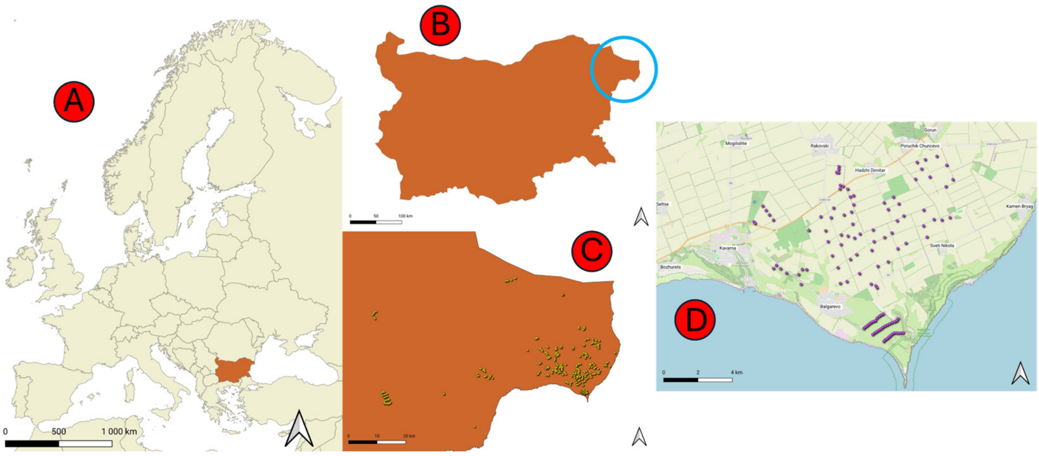


**Figure 1.** Location and spatial context of the study area in Northeastern Bulgaria. (**A**) Map of Europe showing the location of Bulgaria. (**B**) Map of Bulgaria with the study area in the Northeast highlighted. The blue circle highlights the location of the Kaliakra study area within Northeastern Bulgaria. (**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. The dots indicate the spatial distribution of wind turbines included in the long-term collision monitoring.

Turbines belonging to the same habitat class may be spatially clustered within the study area. Accordingly, habitat-related effects are interpreted as landscape-level associations rather than as independent site-specific effects attributable solely to individual turbine locations.

Model adequacy was evaluated using standard diagnostic procedures, including residual inspection and assessment of overdispersion. All statistical analyses were conducted in R (version 4.4.2), using base statistical functions and the mgcv package for GAMs. Mathematical formulations of the models are provided in the Supplementary Information.

As an additional robustness check, Bayesian Poisson regression was applied to assess the temporal trend in number of collision victims. The Bayesian model used the same linear predictor and effort offset as the frequentist Poisson GLM, allowing direct comparison of results across modeling frameworks. Weakly informative priors were specified for regression coefficients, and posterior inference was based on Markov Chain Monte Carlo sampling. Model convergence and posterior stability were evaluated using standard diagnostics.

Formal spatial autocorrelation structures (e.g., spatial random effects or smooth spatial terms) were not included in the primary models, as the main objective was to quantify broad-scale temporal trends and habitat-associated variation in effort-standardized collision rates rather than to disentangle fine-scale location-specific effects. Spatial patterns are therefore interpreted conservatively and in the context of landscape-level heterogeneity.

Collision data were collected under a seasonally structured monitoring framework encompassing migration and wintering periods; the statistical analyses focused on integrating empirical data across the full long-term monitoring period rather than modeling seasonal phases as explicit explanatory factors.

Information on the exact time of collision and concurrent weather conditions (e.g., temperature, precipitation) was not consistently available for all records and was therefore not included as explanatory variables in the statistical models.

## 3. Results

### *3.1. Temporal Trends in Collision Fatalities*

The Poisson GLM was treated as the primary inferential model for assessing long-term temporal trends in collision victims, while GAM and Bayesian models were applied as robustness checks to evaluate sensitivity to modeling assumptions and estimation frameworks.

Effort-normalized statistical modeling revealed a strong and highly significant long-term decline in bird collision victims per turbine over the study period (Table 2; Figure 2). The Poisson GLM incorporating monitoring effort as an offset showed a pronounced negative effect of year on collision counts (Estimate = −0.1304, SE = 0.01425, z = −9.153, $p < 2 \times 10^{-16}$).

**Table 2.** Effort-normalized Poisson GLM results for temporal trend in collision victims (2010–2024).

| Predictor | Estimate (β) | SE | IRR | 95% CI (IRR) | z | *p*-Value |
|---|---|---|---|---|---|---|
| Year | −0.1304 | 0.01425 | 0.878 | 0.854–0.903 | −9.153 | $p < 0.001$ |

On the incidence rate ratio (IRR) scale, this corresponds to IRR = 0.878 (95% CI: 0.854–0.903), indicating an average 12.2% reduction in collision victims per year after standardization for monitoring effort. The narrow confidence interval and extremely low *p*-value provide robust evidence that collision victims at operational wind turbines in the study area have declined substantially between 2010 and 2024.

Monitoring effort was accounted for through the offset term in all models, ensuring that predicted collision rates represent per-turbine values standardized across years despite changes in the number and spatial distribution of turbines after 2018.

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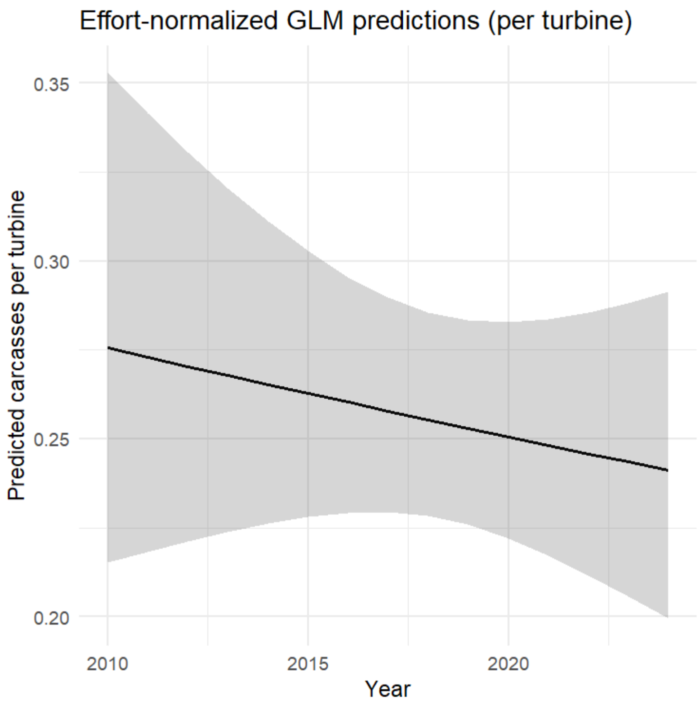


**Figure 2.** Model-predicted effort-standardized collision rate per turbine illustrating the long-term temporal trend, estimated using a Poisson-generalized linear model with monitoring effort included as an offset. Shaded areas represent 95% confidence intervals.

### *3.2. Non-Linear Temporal Dynamics*

To assess whether the observed long-term decline deviated from a strictly linear form, a generalized additive model (GAM) was fitted with year as a smooth term and monitoring effort included as an offset (Figure 3). Consistent with the Poisson GLM, the GAM results indicate that the temporal trend remains consistently negative, while allowing for temporal variation in the magnitude of the decline over time. The smooth term for year was highly significant, and the model explained approximately 3.17% of the deviance, with an adjusted $R^2$ of 0.0021.

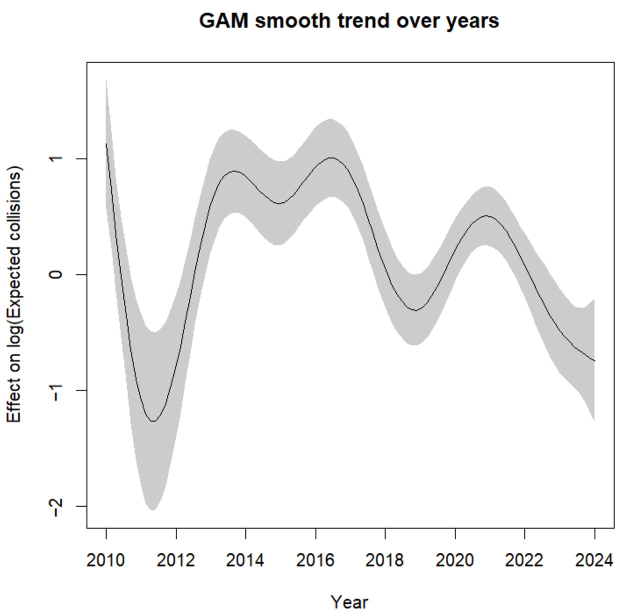


**Figure 3.** GAM smooth depicting long-term temporal variation in collision victim counts. Shaded areas represent 95% confidence intervals.

The fitted smooth revealed phases of more pronounced decline interspersed with periods of relative stability, suggesting that reductions in collision victims were not uniform across years. Such variation likely reflects inter-annual variability in bird abundance, migration intensity, or environmental conditions. Importantly, the GAM analysis did not alter the direction or significance of the temporal trend identified by the primary GLM but rather supports its robustness by indicating variation in the rate, rather than the direction, of long-term change.

### *3.3. Bayesian Confirmation of Temporal Decline*

Bayesian Poisson regression was used as an additional robustness check of the temporal trend identified by the primary Poisson GLM (Figure 4). The posterior mean estimates for the year coefficient was $\beta = -0.05$, with a 95% credible interval of $[-0.08, -0.02]$, entirely below zero. This indicates a high posterior probability that collision victims decreased over time.

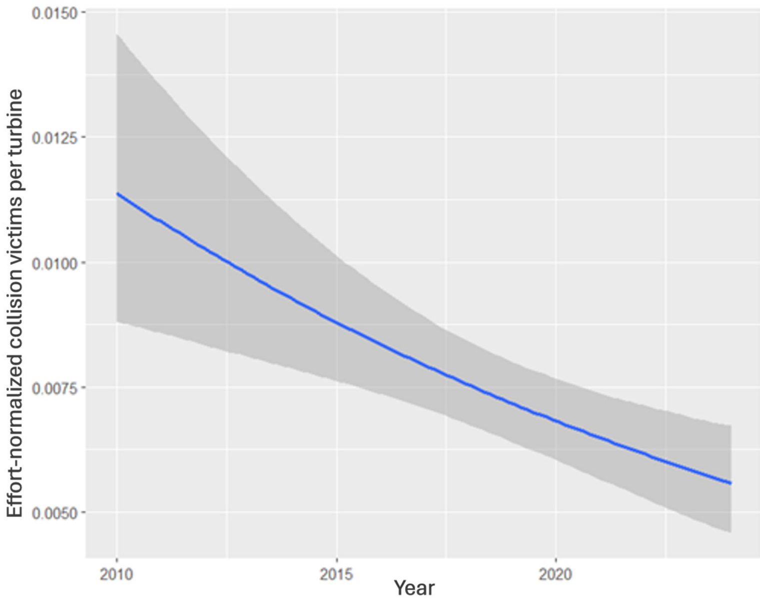


**Figure 4.** Bayesian posterior mean estimates of effort-normalized collision victims per turbine, with 95% credible intervals, illustrating a long-term declining temporal trend between 2010 and 2024.

On the incidence rate ratio scale, this corresponds to an approximate 5% annual reduction in collision victims. Although the magnitude of the effect is smaller than that estimated by the frequentist GLM, the direction and statistical credibility of the temporal trend were fully consistent across modeling frameworks. Overall, the Bayesian analysis did not alter the inference drawn from the primary GLM but further supports the robustness of the observed long-term decline in effort-standardized collision rates.

### *3.4. Habitat-Related Collision Victims: Steppe Landscapes (EUNIS 62C0)*

Although multiple land-cover classes were identified in the habitat classification, habitat-related analyses focused on a steppe versus non-steppe contrast due to the strong ecological relevance of open steppe habitats for bird movement and collision victims, as well as the low representation of several other land-cover categories. Turbines classified as steppe habitats correspond primarily to CORINE Land Cover grassland classes overlapping with the Ponto–Sarmatic steppe habitat type (EUNIS 62C0), a conservation-relevant open habitat characteristic of the Kaliakra region.

Importantly, most monitored turbines were located in non-irrigated arable land rather than in steppe habitats (Table 1), indicating that the higher estimated collision rates in steppe landscapes are not a simple consequence of the sample distribution across land-cover types.

Incorporating habitat context into the effort-normalized Poisson model revealed a tendency towards higher collision victims at turbines located within steppe landscapes (Table 3). The steppe habitat indicator showed a positive effect on collision counts (Estimate = 0.265, SE = 0.142), corresponding to an incidence rate ratio (IRR) of approximately 1.30, or about 30% higher collision victims compared to turbines located outside steppe habitats.

**Table 3.** Effort-normalized Possion generalized linear model results assessing temporal trends and steppe habitat effects on collision victims.

| Predictor | Estimate (β) | SE | IRR | z | *p*-Value |
|---|---|---|---|---|---|
| Year | −0.130 | 0.014 | 0.878 | −9.15 | $p < 0.001$ |
| Steppe habitat (62C0) | 0.265 | 0.142 | 1.30 | 1.87 | 0.0616 |

Although the effect was marginally significant ($p = 0.0616$), the direction and magnitude of the estimate indicate a coherent ecological signal consistent with the known use of open steppe habitats by soaring and hunting raptors, which are among the bird groups most vulnerable to turbine collisions. Given the aggregated nature of the habitat classification and the potential spatial clustering of turbines, this result is interpreted as a landscape-level association rather than a site-specific causal effect, suggesting that steppe landscapes may represent areas of elevated susceptibility within large operational wind farm complexes.

## 4. Discussion

### *4.1. Long-Term Decline in Collision Victims at Operational Wind Farm*

This study provides robust long-term evidence that bird collision victims at an operational wind farm are not temporally static [9,20]. Effort-normalized analyses based on systematic daily monitoring over a 15-year period (2010–2024) demonstrate a pronounced decline in collision victims per turbine. The consistent negative temporal trend detected by Poisson GLM, corroborated by GAM and Bayesian approaches, indicates that the observed pattern is not an artifact of model choice or statistical framework [21].

The magnitude of the decline varies depending on the modeling approach, with the frequentist GLM indicating an average reduction of approximately 12% per year, while the Bayesian model suggests a more conservative estimate of around 5% per year. Importantly, all approaches converge on the same qualitative conclusion: collision victims have decreased substantially over time. Differences in effect size likely reflect methodological contrasts in temporal smoothing, regularization, and uncertainty propagation rather than genuine contradictions in the data [21–23].

Crucially, this decline cannot be attributed to reduced monitoring effort or changes in survey design, as search frequency (weekly) and spatial coverage (200 × 200 m plots) remained constant throughout the study period, and variation in turbine numbers was explicitly accounted for in the statistical models. Importantly, the observed decline in aggregate collision victims per turbine should not be interpreted as direct evidence of reduced collision victims for all species or as a proportional reduction in population-level impacts, but rather as a change in overall collision occurrence under sustained operational conditions.

### *4.2. Interpretation: Adaptation, Avoidance, or Redistribution?*

A central question arising from the observed temporal decline is whether it reflects behavioral adaptation of birds to wind turbines, broader avoidance responses, or spatial redistribution of bird activity. Collision data alone cannot fully disentangle these mechanisms. However, the persistence of bird presence in the study area documented by parallel monitoring within the Integrated System for Protection of Birds suggests that the decline in collision victims is unlikely to be explained solely by large-scale abandonment of the area [5].

Behavioral adaptation, such as improved turbine avoidance through learning or selection against collision-prone individuals, represents a plausible contributing mechanism, particularly for long-lived species with repeated exposure to wind turbines [20,24]. At the same time, partial displacement or changes in flight behavior and altitude may also contribute to reduced collision probability without implying complete habitat loss [15,25].

However, it should be emphasized that the collision dataset analyzed in this study includes all recorded collision victims irrespective of species and is numerically dominated by short-lived, small-bodied species, primarily passerines, which are commonly detected in carcass-based monitoring. Large, long-lived species of high conservation concern, such as soaring raptors and wintering geese, are only rarely represented among recorded collision victims in the study area. Consequently, the long-term trends reported here primarily reflect changes in overall collision occurrence rather than species-specific collision risk or population-level impacts for target species. Detailed information on species composition is available in the regular seasonal and annual monitoring reports of the Integrated System for Protection of Birds and can be provided upon reasonable request. Rather than attributing the observed pattern to a single mechanism, our results are consistent with the interpretation that collision victims at operational wind farms emerge from dynamic bird–turbine interactions, which evolve over time and are shaped by both behavioral responses and spatial context.

### *4.3. Habitat Context and Elevated Victims in Steppe Landscapes*

The habitat analysis revealed a consistent tendency towards higher collision victims at turbines located in Ponto–Sarmatic steppe habitats (EUNIS 62C0) [20]. Although the effect was marginally significant, the magnitude of the estimated increase (~30% higher victims) and its ecological coherence indicate that habitat context plays an important role in shaping collision susceptibility. Given the aggregated habitat classification and the spatial clustering of turbines, these results should be interpreted as landscape-level associations rather than as evidence of site-specific causal effects.

Open steppe landscapes are intensively used by soaring and hunting raptors, which rely on unobstructed airspace and are among the bird groups most frequently involved in turbine collisions [26]. The lack of vertical structure in these habitats may limit early visual detection of turbine blades, increasing collision probability under certain conditions [27]. These findings align with previous studies emphasizing the importance of landscape openness and flight behavior in collision victims assessment [20].

From a planning perspective, the results underscore the need for habitat-sensitive victim assessment, particularly in extensive open landscapes characteristic of Southeast Europe, where wind energy development is expected to expand further.

### *4.4. Implications for Population-Level Assessment and Strategic Planning*

Quantifying collision victims per turbine and per habitat provides a critical foundation for evaluating population-level significance and cumulative impacts [28]. By linking empirically derived collision rates with spatial data on habitat extent, it becomes possible to explore scenario-based assessments at broader scales, including national or regional planning contexts [29]. However, any population-level interpretation of collision victims remains conditional on independent information on species composition, abundance, and baseline mortality, which were not explicitly assessed in the present study and therefore fall beyond its analytical scope.

While such extrapolations must be approached cautiously, the present study offers a data-driven basis for identifying high-sensitivity landscapes and prioritizing mitigation measures [27]. In particular, the combination of long-term monitoring and spatially explicit analysis supports the development of targeted strategies, such as refined turbine siting, habitat-aware micro-siting, and adaptive mitigation in high-risk contexts [30].

### 4.5. Methodological Considerations and Future Directions

The strength of this study lies in its reliance on long-term, standardized, and intensive monitoring under real operational conditions [20]. Nevertheless, several limitations should be acknowledged. Collision data alone cannot fully resolve the mechanisms [9,27] underlying temporal changes in risk, and integration with additional data sources, such as visual observations or movement tracking, would further enhance inference.

Collision Risk Models are inherently dependent on detailed flight behavior data and are therefore best suited for prospective or behaviorally informed assessments, whereas the present study addresses empirical collision occurrence derived from long-term carcass monitoring under real operational conditions.

Previous studies indicate that fine-scale temporal factors, such as time of day and concurrent weather conditions, may influence collision probability under specific circumstances, particularly during nocturnal migration or adverse weather events [20,31]. However, their effects are often context-dependent and difficult to quantify without high-resolution temporal data. Integration of such variables would require continuous time-stamped collision detection and detailed meteorological data, which were beyond the scope of the present study.

Future research should focus on combining empirical collision data with collision risk modeling frameworks and independent measures of bird abundance and movement [32,33]. Such integration would allow more explicit testing of behavioral adaptation [34] versus displacement hypotheses [35] and improve the predictive power of collision risk assessments. Consequently, the temporal and spatial patterns identified here should be viewed as emergent properties of multiple interacting processes rather than as outcomes driven by any single environmental or behavioral factor.

The present analysis is based on long-term, effort-standardized empirical collision monitoring and is not designed as a before-after or BACI-type assessment of population-level impacts. Consequently, the taxonomic composition of the local bird community, physiological condition of individuals, and changes in abundance before and after wind farm operation were not explicitly analyzed. Addressing such questions would require a different study design integrating independent abundance estimates, demographic parameters, and individual health assessments. The results presented here therefore describe patterns in collision occurrence under sustained operational conditions rather than direct population-level effects. This distinction is critical for the appropriate interpretation and application of long-term collision monitoring data.

### 4.6. Implications for Mitigation and Mortality Reduction

The documented temporal and spatial heterogeneity in collision occurrence have direct implications for mitigation at operational wind farms. Previous studies indicate that collision risk cannot be effectively addressed through uniform measures alone but requires context-specific strategies that consider species behavior, temporal variation in bird activity and landscape characteristics [11,20].

A range of mitigation approaches has been proposed and tested in different settings, including turbine design modifications, operational curtailment during high-risk periods, and the application of deterrent technologies. Design-related measures, such as increased blade visibility through contrast enhancement or blade painting, have shown potential to reduce collision victims for large soaring birds under certain conditions [26,36]. Operational measures, particularly temporary turbine shutdowns ("smart curtailment") during periods of elevated activity, such as peak migration or adverse weather conditions, have been identified as one of the most effective tools for reducing collision occurrence, albeit with site-specific economic trade-offs [11,20].

Emerging deterrent technologies, including visual and acoustic deterrents, have produced variable results, with effectiveness often depending on species-specific sensory ecology and habituation effects. As emphasized in recent synthesis studies, the performance of such measures remains highly context-dependent and requires rigorous evaluation under real operational conditions [20,27].

Long-term, standardized collision monitoring, such as that presented in this study, provides a critical empirical foundation for identifying high-risk turbines, and habitat contexts, thereby supporting targeted mitigation rather than blanket application of measures.

## 5. Conclusions

This study provides one of the most comprehensive long-term empirical assessments of bird collision victims at operational wind farms in Southeast Europe, based on systematic monitoring conducted between 2010 and 2024 in the Kaliakra Protected Area. By combining daily carcass searches with effort-normalized statistical modeling and spatial (GIS-based) analysis, we demonstrate that number of collision fatalities per turbine is not static but declines substantially over time.

Effort-normalized models consistently revealed a pronounced negative temporal trend in collision rate, supported across frequentist (GLM, GAM) and Bayesian analytical frameworks. This convergence of evidence indicates that the observed decline reflects genuine changes in bird–turbine interactions rather than artifacts of monitoring effort or survey design. At the same time, spatial analyses showed that collision victims are heterogeneously distributed across the landscape, with turbines located in open steppe habitats exhibiting consistently higher fatalities than those in more structurally complex environments.

Together, these findings highlight the importance of long-term, standardized monitoring for understanding collision dynamics under real operational conditions. The results provide a robust empirical basis for cumulative impact assessment, habitat-sensitive spatial planning, and targeted mitigation, particularly in extensive open landscapes where wind energy development is expected to expand further.

More broadly, this study demonstrates that integrating long-term collision data with spatial analysis can support evidence-based decision-making, helping to balance the continued deployment of renewable energy with the conservation of bird populations in Southeast Europe and comparable regions. While this study does not evaluate the effectiveness of specific mitigation measures, the identified temporal and habitat-related patterns provide an empirical basis for informing the targeting of mitigation strategies in contexts associated with elevated collision occurrence.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18020992/s1: Figure S1: Bayesian posterior diagnostics for the temporal trend model, including posterior distribution of the year coefficient and MCMC trace plots. Table S1: Effort-normalized Poisson GLM results for temporal trends in collision risk (2010-2024). Table S2: Summary diagnostics for the generalized additive model (GAM). Texts S1–S4: Mathematical specification of the effort-normalized Poisson GLM, habitat effect model, generalized additive model, and Bayesian Poisson regression.

**Author Contributions:** Conceptualization, P.Z.; methodology, N.Y.; software, N.Y.; validation, P.Z., D.P.W. and N.Y.; field work and data collection, N.Y.; writing—original draft, N.Y., P.Z. and D.P.W.; writing—review and editing, N.Y.; visualization, N.Y.; supervision, P.Z. and D.P.W.; project administration, P.Z.; funding acquisition, P.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding. The study is a part of PhD project in Institute of Biodiversity and Ecosystem Research at Bulgarian Academy of Sciences.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Collision monitoring data are part of the Integrated System for Protection of Birds and are available from the corresponding author upon reasonable request. Statistical analyses were conducted using standard software tools, and analysis scripts can be provided to support reproducibility.

**Acknowledgments:** We are grateful to Integrated System for Protection of Birds in Kaliakra SPA https://kaliakrabirdmonitoring.eu/ (accessed on 19 September 2025) for the support and long-term monitoring data provided for our analysis. We would like to acknowledge Ekoznanie https://eko-znanie.eu/ (accessed on 19 September 2025).

**Conflicts of Interest:** Author D. Philip Whitfield is employed by Natural Research, a registered charity in Scotland (SC030363). The authors declare no commercial or financial relationship that could be construed as a potential conflict of interest.

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