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Bayesian Estimates of Collision Risk and Fatalities of Columbidae at Wind Turbines in the Isthmus of Tehuantepec

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Simple Summary

Evaluating the environmental impacts of wind farms requires long-term data, particularly for resident birds in expanding energy regions like Latin America. To address this need, we examined nine years of bird counts and systematic carcass searches at a wind farm in Oaxaca, Mexico, to calculate collision probabilities and annual fatalities for five dove and pigeon species. Our results show that collision risk is not strictly tied to how common a species is. The most abundant species had low collision probabilities despite high presence around turbines. In contrast, less abundant species exhibited higher collision probabilities per encounter. Over the entire nine-year period, estimated annual fatalities per turbine were low for all species. Furthermore, our projections showed a downward temporal trend, indicating that absolute fatality numbers are expected to continue declining. These long-term findings demonstrate low observed local mortality rates at wind farms in agricultural landscapes, providing valuable data to help environmental managers balance clean energy production with wildlife protection while accounting for local-scale dynamics.

Abstract

Columbidae (pigeons and doves) are among the most abundant resident birds in agricultural landscapes and recorded as turbine fatalities, but they are rarely included in collision risk assessments. We evaluate nine years (2016–2024) of monitoring data from a wind farm in the Isthmus of Tehuantepec, Mexico, to estimate species-specific collision risk and fatalities for five species using a Bayesian Collision Risk Model (CRM). We integrated long-term visual census data, systematic carcass searches corrected for detection probability and carcass persistence, and biologically informed priors to estimate exposure rates, collision probabilities, and annual fatalities. Results revealed marked interspecific differences in collision risk that were not directly proportional to abundance. The most abundant species, White-winged Dove (*Zenaida asiatica*), showed high exposure but low collision probability. The opposite was found in less abundant species White-tipped Dove (*Leptotila verreauxi*). While overall estimated fatalities remained low, our model revealed a steady downward trend in absolute fatalities, projecting continued declines for 2025. Our findings highlight the importance of long-term monitoring and Bayesian approaches that incorporate uncertainty and species-specific traits. We provide parameterized priors that can be applied in future collision risk models and support the conclusion that wind farms may exhibit limited local mortality impacts on the studied avifauna.

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1. Introduction

Wind energy is widely recognized as an efficient and sustainable alternative for electricity generation, contributing substantially to climate change mitigation [1]. Nevertheless, wind farms can negatively affect wildlife, particularly on avian populations, as collisions with turbines constitute a direct source of mortality [2]. Although turbine-related fatalities account for less than 0.02% of annual avian collision fatalities from anthropogenic structures [3,4], they may still represent a relevant source of concern for certain vulnerable species [5].

Collision risk in birds results from the combined influence of environmental conditions, turbine characteristics, and biological attributes [6,7]. At the environmental level, risk varies with topography, habitat structure, and food availability [8]. Technical aspects such as turbine size, number, and spatial configuration also influence risk [9]. Biological attributes, including species-specific traits (e.g., migratory strategy, wing morphology, flight height) and behavioral patterns (e.g., proportion of time spent at rotor height and distance traveled within the rotor-swept zone), are critical determinants of vulnerability [8,10,11]. Conceptually, collision risk arises from the interaction between the likelihood of entering the rotor-swept zone (sensitivity) and the frequency of occurrence within wind farms combined with turbine density (exposure) [12].

Knowledge of bird mortality at wind farms in Latin America is still limited, restricting the evaluation of ecological impacts and the design of mitigation strategies despite the rapid regional expansion of wind energy [5]. Evidence from the Isthmus of Tehuantepec indicates mortality levels comparable to those reported in the United States [13,14], but with a distinct pattern, since most recorded fatalities correspond to resident rather than migratory species, even during migration periods [13].

Among the most abundant resident species, Columbidae (pigeons and doves) exhibit some of the highest mortality rates at wind farms [15,16]. However, raw mortality counts should be interpreted in relation to species abundance and exposure, as high numbers of carcasses do not necessarily indicate greater individual collision susceptibility [12]. Despite their ecological importance, particularly as seed dispersers and as a food resource for predatory birds [17,18], collision risk models for wind farm impacts have largely focused on raptors and seabirds [7,9,19], whereas columbids are rarely considered [20,21]. This lack of attention could reflect their relative economic relevance, general absence from threatened species lists, and relatively low conservation value largely due to their ability to thrive in human-modified habitats [22,23]. As a result, most references to columbids in the wind energy context come from bird inventories rather than from specific ecological assessments [13,15,16].

Identifying which species are most vulnerable to turbine collisions, and the ecological and behavioral factors that shape this vulnerability, is essential for developing effective mitigation and management strategies [2,8]. Multi-year datasets are particularly valuable, as they increase sample sizes and allow the assessment of interannual variability [24]. Here, we examine nine years of data on five columbid species associated with a wind farm in the Isthmus of Tehuantepec. We hypothesize that species with higher abundance, and greater exposure to turbines, will exhibit increased collision probabilities and higher predicted fatalities than less abundant species. To test this, we applied a Bayesian collision risk model to estimate species-specific collision probabilities and annual fatality rates.

2. Materials and Methods

2.1. Study Area and Data Collection

The Bii Nee Stipa Wind Farm (hereafter Stipa) is in southeastern Oaxaca, within the Isthmus of Tehuantepec region, Mexico. The wind farm comprises 37 turbines, each 81 m tall with a rotor diameter of 52 m, distributed across 413.56 hectares. The predominant land use is sorghum cultivation, alternating with small patches of vegetation characteristic of tropical deciduous forest, mainly species belonging to the Fabaceae family [25]. The northern boundary of Stipa is delimited by an irrigation canal, while the southern borders other active wind farms (Figure 1).

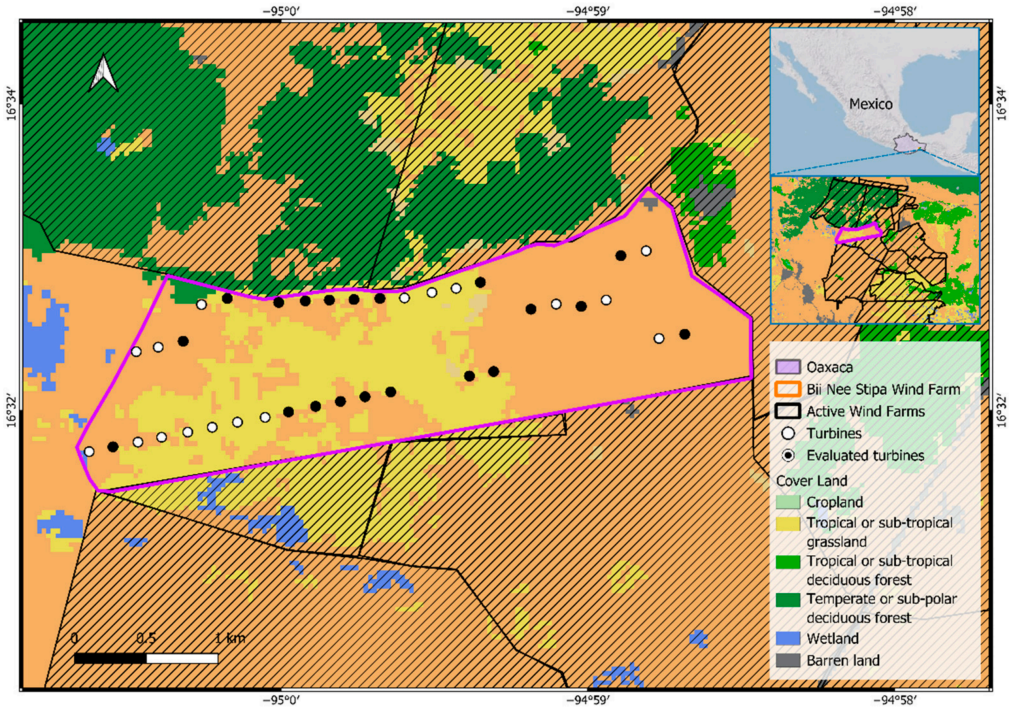


Figure 1. Location of the Bii Nee Stipa Wind Farm (purple outline) within the wind farm complex of the Isthmus of Tehuantepec, Oaxaca, Mexico. White and purple circles indicate turbines within the wind farm, whereas black circles identify the turbines selected for carcass searches. Locations of the surrounding wind farms were obtained from GeoComunes [26]. Vegetation cover within and surrounding the wind farm is also shown [27].

To estimate the density of five columbid species —Common Ground Dove (*Columbina passerina*), Inca Dove (*Columbina inca*), White-winged Dove (*Zenaida asiatica*), Mourning Dove (*Zenaida macroura*), and White-tipped Dove (*Leptotila verreauxi*)—, 1163 diurnal visual censuses were conducted over nine years (2016–2024), between 8:00 AM and 12:00 PM. Each census lasted 90 min, during which all individuals detected within a cylindrical sampling volume 1.6 km in diameter and 81 m in height were recorded. The sampling height corresponded to the maximum height of the wind turbines at the study site. Surveys were conducted by the same observer using Celestron UpClose G2 10 × 50 binoculars (Celestron, California, USA) to maintain consistency in species detection and identification. Observed density was calculated as the mean number of individuals recorded per census divided by the horizontal area of the sampling volume (2.01 km^2).

To estimate the number of bird carcasses resulting from collision events, we conducted 48 systematic searches per year around 20 selected wind turbines, comprising one search per day for 12 consecutive days during each of the four seasons. The 20 wind turbines were selected based on field logistics, site accessibility, and the availability of suitable areas for carcass searches. Searches were conducted within 100 × 100 m plots associated with each

turbine [28]. Each plot was searched by three technicians (hereafter the search team) using a grid pattern with transects spaced approximately 2 m apart for about 60 min, ensuring complete visual coverage of the ground surface [29].

To assess the efficiency of the search team, the percentage of carcasses detected during searches was estimated [30]. An external technician placed 60 experimental carcasses of different sizes during each of the four seasons, with three carcasses placed in each of the 20 search plots associated with the monitored turbines. This resulted in a total of 240 experimental carcasses per year. The search team had no prior knowledge of the carcass locations prior to each trial. No more than three carcasses were placed within a single plot on the same day to prevent increasing carrion availability and attracting scavengers [31]. To evaluate carcass removal rates by scavengers, the persistence of all 60 experimental carcasses placed during each seasonal trial was monitored daily for 14 consecutive days following placement (regardless of whether the carcasses were detected by the search team), recording the number of days each carcass remained in the field [30].

2.2. Collision Risk Model

To estimate collision probability and predict the number of bird fatalities for 2025, we applied the Bayesian Collision Risk Model (CRM) [9,32]. The model predicts the number of bird fatalities (F) based on three parameters: (i) the bird exposure rate (λ), calculated by dividing the total number of birds observed within the turbine's hazardous zone during surveys by the observation effort, expressed in hours per cubic kilometer, accounting for the spatial and temporal extent of sampling; (ii) the collision probability (C), estimated as the proportion of exposures resulting in mortality, using empirical carcass monitoring data corrected for carcass persistence and searcher efficiency [30]; and (iii) the expansion factor (ε), which integrates the number of turbines, rotor radius, height of the hazardous zone, and the total hours of turbine operation during bird activity periods (standardized to 12 h), thereby scaling the observed collision rates to the annual magnitude of the wind farm [9].

The hazardous zone was defined as a cylindrical volume around each wind turbine [9]. The height of the cylinder corresponded to the maximum height of the turbine, while its radius corresponded to the distance between the hub center and the tip of a blade.

Because species-specific data on time spent within the hazardous airspace were not available, bird observations were converted to bird-minutes using a 1:1 assumption, consistent with the default convention established in the USFWS Eagle Conservation Plan Guidance for cases in which duration data are unavailable [33]. This approach standardized the observations across species for implementation in the model.

2.3. Model Implementation

Model implementation proceeded in three stages: (1) carcass detection and persistence trials were used to estimate a corrected within the search area fatality estimate for each species-year using the fatalityCMR framework [30], which accounts for imperfect searcher efficiency and carcass removal by scavengers (Supplementary Material: Data S2); (2) this corrected fatality estimate was used to sequentially update the collision probability prior (C) for each year, following the Bayesian updating procedure described in [9]; and (3) exposure rates (λ) were similarly updated annually using observed bird abundance, effort, and the exposure prior described below. Priors were not held fixed across the study period; rather, both the exposure and collision probability priors were updated sequentially each year, with the posterior distribution from year $t - 1$ serving as the prior for year t. The complete implementation, including all R functions and package dependencies, is provided in Supplementary Materials for full reproducibility.

All model calculations were performed in R (v3.5.3, [34]) using RStudio (v2025.09.0). The re-quired R packages included MASS (v7.3-51.5), mvtnorm (v1.1-0), rv (v2.3.4), tcltk2 (v1.2-11), and tkrplot (v0.0-24). The fatalityCMR package (v3.5.0) was obtained directly from the U.S. Geological Survey website [30]. Additional packages, including highr (v0.8), knitr (v1.28), lsei (v1.2-0), npsurv (v0.4-0), and xfun (v0.13), were used to integrate the original scripts published by USFWS [9,30,32] into a single script (Supplementary Material: Script S1)). This unified script automates fatality estimation and produces standardized summary tables reporting exposure rates, collision probabilities, and predicted fatalities with their respective uncertainties. The integrated framework provides all necessary data to generate priors for subsequent studies aiming to update collision probabilities and exposure rates for the five columbid species assessed in this study.

To obtain the prior parameters (α and β) of the exposure rate (λ), we fitted a Gamma distribution to the empirical density values (individuals/Km^2) reported for Columbidae species in wind farms of the Isthmus of Tehuantepec [35]. The fitting was performed using the fitdistrplus package [36], employing the fitdist() function with the maximum likelihood estimation (MLE) method.

To parameterize the prior distribution (α and β) of the collision probability (C) for Columbidae species, we fitted a Beta distribution using empirical data reported by [21] on bird collisions with modern large wind turbines. In their study, the dataset included the Common Wood Pigeon (*Columba palumbus*), and the average collision risk across the bird species recorded at the wind farms was estimated at 0.14%. Because species-specific estimates were not available for the 5 Columbidae species under study, this average collision risk was used as the closest available empirical approximation for Columbidae species and to calculate the shape parameters (α and β) of the Beta distribution, derived from the mean and standard deviation of p. The resulting parameters defined the prior distribution for collision probability (C) within the Bayesian Collision Risk Model, representing the expected probability of collision and its associated uncertainty [9].

Given the lack of published estimates for exposure rate and collision probability parameters specific to each of the five columbid species, common initial empirical distributions were used for all of them. These initial prior distributions do not imply an assumption that the five species exhibited identical exposure rates or collision probabilities, as they were updated separately, resulting in distinct posterior distributions for each species.

3. Results

Among the Columbid species, White-winged Dove was the most abundant over the nine-year period, accounting for 66.7% of all individuals recorded (21,382). Its abundance peaked in 2017, representing 29.4% of its total count, followed by a second notable increase in 2020 (15.6%). Inca Dove was the second most abundant species, contributing 21.4% of the total, and maintained a relatively stable presence between 2016 and 2022, despite interannual variations in sampling effort. In contrast, White-tipped Dove and Mourning Dove were the least abundant species, representing 2.9% and 3.3% of the total, respectively, and did not show major increases during the study period. Common Ground Dove accounted for 5.8% of all individuals (1230) and exhibited a clear declining trend, decreasing from 1.5% of the total in 2016 to only 0.07% in 2024.

Regarding density, the results indicate that, despite reduced sampling effort during 2023 and 2024, average bird densities remained within ranges comparable to those seen in earlier years (Table 1). White-winged Dove showed the highest density throughout the study (mean 5.46 individuals/km^2), with a maximum of 12.89 individuals/km^2 in 2017. Inca Dove also exhibited consistently high densities (mean 2.05 individuals/km^2), with a slight increase toward 2024 (3.09 individuals/km^2), suggesting that this species

maintained a high relative representation even in years with fewer surveys. In contrast, Common Ground Dove, White-tipped Dove, and Mourning Dove maintained low and relatively stable densities, all with mean values below 1 individual/km^2. Overall, the assemblage-level mean annual density ranged from 1.1 to 3.2 individuals/km^2 across study years. Although annual densities for individual species varied substantially (e.g., peak local abundances in White-winged Dove), the overall concentration of individuals at observation sites remained relatively stable despite decreased sampling effort in recent years (Table 1).

Table 1. Mean annual density (individuals/km^2) of Columbidae species recorded between 2016 and 2024.

Species	Year								
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Inca Dove	2.38	1.77	1.75	1.61	2.01	1.96	2.04	1.88	3.09
Common Ground Dove	1.09	0.67	0.5	0.42	0.4	0.33	0.43	0.44	0.18
White-tipped Dove	0.21	0.28	0.3	0.32	0.29	0.21	0.31	0.93	0.23
White-winged Dove	3.71	12.89	3.98	3.6	7.4	5.3	7.62	2.17	2.49
Mourning Dove	0.62	0.39	0.19	0.24	0.27	0.27	0.19	0.1	0.18

The comparative analysis among species revealed marked differences in the observed carcass-to-abundance ratios. White-tipped Dove exhibited the highest ratio, with one observed carcass per 61.5 individuals recorded, followed by Common Ground Dove (one per 64.7 individuals). Mourning Dove showed an intermediate ratio, with one observed carcass per 87 individuals, whereas Inca Dove and White-winged Dove exhibited the lowest ratios, with one observed carcass per 305.6 and 594 individuals, respectively. Overall, these results indicate that less abundant species tend to concentrate on a higher proportion of observed carcasses compared to the dominant species in the assemblage. The observed carcass-to-abundance ratio should not be interpreted as the collision probability (C), which was estimated separately using the Collision Risk Model.

The model used a Gamma prior for λ (α = 0.367, β = 0.007) and a Beta prior for C (α = 3.505, β = 21.53). Using these priors, the Bayesian Collision Risk Model revealed clear interspecific and temporal differences in exposure rates (λ), collision probabilities (C), and predicted fatalities across the columbid species monitored over nine years (Table 2). White-winged Dove consistently showed the highest exposure to turbines, with λ values ranging from 30.5 to 70.1 bird-minutes·h^{-1}·km^{-3} during 2016–2024, which led to the highest predicted annual fatalities (P.F = 8.7–40.5) and the largest cumulative estimate in the assemblage (155.6 predicted fatalities; 24 carcasses). In contrast, Common Ground Dove exhibited intermediate exposure rates (λ = 4.0–9.0 bird-minutes·h^{-1}·km^{-3}) but maintained one of the highest collision probabilities among the five species (C = 0.015–0.022%). Consequently, its predicted fatalities were relatively high during the first half of the monitoring period (P.F = 8.7–5.0 between 2016 and 2022), summing to 45.8 predicted fatalities and seven carcasses overall, although its annual P.F values declined sharply in the last monitoring years (1.3 in 2024). Inca Dove showed the highest exposure rates among the small-bodied species (λ = 15.4–19.6 bird-minutes·h^{-1}·km^{-3}) but simultaneously had the lowest collision probabilities in the assemblage (C = 0.006–0.011%). This combination produced moderate predicted fatalities (P.F = 8.7–4.9 during 2016–2023) and a cumulative estimate of 61.3 predicted fatalities and 15 carcasses. Like Common Ground Dove, Inca Dove exhibited a strong decline in predicted fatalities in recent years of observation (1.5 in 2024), indicating a consistent downward temporal trend across species. Although Mourning Dove experienced lower exposure to turbines (λ = 2.5–5.1 bird-minutes·h^{-1}·km^{-3}), its relatively high collision probability (C = 0.015–0.032%) resulted in 33.1 predicted fatalities

and nine carcasses. White-winged Dove, the least exposed species (λ = 1.8–2.3), nonetheless showed the highest collision probabilities in the group (C = 0.033–0.100%), resulting in 50.8 predicted fatalities and ten carcasses. Taken together, the five species showed a marked multi-year decline in predicted fatalities, particularly pronounced after 2022.

Table 2. Predicted anual fatalities (P.F), recorded carcasses (Car), exposure rate (λ), and collision probability (C), for five Columbidae species from 2016 to 2024, including posterior fatality pre-dictions for 2025.

Year	Common Ground Dove				Inca Dove				White-Winged Dove				Mourning Dove				White-Tipped Dove			
	P.F	Car	λ	C (%)	P.F	Car	λ	C (%)	P.F	Car	λ	C (%)	P.F	Car	λ	C (%)	P.F	Car	λ	C (%)
2016	8.7	2	9	0.019	8.7	2	19.6	0.009	8.7	12	30.5	0.030	8.7	2	5.1	0.032	8.7	3	1.8	0.1
2017	7.7	3	7.2	0.019	8	3	16.9	0.009	40.6	5	70.1	0.010	7.4	2	4.1	0.028	8	3	2.1	0.085
2018	6.3	1	6.2	0.017	6.9	5	16.1	0.011	40.5	3	58.9	0.008	5.3	0	3.4	0.021	9	0	2.2	0.059
2019	3.9	1	5.5	0.015	7.1	3	15.4	0.011	16.3	0	50.9	0.006	2.6	0	3	0.017	5.4	1	2.3	0.048
2020	3.8	4	5.1	0.018	8	0	15.6	0.009	13.2	3	52.9	0.005	2.4	0	2.8	0.015	5.8	1	2.3	0.042
2021	4	5	4.6	0.022	6.2	1	15.7	0.008	12.5	0	51.1	0.004	1.8	1	2.7	0.015	4.5	1	2.2	0.038
2022	5	2	4.5	0.021	6.4	1	15.8	0.007	11	0	52.7	0.004	2	2	2.6	0.017	4.3	0	2.2	0.033
2023	4	0	4.4	0.020	4.9	0	15.8	0.007	8.4	0	51.2	0.003	1.8	0	2.5	0.016	3.3	0	2.2	0.031
2024	1.3	1	4.3	0.021	1.5	0	16.1	0.006	2.4	1	50.2	0.003	0.6	1	2.5	0.018	1	1	2.2	0.033
2025	1.1				1.3				2				0.5				0.9			

The model also produced posterior predictions for annual fatalities across the entire wind farm (37 turbines) for 2025 (a year without field sampling), indicating uniformly low fatality estimates (mean ± SD): Common Ground Dove = 1.1 ± 0.162, Inca Dove = 1.3 ± 0.206, White-winged Dove = 2 ± 0.252, Mourning Dove = 0.5 ± 0.112, and White-tipped Dove = 0.9 ± 0.17 fatalities per year. These predictions, including their associated uncertainty, support the continuation of the declining fatality risk observed after 2022.

Considering the complete nine-year monitoring period and a total of 37 wind turbines, estimates of average annual mortality per turbine (calculated using fatality CMR) also varied among species. White-winged Dove showed the highest estimated average annual mortality per turbine (0.467), followed by Inca Dove (0.177), White-tipped Dove (0.152), and Common Ground Dove (0.138). In contrast, Mourning Dove exhibited the lowest estimated average annual mortality per turbine (0.099).

Additionally, interspecific variation in the estimated collision probability was synthesized alongside ecomorphological and behavioral traits derived from the literature that could influence collision risk (Table S1).

4. Discussion

Here, we report a continuous nine-year study of collisions involving species of the family Columbidae and provide parameterized estimates that can be directly used as priors in future Bayesian collision-risk models.

Overall mortality estimates were substantially lower than those reported for wind farms in North America and Europe [15,16]. When standardized by the total abundance recorded, the estimated mortality-to-abundance ratio (0.36%) remained well below the 1% threshold commonly applied as a management reference point in European environmental assessments [11,37]. Although this low ratio indicates relatively low observed collision mortality, its ecological significance should be interpreted cautiously, as it compares local mortality with the abundance recorded at the study site and should not be taken as evidence of limited population-level effects. This is because mortality estimates were not evaluated relative to population size, natural mortality, or demographic compensation. Moreover, the consequences of collision mortality may differ among species depending on their population trends.

The mortality associated with wind turbines at our study site represents a minor source of anthropogenic mortality relative to other pressures (e.g., building–window collisions and regulated hunting) acting on Columbidae populations in the region [38–41] which aligns with global evaluations indicating that mortality associated with wind energy accounts for a comparatively low proportion of the millions of birds killed annually by other human activities [3,42].

These comparatively low rates may be related to the characteristics of the landscape surrounding the Stipa wind farm. The project is situated within an already disturbed agricultural landscape dominated by sorghum fields and small remnants of tropical deciduous forest [25]. Evidence indicates that placing energy infrastructure in previously modified environments tends to present a reduced collision risk and numbers of fatalities [3].

Consistent with these patterns, the estimated Columbidae fatality at Stipa is lower than the mortality rates reported by [13] for birds at other wind farms within the Isthmus of Tehuantepec. Although both studies were conducted within the same biogeographic region, differences in estimated mortality may be partially explained by the statistical approaches used. In particular, the collision risk model applied in the present study explicitly accounts for the inherent uncertainty of collision events, allowing the integration of prior knowledge and the incorporation of new information as monitoring progresses [6], resulting in estimates that become progressively more precise over time [9]. Such characteristics are likely to contribute to more reliable and ecologically meaningful fatality estimates, facilitating robust site-level comparisons and improving the assessment of collision risk at wind farms across the Isthmus of Tehuantepec. We hypothesize that the presence of carcasses from Columbidae species across years may reflect differences in flight performance and wing morphology. While primary feather shape in most birds is strongly constrained by aerodynamic efficiency, specific columbid lineages exhibit non-vocal acoustic specializations; notably, ground doves of the genus Columbina feature a modified seventh primary (P7) adapted for sonation during flight [43–45]. Based on biomechanical principles [44], this specialization may represent an aerodynamic trade-off, potentially influencing flight performance and maneuverability relative to species whose primaries are more strictly adapted for efficient flight. The diet of the recorded Columbidae species largely depends on the availability and nutritional quality of the small seeds they consume, which drives them to forage continuously on the ground and makes them sensitive to variations in protein content [22,46]. When available resources have a low protein proportion, as is the case at the wind farm where sorghum crops predominate, Columbidae are required either to move more frequently in search of higher-quality nutritional resources or to spend longer periods feeding on sorghum to meet their metabolic requirements [46]. We propose that both situations increase the amount of time birds remain within the turbine risk zone, which could not only elevates the probability of collisions (particularly for recently fledged juveniles) but also increase their vulnerability to predators by intensifying predator–prey encounters and, consequently, the frequency of escape flights [12,22].

Our analyses revealed clear interspecific differences in collision probability (C) and observed carcass-to-abundance ratios among the Columbidae species assessed. These estimations represent the empirical findings supported by our study. Because functional traits were not directly measured, we cannot establish causal mechanisms for these divergent mortality patterns. Instead, we propose a framework of testable hypotheses for future research based on flight morphology, foraging behavior, habitat use, and sensory ecology may influence collision vulnerability [44–49].

Among the species assessed, White-tipped Dove exhibited the highest collision probability and observed carcass-to-abundance ratio despite its relatively low local abundance. This species is historically associated with tropical forest and dense woodland margins [50],

but has expanded its distribution in recent decades into disturbed and fragmented habitats, indicating an increasing tolerance to landscape modification [51]. This shift toward more open and human-altered environments could increase its spatial overlap with wind turbine installations and consequently its exposure to collision risk [52].

We also propose as a hypothesis for future testing, that the high vulnerability of White-tipped Dove may reflect a combination of ecomorphological constraints, flight mechanics, and sensory ecology [53,54]. As a predominantly solitary, ground-foraging dove [55], White-tipped Dove relies on rapid, directed escape flights toward dense vegetation, a behavior associated with short, rounded wings and relatively high wing loading that may constrain maneuverability. The sensory system of ground-foraging doves is primarily adapted to detecting terrestrial hazards and lateral movements, potentially reducing the detection of obstacles located directly ahead or above during rapid escape flights [54]. This may limit avoidance of fixed structures such as turbine towers, particularly in fragmented landscapes where refuge pathways are reduced [48].

In contrast, White-winged Dove occurs at high abundance in agricultural landscapes and tends to aggregate in foraging areas near wind energy infrastructure, suggesting potentially high exposure to turbines [56]. One possible explanation for its relatively low collision risk despite this high exposure is a combination of morphological and behavioral traits that could act as a protective mechanism. Specifically, White-winged Dove has more elongated, conical wings than Leptotila and Columbina species, a morphology associated with greater aerodynamic efficiency and sustained flight [57]. Its group foraging behavior may also enhance collective vigilance and facilitate early detection of potential threats [58], which may contribute to obstacle avoidance. These traits, along with a potential greater maneuverability in the open spaces characteristic of wind farms [48], are hypothesized to collectively reduce collision risk despite its high abundance. This contrast between high abundance and relatively low collision risk is consistent with previous studies showing that abundance alone may be a weak predictor of collision [12].

For Mourning Dove, both abundance and collision-related mortality were low at the Stipa wind farm. This pattern is likely influenced by its migratory behavior, as the species is only seasonally present in the region, which substantially limits its temporal exposure to wind turbines compared with resident Columbidae species [12,59]. Previous studies indicate that Mourning Doves benefit from nesting opportunities and supplemental food resources associated with urban and agricultural gradients, which may enhance individual condition and flight performance even under early-life stress conditions [47]. Consequently, is feasible that these characteristics may contribute to effective obstacle avoidance and could partly explain the relatively low collision mortality observed for this species at the study site.

Over the study period, Common Ground Dove exhibited an initial decline in local density followed by fluctuations at relatively low levels, whereas Inca Dove showed marked interannual variation. This contrasting pattern suggests the need for further investigation into the potential factors underlying these temporal patterns, including resource availability, site management, local movements, and possible interspecific interactions within the wind farm. Our data do not allow us to determine which factor contributed to the observed patterns, as these variables were not evaluated in this study. Nonetheless, the observed decline in Common Ground Dove may be consistent with its broader population trend, as it is the only one of the five assessed species reported to have a decreasing global population [23]. In contrast, Inca Dove, White-tipped Dove, White-winged Dove, and Mourning Dove are reported to have increasing global population trends [23]. These broader population trends provide context for interpreting the local patterns observed at the study site but should not be interpreted as explanations for the local dynamics or

used to assess global conservation status. None of the five species is currently classified as threatened according to the IUCN [23].

Based on our results, we propose targeted and proportional management recommendations for the Stipa wind farm that address two distinct patterns of collision vulnerability. First, for ground-foraging species exhibiting high collision probability and mortality relative to local abundance, as observed for White-tipped Dove, post-construction monitoring should prioritize species-specific carcass searches and account for potential variation in carcass persistence when estimating mortality [60,61]. Vegetation management around turbine bases could also be evaluated as a potential measure to reduce conditions that may promote abrupt escape movements into the rotor-swept zone [62]. Second, for highly abundant flocking species characterized by high exposure but comparatively low collision probability per encounter, as observed for White-winged Dove, management could focus on identifying and, where feasible, reducing anthropogenic food attractants near turbine corridors [63], including grain accumulation, crop residues, or livestock feeding areas. Such measures should be evaluated in collaboration with local landholders and prioritized during periods of increased resource availability. Given the relatively low estimated local collision mortality observed in this study, blanket operational curtailment does not appear warranted on the basis of our current evidence. If curtailment is considered, it should instead be evaluated as an adaptive measure at turbines or during periods where monitoring identifies consistently elevated collision activity [64]. Overall, incorporating species-specific vulnerability profiles into post-construction monitoring and evaluating the effectiveness of mitigation measures over time can support adaptive management that remains proportional to the observed level of local mortality [8].

5. Conclusions

Our analysis jointly assessed turbine exposure and collision probability while accounting for interannual variability and uncertainty within a Bayesian framework. Species with higher local abundance did not consistently show higher collision-related mortality. Highly abundant species such as White-winged Dove exhibited low collision probabilities and observed carcass-to-abundance ratios, whereas less abundant species such as White-tipped Dove showed higher values for both metrics. The observed interspecific differences, together with evidence from previous studies, allow us to hypothesize that collision susceptibility may be influenced by a combination of ecological, morphological, and behavioral traits rather than local abundance alone. In this context, long-term monitoring is critical for capturing temporal dynamics and generating robust, ecologically meaningful mortality estimates. Furthermore, because local carcass counts cannot directly support population viability conclusions, future studies should incorporate regional populations dynamics of each species to evaluate the potential demographic consequences of collision mortality. Our findings provide a quantitative basis for future monitoring and species-specific risk assessments, particularly in the Isthmus of Tehuantepec and other regions of Latin America, where empirical evidence on wildlife responses to wind energy remains scarce [14].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/birds7040062/s1, Script S1: Bayesian collision risk model R script; Data S1: Monitoring dataset of Columbidae abundance and carcass searches (2016–2024). Data S2: Input datasets for carcass detection and persistent analysis. Table S1: Observed collision vulnerability and literature-derived ecomorphological and behavioral traits hypothesized to influence collision risk among Columbidae species.

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Abbreviations

The following abbreviations are used in this manuscript:

CRM	Bayesian Collision Risk Model
MLE	Maximum Likelihood Estimation
P.F	Annual Predicted Fatalities
IUCN	International Union for Conservation of Nature
USFWS	U.S. Fish and Wildlife Service

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