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Research article

Coexistence between migratory birds and wind energy production: The Gotthard wind park (Switzerland) as a case study

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ABSTRACT

The global demand for wind energy is increasing, making it crucial to evaluate its impact on wildlife, particularly birds. Bird collisions can lead to significant fatalities, raising important questions about the effectiveness of wind power. This study focuses on one of the highest wind farms in the Alps, the Gotthard wind park (GWP), which features five turbines. The GWP's position along a migratory route mainly frequented by nocturnal migratory passerines has led to the implementation of radar systems for movement monitoring. Over a 4-year research period (from 2021 to 2024, covering 6 migration seasons) the purpose of the study was to analyze the GWP's collision rate and determine specific shutdown thresholds for each turbine to minimize collisions and prevent unwarranted turbine shutdowns. While the hours of blade shutdown differed markedly between the first (2021-2022) and second two-year (2023-2024) periods, this did not alter the number of collisions. A comprehensive strategy for managing GWP and optimizing energy production from individual turbines has been developed. This includes efforts to limit the impact on migrating bird populations to ensure it remains within acceptable ranges and to improve the efficiency of energy generation. The accomplishment was due to a detailed search of the carcasses on the ground, the presence of radar and visibility probes that allow for the identification of the most hazardous passages of passerine birds and the authorities' tolerance in developing an efficient GWP management system.

1. Introduction

The growing importance of wind energy, a sustainable and environmentally friendly energy source, is driving the planning and establishment of an expanding number of wind farms on a global scale (Welch and Venkateswaran, 2009; Enevoldsen et al., 2019; Haces-Fernandez et al., 2022). Proper site selection for wind farms is critical to achieve community approval and optimizing their energy production (Spyridonidou et al., 2020). The development of wind farms could result in detrimental effects on biodiversity, such as ecosystem changes, weather fluctuations affecting habitats, altered wildlife behaviors and fatalities (Katzner et al., 2025). Wind turbines contribute to the depletion of aerial habitats used by numerous species, including migrating birds heightening their vulnerability (Drewitt and Langston, 2008; Krijgsveld et al., 2009; Marques et al., 2021; Garcia-Rosa et al., 2023; Katzner et al., 2025). The placement of wind farms frequently coincides with regions that have regular winds, which are also common pathways for migratory birds during their seasonal journeys between northern Europe and the Mediterranean region and Africa (Bruderer, 1978, 1996). The impact of wind farms on birds varies, requiring a case-by-case evaluation of collision implications (Drewitt and Langston, 2006).

The main group among migratory birds is the passerines (Nilsson et al., 2023), which are also the most species-rich bird group (Schmitt and Edwards, 2022). These facts, combined with their considerable diversity, make them useful as biodiversity indicators or as models for diverse studies, including those on resilience to climate change. They have received minimal attention in the context of wind farms so far (Johnson et al., 2002; Grodsky et al., 2013; Erickson et al., 2014; Aschwanden et al., 2018). But in light of the growth of wind farms, often placed in remote, ecologically rich areas, this group should be considered. The cumulative effects of multiple wind farms on migration birds could potentially have a significant influence on passerine group (Fox and Petersen, 2019). Nevertheless, mortality from wind turbines on species with low reproductive potential and long lifespan is a well-documented topic (Nilsson et al., 2023; Duriez et al., 2023; Aschwanden et al., 2024), as the loss of even one individual from a species can greatly impact their conservation efforts.

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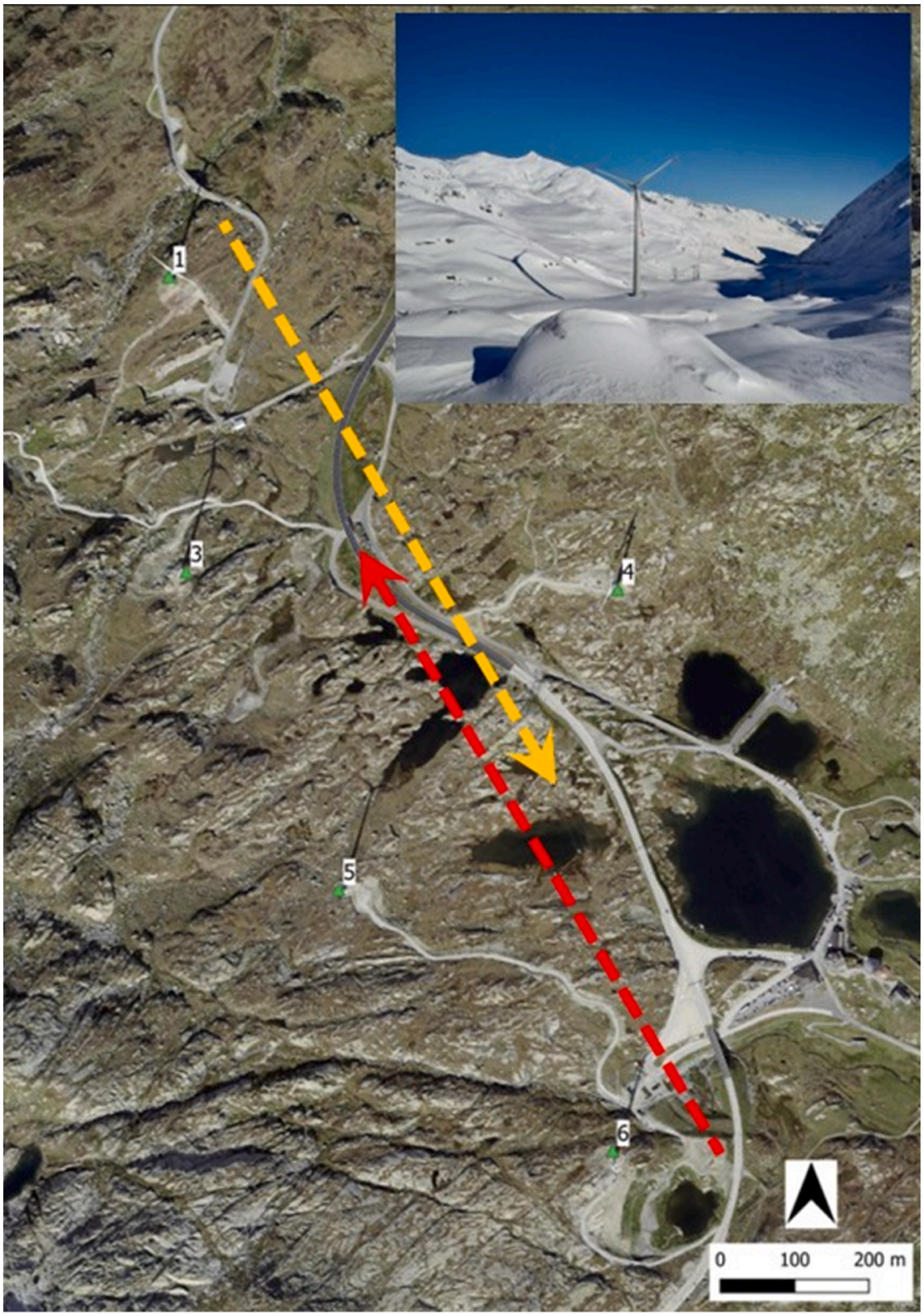

Fig. 1. Situation plan of the Gotthard wind park. The green triangles show the position of the turbines. The red arrow shows the south-north migrations of bird and the orange one the north-south migration. The insert photograph shows the turbine number 1 during spring 2024.

Bird collisions are the most evident impact of wind power development (Drewitt and Langston, 2006; Katzner et al., 2025). Mitigating wind turbine induced mortality is a topic increasingly addressed (Hoge, 2021; Msigwa et al., 2022). Labianca et al. (2025) shed light over the state of the art on bird detection systems. These solutions are increasingly adopted by wind farms focused on mitigating collisions (Lucas et al., 2008; Watson et al., 2018; Pescador et al., 2019; Estellés-Domingo and López-López, 2024; Sassi et al., 2024). It is essential for a wind farm to lessen its impact on biodiversity beforehand (Katzner et al., 2025), but if this is not feasible or has not been observed, steps should be taken after construction. Currently, there exists a lack of research focusing on the procedures necessary to achieve the dual goals of conserving avian migratory populations and improving energy production in an existing wind park.

The present study reports a post-construction investigation conducted at one of the highest wind parks in Europe, comprising five wind turbines situated in the Swiss Alps at an elevation of 2106 m above sea level, the Gotthard wind park (GWP). This area is positioned along a bird migration route through the Alps, since migratory birds frequently use valleys as passage (Hirschhofer et al., 2024). The GWP was initially identified as being of lesser impact on avian species in the park's initial evaluations. Nevertheless, predicting migration intensities and identifying peak migration events for inner Alpine locations remains challenging (Hirschhofer et al., 2024). The complex local terrain and the changing wind and weather conditions significantly influence the behaviors of migratory birds in the Alps (Erni et al., 2005). Therefore,

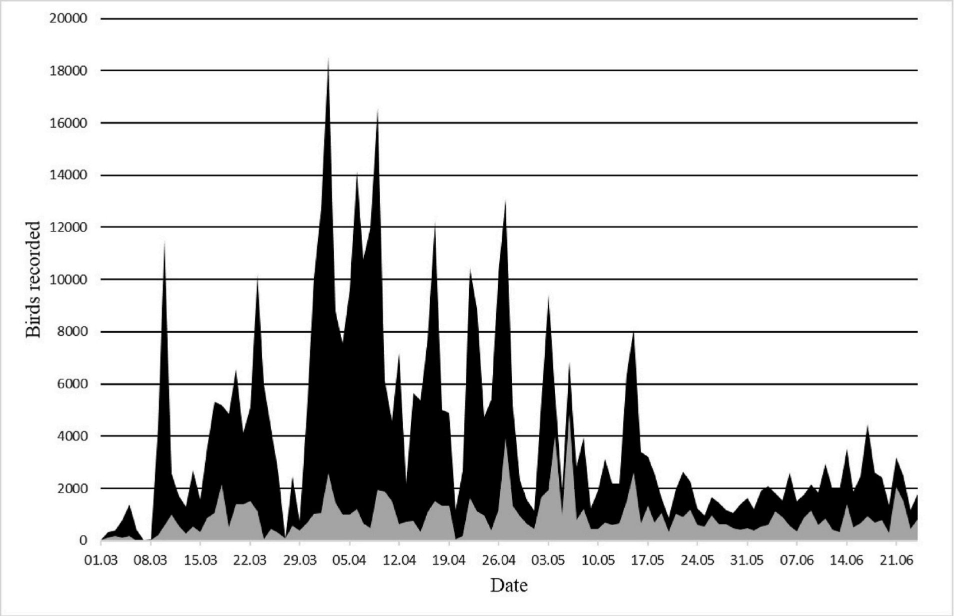

Fig. 2. Sum of bird passages recorded by the radar at the Gotthard wind park during the spring migration 2023 and 2024. Black surface indicated the sum of birds recorded at night, while grey surfaces indicates those detected at day.

although the initial evaluation of the GWP construction was favorable, the relevant authorities demanded a comprehensive and ongoing monitoring plan for the first four years of the GWP's operation to evaluate its effects on migratory bird populations.

In this study, the effect of GWP on avian wildlife has been examined using traditional methods: carcass search, detection probability and disappearance probability (Krijgsveld et al., 2009; Marques et al., 2014; Aschwanden et al., 2018; Coppes et al., 2020; Nilsson et al., 2023). Furthermore, a custom-installed radar (BirdScan MV1, *Swiss Birdradar Solution*) facilitated the tracking of migratory bird movements and the communication of shutdown thresholds to the wind farm turbines. Based on four years of observation at the GWP, the strategy emphasizes the adaptation of turbine-specific mitigation measures informed by empirical data gathered through radar technology and research efforts. This approach seeks to harmonize the conservation of avian species with the demands of energy production. The objective is to provide a replicable framework that improves a wind park's operational effectiveness and migratory bird protection.

2. Methods

2.1. Study area - Gotthard wind park (GWP), Switzerland

The wind farms object of this study is one of the first wind farms built on the Swiss Alps located at 2106 m.a.s.l. on the Gotthard Pass, Canton Ticino, Switzerland (46°33′19”N, 8°34′01”E). GWP counts five wind turbines Enercon E92 and is situated on the top of the pass (Fig. 1). The wind park was completed in 2020. The turbines have a 92 m diameter rotor, a 98 m hub height and a 2′350 kW rated power. The estimated production of electricity is equivalent to the consumption of roughly 4000 family units. The wind park is accessible by road from late spring until mid-autumn. During the rest of the year is not accessible by car but only by helicopter or on skis, because of the snow cover in this period. The creation procedure of the park took more than 10 years. As requested for all wind farms in Switzerland, a study on the bird migration in the area where the wind turbines were to be installed was carried out (Aschwanden et al., 2011) as well as a study on the possible impact of the wind turbines on sedentary birds (Horch et al., 2012). This study revealed the presence of a migratory pathway for birds during the spring and autumn seasons within the region, with an approximate transit of up to 2000 birds/(Km*h).

2.2. Radar

In 2020 a radar (model BirdScan MV1, *Swiss Birdradar Solution*) monitoring the passage of birds at day and night was installed, in order to facilitate the deactivation of the turbines when the migratory bird count surpasses a predefined limit set by regulatory authorities. The radar was positioned 600 m as the crow flies from the turbines and 500 m lower in altitude (46°32′08″N, 8°35′13″E). The radar could not be positioned closer to the wind farm due to restrictions posed by the flight paths of rescue helicopters and military aircraft crossing the area and due to the high accumulation of snow during wintertime. The initial setup and installation of the radar were carried out by the responsible authorities overseeing the GWP project. Birds flying between 600 and 700 m above ground level are detected and counted by the radar, as individuals within this altitude band are considered particularly vulnerable to turbine collisions. The choice was made following a 2011 preliminary study (Aschwanden et al., 2011), which observed that most birds arrived at the Gotthard Pass at high altitude. The radar registers birds' passage both at night and day, and its capacity to monitor bird migration is well demonstrated (Nilsson et al., 2018; Giuntini et al., 2024). The data are grouped as recorded echoes in an excel format. Birds are classified in five different classes based on size and flight patterns as: passerine, birds-flock, large bird, swift type, wader type and undetermined birds (Zaugg et al., 2008). Additionally, this radar tracks the Migration Traffic Rate (MTR, individual/h/km) and when the recorded MTR exceeds the entered thresholds, it can halt wind turbines.

The BirdScan MV1 system is designed to trigger curtailments only during times of increased migratory activity, operating continuously to reduce the likelihood of bird collisions. Initially, the radar was configured to monitor MTR at altitudes ranging from 600 to 700 m above ground level. It would then halt turbine operations if a threshold of 200 MTR was detected at night and 150 MTR during the day, with these thresholds being consistent across all turbines. The fact that there are more migratory birds at night than during the day at the Gotthard Pass influences the variation in MTR thresholds (Aschwanden et al., 2011; Fig. 2). Birds' ability to see obstacles in finer detail is better during the

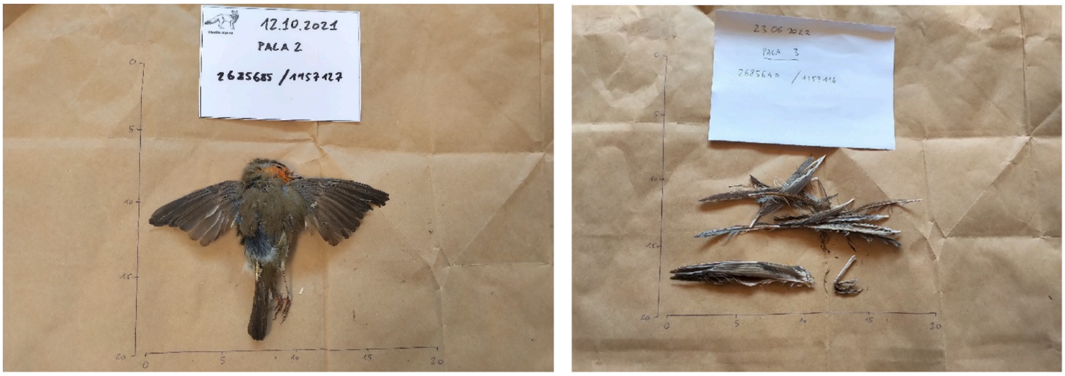

Fig. 3. Two examples of victims: left, whole corpse of *Erithacus rubecula* found at the turbine number 2; right, feathers of *Turdus philomelos* found at the turbine number 3.

day (Desholm and Kahlert, 2005) and this led to the decision to decrease the switch-off threshold during daytime hours.

2.3. Searching methods and collision rate

The research was carried out over four consecutive years: from August 2021 to June 2024. Searches were carried out on three autumn migrations (15 August - 30 October during 2021/2022/2023) and three spring migrations (1 March - 15 June during 2022/2023/2024). An area with a radius of 100m at the foot of each turbines was searched for birds victims (according to method proposed by World Bank, 2023). Search frequency was set to once every 6 days on average. The disappearance rate test confirmed the validity of the specified search range. Searching was conducted in a demanding and highly time-consuming environment often subject to avalanche hazard and bad weather conditions. The research area could be reached only by helicopter or sky in spring and by car in autumn therefore, it was not possible to conduct the searching with a higher frequency. The searched area was monitored by two observers (always the same during the four years of the search), moving in parallel at about 6 m from each other (World Bank, 2023). In total, each operator covered a distance of 14 km for every search carried out. Bird victims found in the searched area were photographed at the site, the coordinates of the finding were recorded and the corpse was then collected in a bag indicating species identification where possible, date of finding, wind turbine number and conditions of the corpse (Fig. 3). Cadavers found in the monitored area were labeled as collision victims if three or more feathers were detected in proximity. Previous studies (Hull et al., 2013; Aschwanden et al., 2018) considered cadavers as collision victims only when more than 10 feathers were found. At the GWP a few feathers from the wing are typically left when a bird is eaten by a predator on the ground, resulting in a total of >3 feathers, as demonstrated by camera traps set up at the GWP (FT personal observation). Thus, the presence of three or more wing feathers led to their classification as victims. While a minimum of 10 pieces on the ground was required for feathers from other parts of the body, to be counted as collision victims. The findings were classified as “whole” (whole bird), “wings” (wings only), “feathers” (feathers found scattered on the ground following impact and probably predation and consumption on the spot). The distance of the carcass from the turbine where the search was conducted was calculated using QGIS (QGIS.org, 2024). The techniques employed for locating victims, as well as the search efficiency and the rate of disappearance, align with methodologies utilized in prior studies of a comparable nature and recommended for onshore wind farms by the World Bank (2023). Search was difficult to carry out in GWP due to the difficulty of reaching the area, particularly in spring with important snow presence. To implement search efficiency test, the two operators proceeded individually, with one searching for carcasses to a wind turbine while the other strategically placed the carcasses near the subsequent wind turbines. The adopted system, although very laborious, led to a statistically satisfactory outcome. However, it is important to note that, relative to other areas with simpler access than the GWP, there were fewer search tests performed, mainly owing to the geographical and access circumstances of the GWP. Although conducting further search tests could have improved the reliability of collision data, the test that was executed is considered sufficient for the study. 20 tests on the rate of disappearance (or carcass persistence) were conducted using camera traps (Browning BTC-7E-HP4) positioned at the base of the turbines within the designated search area. A bird cadaver was placed in front of each camera and the length their permanence on the ground was recorded. Camera traps were checked at every search. To obtain an estimate of collision rate for the GWP the Generalized Estimator (GenEst) software (v1.4.9) proposed by Dalthorp et al. (2018) was used. GenEst is currently considered as one of the most robust software tools for mortality estimation at wind energy farms, providing enhanced accuracy in estimates due to its capability to account for uncertainties in the estimators (Ravache et al., 2024).

2.4. Visibility probe

A visibility probe was installed in 2023, after two years of operation of the GWP. This probe allows visibility to be assessed directly at the height of the wind turbines’ rotors. The probe measures visibility in meters, with a range spanning from 6 to 2000 m. Recording visibility data at 5-min intervals allows for the transmission of accurate information to the radar system and provides the necessary details for implementing shutdown parameters in case of poor visibility. With the help of this probe, it is now possible to establish new shutdown threshold that stop the turbines during times of low visibility, as it can be a primary factor in bird collisions (Aschwanden et al., 2018).

2.5. Mitigation strategies

A Pearson correlation was used to examine the relationship between shutdown time and mortality events for each individual turbine (Best and Roberts, 1975). Differences in shutdown time and in mortality estimates during the period without individual shutdown thresholds (2021-2022) with the period 2023-2024 were tested using the Student's *t*-Test (Zar, 1999). In order to determine if the news thresholds that were put into place in 2023-2024 effectively achieved the intended outcomes for each turbine by reducing shutdowns and ensuring the safety of birds, a distinct linear model was employed to analyze the two specific factors (R Core Team, 2021).

All statistical analysis was performed in R 4.1.1 (R Core Team, 2021) and in GenEst v1.4.9 (Dalthorp et al., 2018).

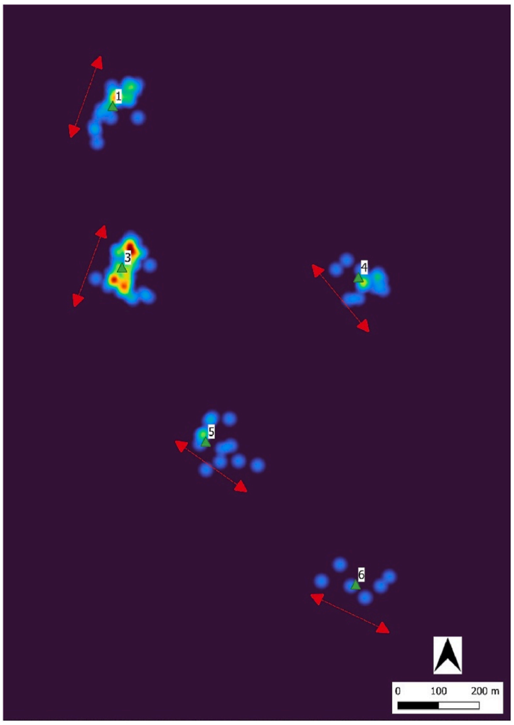

Fig. 4. Heat map indicating the distribution of bird cadavers found during the study period (2021-2024) at the Gotthard wind park. Red indicates the highest concentration of victims, blue the lowest one. Red arrows indicate the potential direction of bird migration close to each turbine.

3. Results

3.1. *Searching methods and collision rate*

A total of 80 searches were made over 6 migration periods: 3 autumn periods (2021, 2022 and 2023) and 3 spring periods (2022, 2023 and 2024; the detailed time span is provided in Appendix 1). The average frequency of searches during each research period was six days. A total of 107 fatalities were ascertained to be the result of collisions with wind turbines. The average distance between the bodies and the nearest turbine was 45.5 m (± 2.2 m, min. 1 m, max. 140 m). There was no evident pattern evident in the placement of the carcasses on the ground, although the potential routes of migration can be inferred from the distribution of the victims (Fig. 4). Isolated feathers of deceased birds constituted the majority of the discoveries (Fig. 5). The species identified on the ground at the research site are detailed in Appendix 2. Search efficiency was estimated at 66.7% (95% CI: 0.485, 0.811) over the entire study period. Median persistence of carcass on the ground was of 11.84 days (95% CI: 7.641, 18.366), with a probability of recovering victims after 7 days of 82.0% (95% CI: 0.742, 0.878; Fig. 6). Mortality estimation (run with 10000 number of iterations and a CI of 0.95) for the GWP over the entire period results in a total number of victims of 189.72 (95% CI: 145.6, 270.5). Considering the two seasons separately, the number of victims in autumn stands at 92.51 (95% CI: 73.23, 123.67) and in spring at 95.56 (95% CI: 72.13, 134.31).

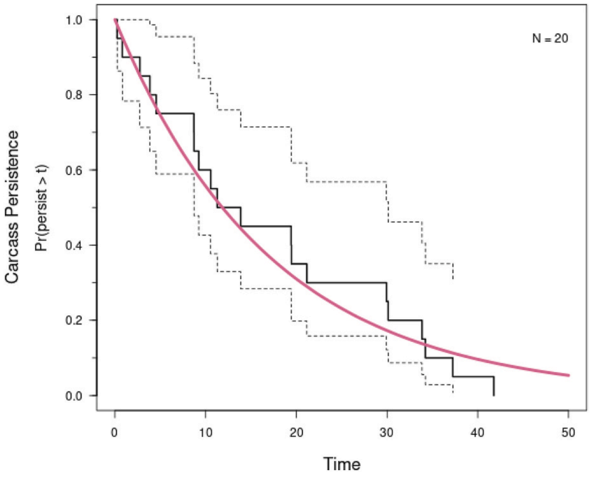

Fig. 6. Carcass persistence on the ground from day 1 to day 50 showing the probability of recovering the animals in the next research, fitted with an exponential distribution trendline.

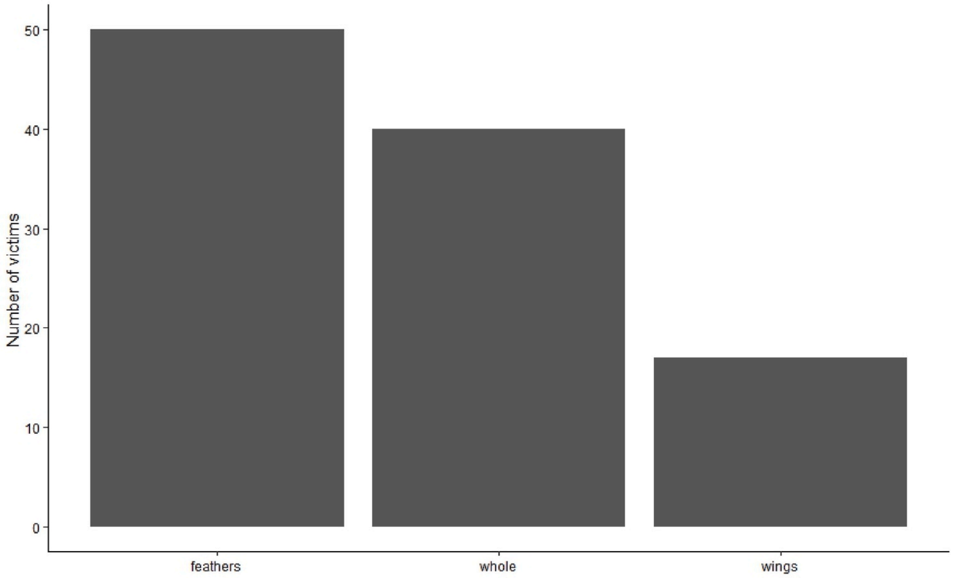

Fig. 5. Victims found in search operations conducted from 2021 to 2024 at the Gotthard wind park were categorized into three distinct groups: isolated feathers, wings and whole bodies.

Table 1
Mean shutdown time (in hours) recorded by the radar of the 5 wind turbines during autumn (August, September and October) and spring (March, April, May and June) 2021-2022 and 2023-2024.

turbine	season	Periods	mean shutdown time (h)
t1	autumn	2021-2022	40.5
t3	autumn	2021-2022	40.5
t4	autumn	2021-2022	40.5
t5	autumn	2021-2022	40.5
t6	autumn	2021-2022	40.5
t1	spring	2021-2022	318
t3	spring	2021-2022	318
t4	spring	2021-2022	318
t5	spring	2021-2022	318
t6	spring	2021-2022	318
t1	autumn	2023-2024	5.9
t3	autumn	2023-2024	5.9
t4	autumn	2023-2024	0
t5	autumn	2023-2024	5.9
t6	autumn	2023-2024	1.8
t1	spring	2023-2024	69.55
t3	spring	2023-2024	96.2
t4	spring	2023-2024	28.25
t5	spring	2023-2024	76.05
t6	spring	2023-2024	48.85

Table 2
Bird counts recorded by radar during migration seasons from 2021 to 2024.

season	year	bird detected	Mean bird detected over 24h
spring	2021	382′147	2830
autumn	2021	161′594	1923
spring	2022	234′902	1740
autumn	2022	189′553	1825
spring	2023	317′856	2354
autumn	2023	57′083	577
spring	2024	149′485	1123

Table 3
Mean number of passages during day and night for different seasons across the four years of research (2021 to 2024).

		DAY	NIGHT
season	year	Mean bird detected per day	Mean bird detected per night
spring	2021	585.2	2885.1
autumn	2021	549.9	1360.7
spring	2022	515.9	1566
autumn	2022	889.3	1297.7
spring	2023	591	2378.6
autumn	2023	236.4	347.5
spring	2024	312.8	1040.9

3.2. Radar

The radar detected 1.7 million birds from 2021 to 2024. Because each wind turbine functions independently from others, we utilized collision rate data to establish specific thresholds for nighttime and daytime switch-off for each turbine. The radar system documented the periods during which wind turbines were not operational (Table 1) and recorded the change of the shutdown parameters. Radar enables the observation of yearly fluctuations in migration rates in spring and autumn, helping understand how migration levels differ from year to year (Table 2).

3.3. Daytime vs nighttime migration

GWP is utilized more frequently by migratory birds during the night than in daylight hours (the four-year average for nocturnal bird crossings at the GWP: 166′996.3 ± 77′125.34 birds; for diurnal passage: 63′303.6 ± 34′748.3 birds). During spring migration seasons, passages can reach peaks of 14′210 birds at night (recorded the 09.04.2023) and 3′863 birds during the day (recorded the 08.05.2024). In autumn migration, the highest counts at night can reach 3′287 birds (recorded the 06.10.2022), whereas during the day, peaks can reach 5′383 birds (recorded the 28.08.2022). While autumn migration shows a daytime peak, the overall average number of passages is always higher at night in every migration season and throughout all years examined (Table 3).

3.4. Visibility probe

The visibility probe during its activity from spring 2023 to spring migration 2024 recorded a total of 23.48 days with very bad visibility (less than 60 m of visibility), 21.04 days with discrete visibility (from 61 to 100 m) and 578 days with good visibility (greater than 100 m). A total of 27 h of shutdowns due to poor visibility were recorded over the three seasons of activity. Over the course of the three operating seasons, the shutdown time for poor visibility was 24.9 h in spring 2023, 0 h in autumn 2023, and 2.12 h in spring 2024, for a total of 27 h for the entire GWP. The option to switch off the rotations was not considered during the first two years (2021-2022), as there was no visibility probe. Consequently, these shutdowns are to be seen as additional to the usual shutdowns noted by the radar.

3.5. Mitigation strategies GWP

Total shutdown time for each single turbine was not correlated with the mortality estimate (r (18) = −0.31, $P > 0.05$). The shutdown time threshold during the periods 2021-2022 and 2023-2024 was significantly different, indicating a higher number of turbine stops during the first period of the study ($t = 3.05$, $P < 0.05$). Conversely, there was no difference in mortality estimates during the two periods observing the entire GWP ($t = -0.13$, $P = 0.89$; Fig. 7).

3.6. Individual mitigation strategies for each turbine

Table 4 and Fig. 8 show the mortality estimations independently for each wind turbine of the GWP according to the season. Observing the turbine number 3, the new shutdown threshold set during the second period (2023-2024) provides valuable insights on decreasing collisions (estimates±SE = 11.79 ± 6.2, $t = 1.88$, $P = 0.08$). Despite showing a lower collision rate than turbine number 3 in the first two years, the other four turbines did not experience any significant shifts in collision rates during the subsequent two years, although their shutdowns have been greatly reduced ($t = 3.05$, $P < 0.05$).

4. Discussion

At times, increasing turbine shutdowns is not the most effective strategy to protect birds, as demonstrated by the GWP results: despite a substantial reduction in shutdowns during the second two-year period (2023–2024), collision rates did not differ from those recorded in the first. This is due to the adjustment of the individual shutdown thresholds for each turbine during both night and day using a radar, as well as the installation of a visibility probe. The management plan for individual turbines was ultimately created through an in-depth examination of mortality events. It has been observed, in another wind farms, that the deployment of a radar has notably lowered shutdown rates without an accompanying increase in collisions (Tomé et al., 2017).

The GWP was activated right away with the radar and shutdown thresholds already in place. Given the importance of the migration corridor used predominantly at night, a slightly elevated shutdown threshold was established for nighttime intervals. The low number of collisions observed in the first two years (2021-2022) can be attributed to the radar, which prevented many fatalities that would have otherwise occurred. This leads to a lack of substantial difference in carcass

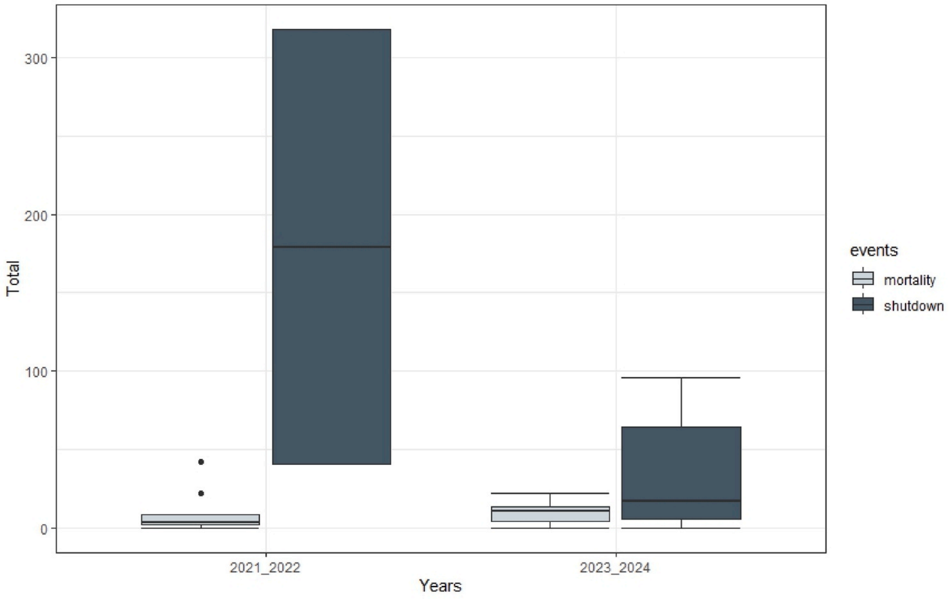

Fig. 7. Mortality events (number of birds deaths) estimate by GenEst v1.4.9 and shutdown time (hour) for the entire wind park, in the periods 2021-2022 and 2023-2024. The shutdown threshold remains constant for all wind parks during the period from 2021 to 2022, while in the subsequent timeframe of 2023 to 2024, individual turbines are assigned unique shutdown thresholds based on the number of birds passing through the wind farm during day and night, as well as considering visibility factors (consult Table 3 in order to analyze the different thresholds).

Table 4
Estimated mortality by turbine and season 2021-2022 and 2023-2024. 95% confidence interval.

2021-2022

Season	Turbine	5%	50%	95%
autumn	t1	5	8.8	14.46
autumn	t3	31.68	42.51	58.88
autumn	t4	2	3.65	6.81
autumn	t5	1	1.73	3.82
autumn	t6	2	3.25	6.25
spring	t1	1	1.7	3.47
spring	t3	10.41	22.01	44.18
spring	t4	0	0	0
spring	t5	4	7.2	12.23
spring	t6	0	0	0

2023-2024

Season	Turbine	5%	50%	95%
autumn	t1	11.03	17.83	26.53
autumn	t3	5	9.87	16.68
autumn	t4	0	0	0
autumn	t5	2	3.62	6.76
autumn	t6	1	1.7	3.77
spring	t1	7.01	12.44	19.49
spring	t3	7.35	13.45	21.3
spring	t4	14.41	22.14	33.11
spring	t5	6	10.83	17.25
spring	t6	3	5.26	9.07

numbers during the two periods investigated for the entire GWP. A first two-year monitoring period indicated as turbine 3 was the most problematic component, exhibiting a higher collision rate than the other turbines. It implies that, in a migration corridor as is GWP, the location of every turbine should be extensively studied over several years before being installed (Hirschhofer et al., 2024). Most of the carcasses discovered at the base of the wind turbines were from passerine birds, indicating the importance of the route for this species' migration.

The positions of the carcasses at the turbines' foot suggest that birds traverse the GWP at low speeds (Vicovaro, 2014). A comparable distance has also been observed in other research (Krijgsveld et al., 2009; Aschwanden et al., 2018). The information indicates that turbines shutdown thresholds can be relayed in a short period, facilitating the formation of safety boundaries very close to the wind farm or turbine sector, within which different parameters like shutdown thresholds or visibility metrics are implemented. Despite the GWP radar being placed at a distance from the turbines for safety and weather-related reasons, the turbine blades cease movement in roughly 25 s once the shutdown command is issued. For optimal performance, the radar ought to be situated at the perimeter of our safety limits, guaranteeing full effectiveness when necessary (Tomé et al., 2017).

The only system that can be employed for GWP so far is radar, which facilitates the detection of birds at nighttime (Hüppop et al., 2019). The radar noted that the majority of birds at the GWP migrate through at night and revealed considerable seasonal changes with higher migration activity in spring compared to autumn (as also highlighted for other migration route in the Alps by Hirschhofer et al., 2024). The notable reduction in shutdowns during the second two-year phase of this study is due to each turbine being operated with independently set shutdown thresholds controlled by the radar. GWP's five turbines highlight the possibility of optimizing energy production on an individual turbine level. Turbines with a low or negligible collision rate in the initial two years (2021-2022) experienced an increase in shutdown thresholds, especially during daytime hours when bird activity is generally lower. Conservative shutdown thresholds were implemented for turbines with high collision rates (especially the number 3), mainly during nighttime. In addition, the implementation of a visibility probe enabled the blades to be deactivated at times when visibility was limited and the likelihood of bird strikes was greater, as indicated by other (Johnson et al., 2002; Aschwanden et al., 2018). During 2023 and 2024, the visibility probe caused a total of 27 h of shutdowns. These shutdowns were both timely and required when visibility was below 50 m. The turbines remained active for the rest of the time, even though radar picked up a large flock of birds, but since the weather was nice, they were not shut down.

The distance between the radar and the wind farm (600 m) prevents from identifying how many individuals are in the GWP collision danger zone. But looking this research, it can be observed the reduction in operational interruptions over the course of four years, alongside the

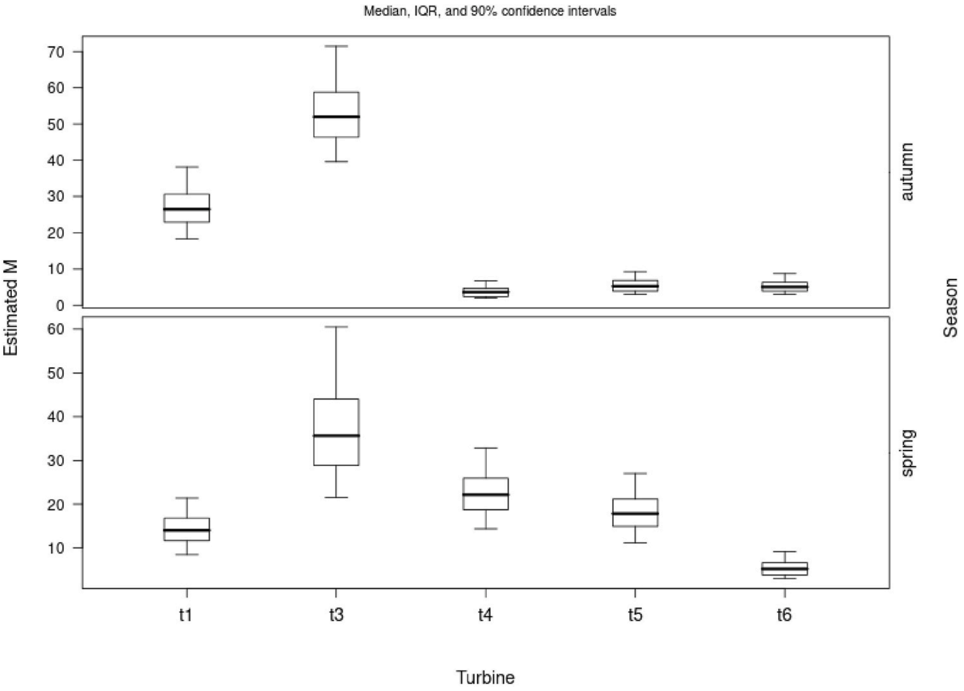

Fig. 8. Estimated mortality by turbine and season.

concurrent stable bird mortality rates and the almost significantly decreasing of fatalities for the turbine number 3, confirms that the generation of wind power is in alignment with conservation efforts for avian species. The formulation of methodologies to calibrate the parameters associated with turbine shutdowns is crucial for attaining a state of equilibrium between lowering shutdown times and preventing collisions with migrating birds. A wind farm placed in a migration corridor faces the risk of having excessively strict measures to block the turbine, despite such restrictions being unnecessary.

5. Conclusion

Overall, the data support optimism regarding bird conservation in wind farms located in migratory pathways. This study outlined a route for advancement and highlighted the importance of proactively modifying the parameters of wind energy installations, supported by comprehensive post-construction studies conducted over multiple years (Aschwanden et al., 2018; Garcia-Rosa et al., 2023; Nilsson et al., 2023; World Bank, 2023). Within a migration corridor, passerines tend to be the most affected species (Alerstam, 1990), making it crucial to set up a system that tracks their movements at night, with visibility probes potentially aiding further in collision prevention depending on the area. Additionally, a thorough assessment of the precise positioning of each turbine is crucial to effectively manage and minimize the impact on migrating bird populations. Future wind farms in migratory pathways might benefit from combining the previously discussed technologies and design with thermal imaging of turbines to quickly address bird collision hazards.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.128979.

Data availability

Data will be made available on request.

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