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Source: Journal of Raptor Research, 60(3) : 1-19

Published By: Raptor Research Foundation

URL: https://doi.org/10.3356/jrr2516

Journal of Raptor Research

Advancing the science, conservation, and understanding of birds of prey

Journal of Raptor Research 60(3):jrr2516
doi: 10.3356/jrr2516

Behavioral Responses of Large Soaring Raptors to Audio Deterrents at Commercial Wind-energy Facilities in the Western USA

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ABSTRACT.—As wind-energy development continues to expand globally to help slow impacts from climate change, so does the need to mitigate impacts to birds from collisions with wind turbines. DTBird is an automated detection, audio deterrent, and turbine curtailment system designed to discourage birds from entering the rotor-swept zone (RSZ) of spinning wind turbines. With Golden Eagles (*Aquila chrysaetos*) a primary species of interest, we summarize the behavioral responses of a suite of large soaring raptors exposed to DTBird audio deterrents (approximate broadcast volume 117–121 dB at 1 m and generally <40 dB at 330–350 m). We quantify the probability of effective deterrence and describe variation in deterrence effectiveness related to study sites (two commercial facilities, one in California and one in Washington, USA), species groups (eagles, vultures, and buteos), wind speed, and risk of collision before deterrent triggering. Generalized linear modeling indicated: (1) lower probability of effective deterrence (PED) for all species groups in Washington; (2) positive relationship between PED and wind speed for eagles and vultures, but a negative relationship for smaller buteos; and (3) higher PED for raptors at high and especially moderate risk of exposure prior to deterrent triggering than for those at low risk. Among probable (confirmed and suspected) Golden Eagles ($n = 158$), 79% in California and 61% in Washington responded to deterrents in a way that likely reduced their risk of entering the RSZ of spinning turbines. Probable Turkey Vultures ($n = 127$; *Cathartes aura*) and buteos ($n = 229$; primarily *Buteo jamaicensis* and *B. lagopus*) responded similarly, whereas Bald Eagles ($n = 40$; *Haliaeetus leucocephalus*) more often responded positively in Washington (species mostly absent in California). The Washington assessment also uniquely supported a control-treatment design to distinguish the deterrence effects of spinning turbines alone versus spinning turbines plus audio deterrents. This analysis confirmed that broadcasted audio deterrents generally at least doubled the probability of effective deterrence compared to spinning turbines alone. Stated another way, the percentage of raptors that showed no response was much lower when the deterrents were broadcasted (treatment group; 27%) than when the deterrents were muted (control group; 65%). Our study results indicate that DTBird audio deterrents can be effective in discouraging Golden Eagles and other large soaring raptors from approaching the RSZ of spinning turbines.

KEY WORDS: *automated detection and deterrence*; *collision risk reduction*; *Golden Eagle*; *impact minimization technology*; *probability of deterrence*; *renewable energy–wildlife mitigation*; *wind turbine.*

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RESPUESTAS CONDUCTUALES DE GRANDES RAPACES PLANEADORAS A DISPOSITIVOS DE DISUASIÓN ACÚSTICA EN INSTALACIONES COMERCIALES DE ENERGÍA EÓLICA EN EL OESTE DE EE. UU

RESUMEN.—A medida que el desarrollo de la energía eólica continúa expandiéndose globalmente para ayudar a mitigar los impactos del cambio climático, también aumenta la necesidad de reducir los impactos sobre las aves por colisiones con turbinas eólicas. DTBird es un sistema automatizado de detección, disuasión acústica y detención de turbinas diseñado para desalentar a las aves de ingresar en la zona de barrido del rotor (ZBR) de las turbinas eólicas en funcionamiento. Con *Aquila chrysaetos* como especie principal de interés, resumimos las respuestas conductuales de un conjunto de grandes rapaces planeadoras expuestas a dispositivos de disuasión acústica DTBird (volumen de emisión aproximado de 117–121 dB a 1 m y generalmente <40 dB a 330–350 m). Cuantificamos la probabilidad de disuasión efectiva y describimos la variación en la eficacia de la disuasión en relación con los lugares de estudio (dos instalaciones comerciales, una en California y otra en Washington, EE. UU.), los grupos de especies (águilas, buitres y buteos), la velocidad del viento y el riesgo de colisión previo a la activación del dispositivo disuasorio. Los modelos lineales generalizados indicaron: (1) una menor probabilidad de disuasión efectiva (PDE) para todos los grupos de especies en Washington; (2) una relación positiva entre la PDE y la velocidad del viento para águilas y buitres, pero una relación negativa para buteos de menor tamaño; y (3) una mayor PDE para rapaces con alto y especialmente moderado riesgo de exposición antes de la activación del dispositivo disuasivo en comparación con aquellas con bajo riesgo. Entre los probables individuos (confirmados y sospechados) de *A. chrysaetos* ($n = 158$), el 79% en California y el 61% en Washington respondieron a los dispositivos de disuasión de una manera que probablemente redujo su riesgo de ingresar en la ZBR de las turbinas en funcionamiento. Los individuos probables de *Cathartes aura* ($n = 127$) y buteos ($n = 229$; principalmente *Buteo jamaicensis* y *B. lagopus*) respondieron de manera similar, mientras que *Haliaeetus leucocephalus* ($n = 40$) respondió con mayor frecuencia de forma positiva en Washington (especie mayormente ausente en California). La evaluación en Washington también permitió implementar un diseño control–tratamiento para distinguir los efectos de disuasión de las turbinas en funcionamiento por sí solas frente a las turbinas en funcionamiento combinadas con dispositivos de disuasión acústica. Este análisis confirmó que los audios de disuasión emitidos duplicaron al menos generalmente la probabilidad de disuasión efectiva en comparación con las turbinas en funcionamiento por sí solas. En otras palabras, el porcentaje de rapaces que no mostraron respuesta fue mucho menor cuando los dispositivos de disuasión estaban activos (grupo tratamiento; 27%) que cuando estaban silenciados (grupo control; 65%). Los resultados de nuestro estudio indican que los dispositivos de disuasión acústica DTBird pueden ser eficaces para desalentar a *A. chrysaetos* y a otras grandes rapaces planeadoras de aproximarse a la ZBR de las turbinas en funcionamiento.

[Traducción del equipo editorial]

INTRODUCTION

The global need to expand renewable energy to reduce carbon footprints has led to growing conservation interests to balance this need with mitigating biodiversity loss (Gibson et al. 2017, Allison et al. 2019, Jager et al. 2021, Katzner et al. 2022). For land-based development of wind energy, much of this attention has focused on minimizing collision risk for large soaring raptors (Allison et al. 2017, 2019). Wind-energy developers in the USA are particularly concerned with minimizing risks to eagles to maintain regulatory compliance under the Bald and Golden Eagle Protection Act (16 USC §668–668d). Golden Eagle (*Aquila chrysaetos*) populations may be at particular risk of decline from a combination of factors, including fatalities caused by collisions with wind turbines (Millsap et al. 2016, Allison et al. 2017, Katzner et al. 2016, 2020, 2022).

Diurnal raptors, including vultures, appear to be particularly susceptible to collisions with wind turbines (Dwyer et al. 2018). With excellent binocular vision, many large soaring raptors (e.g., eagles, buteos, and vultures) are adapted to visually locate prey while in flight (Potier et al. 2017, Vidal-Mateo et al. 2022) but are often relatively blind to objects ahead of them while searching the ground for prey (Potier et al. 2018, Fernández-Juricic et al. 2020). This limitation may be especially relevant regarding their ability to notice spinning turbine blades while hunting (Madders and Whitfield 2006). Additionally, several experiments have shown that diurnal raptors have difficulty visually processing low contrast, moving objects such as spinning turbine blades (Hodos 2003, Blary et al. 2023, 2024).

In contrast, raptors have demonstrated strong responses to auditory cues (McGee et al. 2019). While Sharp et al. (2011) found that spinning turbines alone had a deterrent effect for Bald Eagles (*Haliaeetus leucocephalus*) in Alaska, Fielding et al. (2024) did not find this to be true for Golden Eagles in Scotland.

Additionally, Goller et al. (2022) found that these species each have unique auditory capabilities that may limit their ability to hear certain sounds over background noise (Golden Eagles more limited than Bald Eagles). Regardless, sound has been used as a standard practice to deter eagles from airports (Matyjasiak 2008). Given deterrence effectiveness in other spaces, engineers in the wind-energy industry have increasingly focused on developing automated surveillance and visual or auditory deterrence systems to reduce the potential for diurnal raptors to collide with wind turbines without substantially reducing energy production (May et al. 2012, Albertani et al. 2021, Gradolewski et al. 2021, Felton et al. 2024). Other complementary efforts have focused on employing and evaluating automated turbine curtailment as a means of reducing collisions (Willmott et al. 2015, McClure et al. 2021).

DTBird (Liquen Consultoría Ambiental, S.L., Madrid, Spain; https://www.dtbird.com) is a technology comprising turbine-mounted automated detection, audio deterrent, and turbine curtailment systems designed to reduce collision risk for targeted birds. Here we evaluate the behavioral responses of large soaring raptors exposed to DTBird audio deterrents as part of a larger effort to quantify DTBird's effectiveness in reducing the probability of eagles and other large raptors entering the rotor-swept zone (RSZ) of spinning wind turbines (Felton et al. 2024). Previous, mostly limited DTBird pilot studies conducted in Europe are described in May et al. (2012), Hanagasioglu et al. (2015), and Litsgård et al. (2016). Our study was the first extensive effort to evaluate the DTBird system in North America, with the specific intent of helping to improve the technology and providing quantitative metrics useful in projecting the benefits of turbine-specific DTBird deployments for reducing collision risk for eagles and other large soaring raptors.

This investigation encompassed two commercial wind facilities in the western USA: the Manzana Wind Power Project in a desert foothills landscape in southern California and the Goodnoe Hills Wind Farm in a temperate, grassland landscape on a ridgetop above the Columbia River in south-central Washington (Felton et al. 2024, Smith et al. 2025). Our primary goal for this investigation was to quantify the probability of effective deterrence (PED) while developing insight about key factors influencing the responses of large soaring raptors, especially Golden Eagles, to the DTBird audio deterrents. We investigated whether PED differed between wind facilities, among species groups (eagles, vultures, and buteos), depending on the risk of collision raptors faced before being exposed to DTBird deterrents, or in relation to wind speed.

We hypothesized that raptors at relatively high risk of collision prior to triggering a deterrent would respond more definitively when exposed to the deterrents compared to raptors at low risk. We expected this outcome given the high-risk birds' closer proximity to risk and the stronger combined influences of a nearby spinning turbine and relatively loud deterrent warnings alerting them to potential risk. We evaluated wind speed as an environmental covariate, hypothesizing that higher wind speeds would (1) generally limit the audible range of the deterrent broadcasts, (2) limit a bird's ability to hear the broadcasted deterrents, and/or (3) inhibit a bird's ability to quickly move away from danger when prompted by a deterrent broadcast. The setup at the Washington facility also enabled a unique control-treatment experiment to determine if DTBird audio deterrents broadcasting from spinning turbines were more effective in deterring target raptors than spinning turbines alone.

METHODS

Study Area. The Manzana Wind Power Project began operations in 2012 and comprised 126 1.5-MW General Electric 1.5-77 wind turbines, with a hub height of 65 m and a rotor-swept diameter of 82.5 m. The facility was in the southwestern foothills of the Tehachapi Mountains of southern California in northwestern Antelope Valley, which constitutes the westernmost extension of the Mojave Desert (Fig. 1). The landscape transitioned from foothill topography to a gradually sloping alluvial fan incised by dry desert washes, with desert-scrub, grassland, and sparse woodland (i.e., *Juniperus* sp., *Yucca brevifolia,* and *Pinus-Quercus* spp.) vegetation typical of the upper Mojave Desert. Seven DTBird systems were strategically installed at this facility to support our research. The nonrandomized placements achieved practical feasibility for the facility while also representing both upper foothill and lower alluvial-fan habitats. Typical spacing between turbines at this facility was 200–250 m within strings of turbines and more than 350 m between strings.

Goodnoe Hills Wind Farm began operations in 2008 and comprised 47 2.2-MW Vestas V110 Mark C and B wind turbines, with a hub height of 87 m and a rotor-swept diameter of 110 m. The facility was in south-central Washington atop an east-west ridgeline flanking the Columbia River approximately 3–6 km away (Fig. 1). The topography descended steeply south of the ridgeline approximately 610 m to the river and more gradually to the north approximately 500 m into Rock Creek Canyon and associated riparian corridors. The facility landscape was dominated by a mosaic of grazed grassland and shrub-steppe, with

Figure 1. Layout of Goodnoe Hills Wind Farm in Washington (upper panel) and Manzana Wind Power Project in California (lower panel) showing the locations of installed DTBird systems.

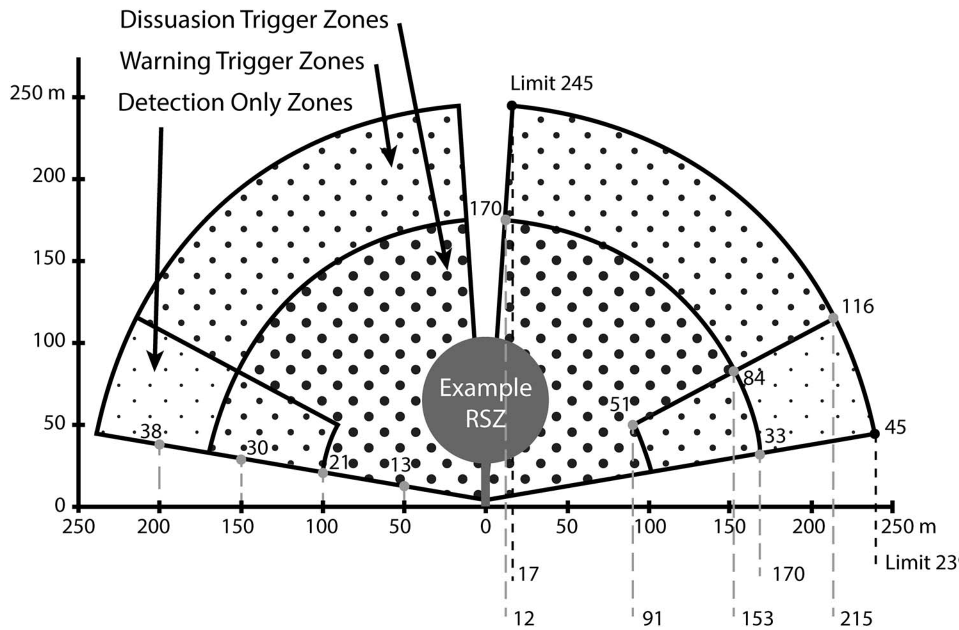

Figure 2. Depiction of expected DTBird detection and deterrent-triggering zones and distances (m) calibrated for Golden Eagles.

inclusions of pine-oak woodlands (*Pinus ponderosa* and *Quercus garryana*) on north-facing slopes. Fourteen DTBird systems were systematically installed around the perimeter of this facility to support our research, 11 of which provided useable data. Typical spacing between turbines at this facility was 200–450 m within strings and 500–1200 m between strings.

At both facilities, DTBird systems were placed on turbines at least 750 m apart to minimize the potential for simultaneous exposure of a raptor to deterrents broadcasted at multiple turbines. DTBird deterrents typically broadcast at <40 dB at a distance ≥ 750 m (Litsgård et al. 2016). That sound level is typical of bird songs and nominal urban background noise (Engel et al. 2024), and typically would not be expected to elicit behavioral responses among passing raptors.

Focal large soaring raptors commonly included Golden Eagles, Red-tailed Hawks (*Buteo jamaicensis*), and Turkey Vultures (*Cathartes aura*) at both study sites, but vultures were uncommon during winter at Goodnoe Hills. In contrast, Bald Eagles and Rough-legged Hawks (*B. lagopus*) commonly occurred only at Goodnoe Hills and mostly during winter.

DTBird System Operation. Comprehensive descriptions of how the DTBird detection and deterrent-triggering systems were configured and operated, along with detailed graphical illustrations of the expected camera viewsheds and deterrent-triggering zones, can be found in H. T. Harvey & Associates (2018) and Felton et al. (2024) (also see Smith et al. 2025). For effective reference herein, Figure 2 portrays the expected overall hemispheric detection envelope (240-m radius) calibrated for raptors the size of Golden Eagles, and variable deterrent triggering zones therein. DTBird targeting in this study was based on how many image pixels a Golden Eagle with fully spread wings and its flying profile fully exposed to the cameras was expected to fill at given distances. Targeting did not distinguish between birds of various kinds and sizes and other inanimate "flying" objects, with larger objects such as airplanes often targeted at much farther distances and smaller objects (e.g., small birds, debris, snowflakes) often targeted at much closer distances. Throughout most of the detection envelope, the deterrent systems produced an initial warning signal (a relatively benign whistle-whoop sound intended to draw a bird's attention) around the same time an initial detection occurred (i.e., when the system registered an apparently eagle-sized target approaching within 240 m of the cameras on a relevant turbine). If the detection system then registered an eagle-sized target approaching to within approximately 170 m, the deterrent system triggered a dissuasion signal (a more raucous series of mechanical sounds intended to actively discourage birds from approaching closer). When targets approached at low altitudes considered to represent a lower collision risk, warning signals were not triggered until the target approached within 170 m and dissuasion signals were not triggered until a target approached within 100 m. For the analyses summarized herein, we did not distinguish between responses to warning and dissuasion signals. Instead, we focused only on determining if the deterrence system in general deterred focal raptors from approaching the RSZ of spinning turbines. For reference, deterrents were broadcasted at approximately 117 dB (warning) and 121 dB (dissuasion) at 1 m from the source. The signals generally attenuated to <40 dB at 330–350 m, but with broadcast distances greatly affected by topography, wind, and other environmental factors (Litsgård et al. 2016).

The only noteworthy difference between the installations at the Manzana (DTBirdV4D4 Model 2016) and Goodnoe Hills (DTBirdV4D8 Model 2019) sites was that the Manzana systems included only one ring of four broadcast speakers installed on the turbine tower just below the RSZ, whereas the Goodnoe Hills systems included a second ring of four broadcast speakers attached just below hub height. The second ring of speakers accounted for larger turbines at Goodnoe Hills and helped ensure effective broadcasting throughout a larger overall detection and collision-risk zone (Felton et al. 2024).

DTBird neither identified, enumerated, nor specifically recorded tracks of detected raptors, but recorded video clips (one for each of the four cameras, with overlapping viewsheds) depicting the overall detection and, if relevant, deterrent-triggering period for each recorded occurrence. Technicians then reviewed the videos and assigned species and behavioral responses to characterize each detection/deterrence event. Confidently identifying species based on low-resolution and often poor-quality video clips was difficult and resulted in many uncertain identifications recorded to the most precise taxonomic category possible. In some cases, more than one target raptor was present; if we were unable to determine which bird triggered the system, we discarded the record (May et al. 2012).

Control-Treatment Design in Washington. Our research at the Goodnoe Hills facility uniquely involved a 2-yr experimental design that supported addressing multiple objectives (Felton et al. 2024). The setup enabled a blinded control-treatment design that supported distinguishing raptor responses to spinning turbines alone versus spinning turbines plus broadcasted deterrents. For the Goodnoe Hills performance assessment, the DTBird-equipped turbines were variably operated normally with deterrents broadcasting (treatment group) versus with the deterrents triggered virtually but muted (i.e., silent; control group). The suite of DTBird units operating in each mode varied daily according to a stratified, randomized schedule that sought to equitably distribute broadcasting and non-broadcasting units across the facility each day (Felton et al. 2024). The master records we kept indicated whether or not a triggered deterrent was broadcasted. The blind assessment of raptor behavioral responses to the deterrents involved technicians reviewing all Goodnoe Hills videos without knowledge of whether or not triggered deterrents were broadcasted.

Sampling Data and Data Classifications. The Manzana dataset derived from 1 yr of daily data collected by the DTBird systems from January through December 2017. For each of the seven DTBird installations, we randomly selected 10 d/mo and had technicians identify the targets associated with all detection events recorded on those days that triggered a deterrent. The Goodnoe Hills dataset derived from 1 yr of daily data collected from September 2021 through August 2022. Technicians identified the targets of all detections recorded at 11 consistently operable DTBird installations on randomized selections of 10 d/mo during that year. From these initial all-target datasets, we selected all records pertaining to focal raptors for analysis.

Technicians identified raptors to species whenever possible but often were limited to uncertain classifications such as potential/probable Golden Eagle, unknown eagle, eagle/vulture, eagle/buteo, or simply unidentified large raptor. Hence, we routinely frame our species-specific results as reflecting confirmed plus potential identifications, hereafter together referred to as "probable" identifications (Felton et al. 2024). We also took a tiered approach to evaluating the datasets to provide insight about large soaring raptors in general, potential differences among relevant species groups, and ultimately Golden Eagles.

After identifying all targets detected during randomly selected sampling days, technicians classified the behavioral responses of all probable eagles and representative selections of probable buteos and vultures that triggered deterrents. The technicians used several subjective and objective criteria to classify the behavioral responses of raptors, culminating in a final response classification as described in Table 1. They used an on-screen protractor (Straffi 2016) to determine through 2D on-screen measurements whether a bird's flight path appeared to diverge appreciably away from the RSZ within 5 sec of a deterrent being triggered. We considered a sustained flight path divergence of >15° away from the deterrent source that precluded further passage toward the spherical RSZ of the turbine as indicative of a meaningful avoidance response (also see May et al. 2012). Measuring 3D response patterns based on 2D DTBird video clips

Table 1. Categories used to classify the behavioral responses of raptors exposed to audio deterrents as revealed in videos stored by the DTBird systems operating at two commercial wind-energy facilities, one in California and one in Washington.

Classification Category	Description
Confirmed effective	Raptor reacted in a way that, based on the change in flight pattern and direction, reduced the risk of collision with turbine blades—did not enter RSZ.
Potentially effective	Raptor appeared to react to deterrent, including a flight diversion, but the response was not definitive or discernable enough to be confident that the bird was at less risk after deterrent emission—likely did not enter RSZ.
Not effective	Raptor reacted to deterrent (e.g., temporarily altered its flapping rate) but did not alter its flight path away from RSZ.
No response	Raptor did not visibly react to deterrent.
Ineffective	Not effective + No response
Unknown/undetermined[a]	Raptor already moving away from turbine when deterrent broadcasted; video quality or bird image quality was not favorable for determining the 3D reaction of the bird on the 2D video screen; or it was not possible to confidently determine whether a reaction occurred. We excluded these data points from analyses.

[a] Excluded from analyses.

was not straightforward and often led to uncertainty in classifying responses as confirmed effective versus potentially effective (Table 1). To support final classifications, technicians also carefully examined video footage for evidence of correlations between detectable changes in flapping pattern or flight style and the triggering of deterrents.

Along with evaluating behaviors and flight trajectories to classify a bird's response pattern when it triggered a deterrent, technicians also classified each bird's risk of approaching the RSZ prior to triggering a deterrent (hereafter Pre-exposure Risk). The categories were high (trajectory and altitude could take it into RSZ), moderate (trajectory and altitude could take it near turbine but likely below or above RSZ), or low (bird moving tangential to or away from turbine distant from RSZ or at altitude high above RSZ). We considered Pre-exposure Risk as a predictor of behavioral responses in the analytical models described below.

Multi-site Analyses of Deterrence Responses. We conducted initial descriptive comparisons of the responses of eagles, vultures, and buteos to broadcasted deterrents classified as confirmed effective, potentially effective, or ineffective (Table 1). Then we composed binary logistic generalized linear models (LGLMs) to provide further inferential insight into the drivers of variation in PED at the two facilities (see Discussion regarding unsuccessful attempts to compose generalized linear mixed-effects models [GLMMs] with Turbine ID as a random effect). To compose the LGLMs, we collapsed the PED response variable into two categories: 1 = probable effective response (confirmed effective + potentially effective) and 0 = ineffective response (not effective + no response; Table 1). We prepared multi-site models based on: (1) all cases classified as involving a probable eagle, vulture, or buteo (excluding uncertain cases such as eagle/vulture and eagle/buteo), with Species Group included as a potential predictor; and (2) models limited to probable Golden Eagles.

For the multi-site, multi-species analysis, the initial full LGLM was as follows:

PED ∼ Site (Manzana or Goodnoe Hills) + Species Group (probable eagles, vultures, or buteos) + Pre-exposure Risk (low, moderate, or high) + Wind Speed (continuous variable [m/sec] measured by turbine anemometer) + all possible 2-way interactions

The initial full LGLM for Golden Eagles alone was the same except for excluding Species Group and all associated interactions.

We used the *glm* function in R (R Core Team 2025) to implement the LGLM analyses. To select final models, we compared Akaike information criterion scores corrected for small samples sizes (AICc) to evaluate candidate models and identify the most parsimonious combinations of predictors (Burnham and Anderson 2010). Upon identifying the top models for which ΔAICc was ≤ 2, we used the AIC-based *model.avg* function in R to produce final model coefficients and represent the relative contributions of all predictors retained in the top models based on full average values (Burnham and Anderson 2010). To further evaluate the top models, we used McFadden's pseudo-R^2 to assess explanatory power (McFadden 1974, 1979, Friendly and Meyer 2016), and we compared log-likelihood values for candidate models and

Table 2. DTBird events recorded from January through December 2017 at the Manzana Wind Power Project in California and from September 2021 through August 2022 at the Goodnoe Hills Wind Farm in Washington that formed the basis for assessing the behavioral responses of eagles and other large raptors to DTBird audio deterrents.

		Goodnoe Hills		
Species[a]	Manzana Deterrents Broadcasting	Deterrents Broadcasting	Deterrents Muted	Total
Golden Eagle	80	33	45	158
Bald Eagle	1	14	25	40
Unidentified eagle	0	11	9	20
Turkey Vulture	21	52	54	127
Buteo[b]	122	52	55	229
Golden Eagle or vulture[c]	39	7	3	49
Golden Eagle or buteo[c]	7	3	6	16
Unidentified eagle/vulture [c]	11	34	49	94
Unidentified eagle/buteo[c]	0	16	22	38
Total	281	222	268	771

[a] Classifications represent all cases where we either confirmed or suspected involvement of the relevant species or species group.
[b] Primarily Red-tailed Hawks year-round at both sites and Rough-legged Hawks during winter at Goodnoe Hills.
[c] Excluded from modeling analyses.

predicted relationships with 85% confidence intervals to guard against including uninformative parameters (Arnold 2010, Sutherland et al. 2023).

Goodnoe Hills Control-Treatment Analysis. To evaluate differences in the categorical response rates for the control (deterrents muted) and treatment (deterrents broadcasted) groups at Goodnoe Hills, we conducted initial descriptive comparisons based on responses classified as confirmed effective, potentially effective, or ineffective (Table 1). We examined the deterrent response patterns reflected in all classified cases involving eagles, vultures, and buteos, as well as subsets of all probable Golden Eagles and all probable Bald Eagles. Then we evaluated LGLMs with the PED response variable collapsed to a binary variable as above to provide additional inferential insight. We prepared two analyses based on: (1) all cases classified as involving a probable eagle, vulture, or buteo, with Species Group included as a potential predictor; and (2) cases limited to probable Golden Eagles.

The initial full LGLM for the multi-species analysis was as follows:

> PED $\sim$ Treatment Group (control or treatment) + Species Group (probable eagles, vultures, or buteos) + Pre-exposure Risk (low, moderate, or high) + Wind Speed + all two-way interactions between Treatment Group and other variables

The initial full model for Golden Eagles alone was the same except for excluding Species Group and the Treatment Group * Species Group interaction. Upon identifying the top models for which ΔAICc was ≤ 2, we used model averaging to produce final model coefficients and represent the relative contributions of all predictors retained in the top models. We also used McFadden's pseudo-R^2 values to further evaluate the merits of the selected models and compared log-likelihood values for candidate models and predicted relationships with 85% confidence intervals to guard against including uninformative parameters (Arnold 2010, Sutherland et al. 2023).

RESULTS

We amassed 281 events of large soaring raptors exposed to broadcasted deterrents at the Manzana study site, 222 events at the Goodnoe Hills study site (treatment group), and 268 events at the Goodnoe Hills where raptors triggered one or both deterrents but the broadcasts were muted (control group; Table 2). Of these totals, probable eagles composed 29% of the Manzana events, 26% of the Goodnoe Hills treatment events, and 29% of the Goodnoe Hills control events. The Manzana eagle dataset was heavily weighted in favor of Golden Eagles (only one Bald Eagle), whereas the Goodnoe Hills control and treatment datasets included variable mixes of probable Golden Eagles (57% of both control and treatment samples), probable Bald Eagles (24% and 31%, respectively), and unidentified eagles (11% and 19%, respectively). At both sites, the remaining cases involved variable representation of probable vultures and buteos, plus other cases where we could not distinguish an eagle/vulture or an eagle/buteo.

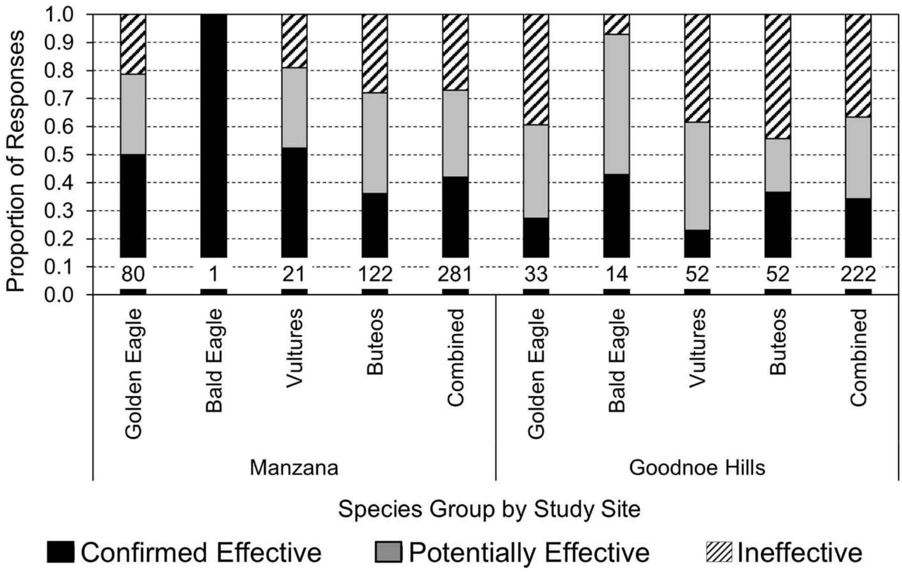

Figure 3. Classified behavioral responses of large soaring raptors to broadcasted DTBird audio deterrents at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington. The combined category includes cases identified only as unidentified eagle/vulture or unidentified eagle/buteo. Sample sizes are shown at the base of each column.

Multi-Site Analyses of Deterrence Response Patterns. Based on all 503 cases involving large soaring raptors exposed to broadcasted deterrents at the two study sites (Table 2), we classified 73% of the Manzana events and 63% of the Goodnoe Hills events as involving PED. For all species groups and eagle species, initial descriptive comparisons of the overall response patterns at the two sites suggested at least marginally higher proportions of probable effective responses and concomitantly lower proportions of ineffective responses (Table 1) at Manzana than at Goodnoe Hills (Fig. 3).

For Golden Eagles, the Manzana data indicated 50% confirmed effective responses and 29% potentially effective responses, yielding a combined 79% estimate of PED (Fig. 3). In comparison, the Goodnoe Hills

Table 3. Parameters of final binary logistic generalized linear model selected to represent relationships between the probability of DTBird deterring large soaring raptors (eagles, vultures, and buteos) from entering the rotor swept zone (RSZ) of spinning wind turbines and selected predictors at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington.

Parameter	Estimate	SE	*z*	*P*	Odds Ratio	90% CI
Intercept	−1.5623	0.5047	−0.310	0.757	–	–
Site–Manzana[a]	0.6539	0.2678	2.44	0.015	1.92	1.48–2.36
Species Group–vulture[b]	0.2385	0.7581	0.32	0.753	1.27	0.02–2.52
Species Group–buteo	0.9256	0.6113	1.51	0.130	2.52	1.52–3.53
Pre-exposure Risk–moderate[c]	0.7307	0.2741	2.67	0.008	2.08	1.63–2.53
Pre-exposure Risk–high	0.6028	0.3942	1.52	0.128	1.83	1.18–2.48
Wind Speed (m/sec)	0.1383	0.0777	1.78	0.075	1.15	1.02–1.28
Species Group–vulture * Wind Speed	−0.0906	0.1186	−0.76	0.445	0.91	0.72–1.11
Species Group–buteo * Wind Speed	−0.2266	0.0941	−2.41	0.016	0.80	0.64–0.95

[a] Site reference category = Goodnoe Hills.

[b] Species Group reference category = eagle.

[c] Pre-exposure Risk reference category = low – raptor moving tangential to or away from turbine distant from RSZ or at altitude high above RSZ (see Fig. 2). Other categories: moderate – trajectory and altitude could take raptor near turbine but likely below or above RSZ; and high – trajectory and altitude could take raptor into RSZ.

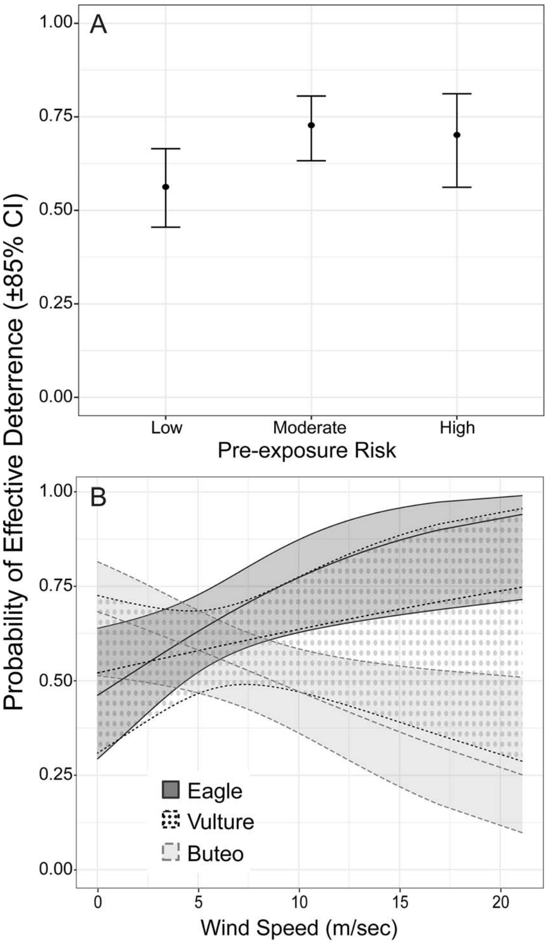

Figure 4. Modeled probability of effective DTBird deterrence for all large soaring raptors combined (eagles, vultures, and buteos) at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington in relation to (A) classified Pre-exposure Risk, and (B) the interactive influence of Wind Speed and Species Group.

data indicated a lower proportion of confirmed effective responses (27%) but a similar level of potentially effective responses (33%), yielding a lower combined 60% PED estimate for Golden Eagles. Similar patterns occurred for vultures and all species combined. In contrast, for buteos the proportions of confirmed effective responses were relatively low and did not differ at the two sites (27–29%); however, the combined proportion of probable effective responses was again notably higher at Manzana (72%) than at Goodnoe Hills (56%; Fig. 3).

The multi-site, multi-species LGLM analysis identified two models with ΔAICc $\leq$ 2 (see Table S1 for comparisons of candidate models). The only difference between the top two models was inclusion of the Site * Wind Speed interaction, which resulted in a nominal ΔAICc of 0.02, no improvement in the AIC model weight, and only a small improvement in the log-likelihood value (−189.31 vs. −190.36). Accordingly, we concluded that the Site * Wind Speed interaction was an uninformative parameter (Arnold 2010) and adopted the simpler model as the final model:

$$\text{PED} \sim \text{Site} + \text{Species Group} + \text{Pre-exposure Risk} + \text{Wind Speed} + \text{Species Group} * \text{Wind Speed}$$

The AICc score for the final model indicated a modest improvement compared to the null model, a modest AICc model weight, and a McFadden's peusdo-R^2 estimate that indicated fair explanatory power (Table S1).

Model coefficients, associated parameter tests, and odds ratios (Table 3) indicated that PED was highest for raptors classified at moderate Pre-exposure Risk, slightly lower for raptors at high risk, and lowest for raptors at low risk (Fig. 4A). The main-effect coefficient for Site indicated that PED averaged slightly higher overall at Manzana than at Goodnoe Hills (Table 3). The Species Group * Wind Speed interaction indicated that, at low wind speeds below approximately 4 m/sec (turbine cut-in speed = 3 m/sec), PED averaged similar for vultures and eagles but slightly higher for buteos; however, as wind speeds increased beyond that, PED decreased markedly for buteos but increased progressively for vultures and especially eagles (Fig. 4B).

The multi-site Golden Eagle LGLM analysis identified four top models with ΔAICc $\leq$ 2 (Table S2), which yielded the following integrated final model:

$$\text{PED} \sim \text{Site} + \text{Pre-exposure Risk} + \text{Wind Speed} + \text{Site} * \text{Wind Speed}$$

AICc scores for the top models indicated modest improvement compared to the null model and modest combined model weights, and McFadden's pseudo-R^2 estimates for the top models indicated fair to good explanatory power (Table S2).

Model-averaged coefficients, associated parameter tests, and odds ratios for the selected Golden Eagle model (Table 4) indicated that PED was generally higher at Manzana than at Goodnoe Hills, and the estimated odds of effective deterrence increased 7% with each unit (m/sec) increase in Wind Speed. Inclusion of the Site * Wind Speed interaction further indicated that PED increased more strongly with

Table 4. Model-averaged (full average) parameters of final binary logistic generalized linear model selected to represent the relationship between the probability of DTBird deterring Golden Eagles from entering the rotor swept zone (RSZ) of spinning wind turbines and selected predictors at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington.

Parameter	Estimate	SE	*z*	*P*	Odds Ratio	90% CI
Intercept	−0.2949	1.0206	0.287	0.774	–	–
Site–Manzana[a]	0.8523	1.0405	0.815	0.415	2.34	0.63–4.06
Pre-exposure Risk–moderate[b]	1.2859	0.5579	2.276	0.023	3.62	2.70–4.54
Pre-exposure Risk–high[b]	1.3743	0.8464	1.603	0.109	3.95	2.56–5.34
Wind Speed (m/sec)	0.0718	0.1527	0.468	0.640	1.07	0.82–1.33
Site–Manzana * Wind Speed	−0.0400	0.1377	0.288	0.773	0.96	0.73–1.19

[a] Site reference category = Goodnoe Hills.

[b] Pre-exposure Risk reference category = low – raptor moving tangential to or away from turbine distant from RSZ or at altitude high above RSZ (see Fig. 2). Other categories: moderate – trajectory and altitude could take raptor near turbine but likely below or above RSZ; and high – trajectory and altitude could take raptor into RSZ.

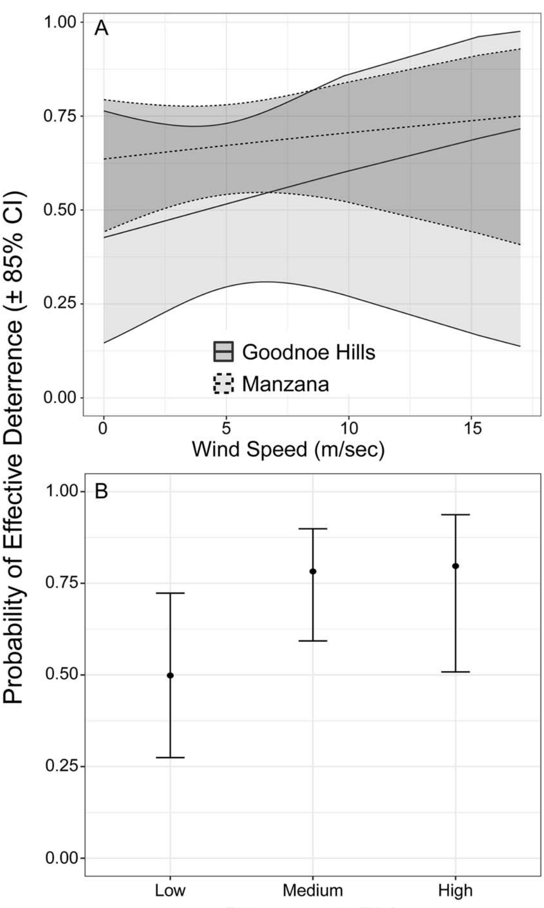

Figure 5. Modeled probability of effective DTBird deterrence for Golden Eagles at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington in relation to (A) the interactive influence of Wind Speed and Site, and (B) classified Pre-exposure Risk.

increasing Wind Speeds at the Goodnoe Hills, diminishing the difference between Sites at higher Wind Speeds (Fig. 5A). PED was also higher overall for eagles at medium and high Pre-exposure Risk compared to eagles at low risk (Fig. 5B).

Goodnoe Hills Control-Treatment Analysis. The multi-species dataset involving all 490 cases from Goodnoe Hills (Table 2) indicated that confirmed effective responses were more likely to occur when the deterrents were broadcasting (34% of relevant cases) than when they were muted (7%; Fig. 6). Apparently effective responses also occurred when the deterrents were not broadcasting, however, suggesting that spinning blades alone sometimes elicited avoidance behavior around the time that the deterrents were triggered virtually but the audio broadcasts were muted. We classified 27% of the analyzed cases as potentially effective responses and the percentage of such cases was slightly higher for the treatment group (31%) than for the control group (24%). The percentage of not effective responses (see Table 1) also was slightly higher for the treatment group (8% of relevant cases) than for the control group (4%). In contrast, the percentage of raptors that showed no response was much lower for the treatment group (27%) than for the control group (65%).

Small samples hindered developing independent control-treatment LGLMs for Bald Eagles alone; however, the classified outcomes suggested that Bald Eagles exhibited a higher overall sensitivity to broadcasted deterrents (93% probable effective responses) than Golden Eagles (63%; Fig. 6). In addition, similar to the scenario for all large raptors, 31% of the relevant events involving Golden Eagles and 28% of the relevant events involving Bald Eagles demonstrated probable effective responses even when the deterrents were not broadcasting.

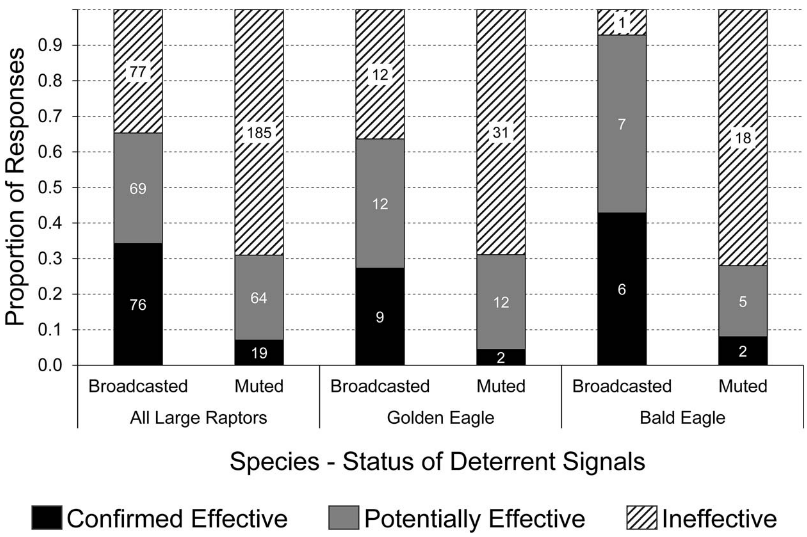

Figure 6. Classified behavioral responses of all large soaring raptors combined (eagles, vultures, and buteos), Golden Eagles, and Bald Eagles at the Goodnoe Hills Wind Farm in Washington depending on whether DTBird audio deterrents were broadcasting (treatment group) or triggered virtually but muted (control group). Case sample sizes are identified within bars.

The Goodnoe Hills combined-species LGLM analysis identified two top models with ΔAICc ≤ 2 (Table S3), with the addition of Wind Speed the only difference between the two. The addition of Wind Speed only nominally increased the log-likelihood and McFadden's pseudo-R^2 values (Table S3), and the predicted odds ratio (0.99, CI 0.96–1.03) also indicated only a limited, equivocal effect. Therefore, we concluded that Wind Speed constituted an uninformative parameter (Arnold 2010) and we selected the simpler model as the final model:

$$\text{PED} \sim \text{Treatment Group} + \text{Pre-exposure Risk}$$

The AICc score for the top model indicated substantial improvement compared to the null model and a modest model weight, and the McFadden's pseudo-R^2 estimate indicated good explanatory power (Table S3).

Model coefficients, associated parameter tests, and odds ratios (Table 5) confirmed that PED averaged greater overall with broadcasted (treatment) versus muted (control) deterrents (Fig. 7), and that PED for raptors at moderate and high risk was markedly higher than for raptors at low risk. Although the Treatment Group * Pre-exposure Risk interaction was not retained in the final integrated model, it was instructive to note that PED for raptors confronted

Table 5. Parameters of final binary logistic generalized linear model selected to represent the probability of effective deterrence for large soaring raptors (eagles, vultures, and buteos) dependent on whether DTBird audio deterrents were broadcasted or muted (Treatment Group) and in relation to other selected predictors at the Goodnoe Hills Wind Farm in Washington.

Parameter	Estimate	SE	z	P	Odds Ratio	90% CI
Intercept	−1.0065	0.2074	−4.85	<0.001	–	–
Treatment Group–on[a]	1.4199	0.2413	5.88	<0.001	4.14	3.74–4.53
Pre-exposure Risk–moderate[b]	0.6091	0.2587	2.36	0.019	1.84	1.41–2.26
Pre-exposure Risk–high	0.7017	0.3663	1.92	0.055	2.02	1.41–2.62

[a] Treatment Group reference category = off – control, deterrents muted; on – treatment, deterrents broadcasted.
[b] Pre-exposure Risk reference category = low – raptor moving tangential to or away from turbine distant from rotor-swept zone (RSZ) or at altitude high above RSZ (see Fig. 2). Other categories: moderate – trajectory and altitude could take raptor near turbine but likely below or above RSZ; and high – trajectory and altitude could take raptor into RSZ.

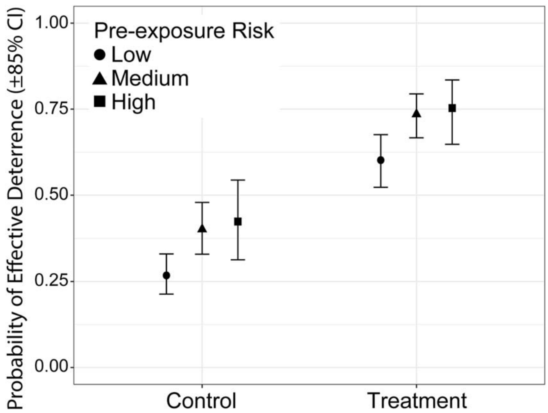

Figure 7. Modeled probability of effective deterrence for all large soaring raptors combined (eagles, vultures, and buteos) at the Goodnoe Hills Wind Farm in Washington in relation to the additive influences of Treatment Group (i.e., whether or not birds were subjected to broadcasted [treatment] or muted [control] DTBird audio deterrents) and classified Pre-exposure Risk.

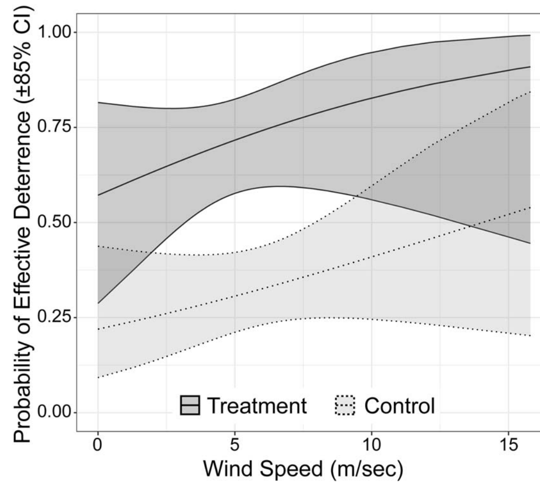

Figure 8. Modeled probability of effective deterrence for Golden Eagles at the Goodnoe Hills Wind Farm in Washington in relation to the interactive influence of Treatment Group (i.e., whether birds were subjected to broadcasted [treatment] or muted [control] DTBird audio deterrents) and Wind Speed.

with spinning turbines and broadcasted audio deterrents was highest for those at moderate Pre-exposure Risk (a common pattern also shown in Figs. 4A and 5B), whereas PED for raptors confronted with only spinning turbines (deterrents muted) averaged lower overall and increased progressively as their risk of entering the RSZ increased (Fig. 7).

The Goodnoe Hills LGLM analysis for Golden Eagles alone identified three top models with ΔAICc ≤ 2 (Table S4), which yielded the following integrated final model:

PED $\sim$ Treatment Group + Wind Speed + Treatment Group * Wind Speed

AICc scores for the top models indicated modest improvement compared to the null model and modest combined model weights, and McFadden's peusdo-R^2 estimates for the top models indicated good explanatory power (Table S4).

Model-averaged coefficients, associated parameter tests, and odds ratios (Table 6) indicated that PED averaged higher when the deterrents were broadcasting than when they were muted. A positive main effect coefficient for Wind Speed and the estimated odds ratio indicated that the odds of effective deterrence for Golden Eagles increased approximately 15% per unit (m/sec) of increasing wind speed overall, and that effect was markedly enhanced with broadcasted deterrents compared to spinning turbines alone (Fig. 8).

DISCUSSION

Large soaring raptors at the Manzana facility in a California foothills/desert landscape tended to

Table 6. Model-averaged (full average) parameters of final binary logistic generalized linear model selected to represent the probability of effective deterrence for Golden Eagles dependent on whether DTBird audio deterrents were broadcasted or muted (Treatment Group) and in relation to other selected predictors at the Goodnoe Hills Wind Farm in Washington.

Parameter[a]	Estimate	SE	*z*	*P*	Odds Ratio	90% CI
Intercept	−1.2679	0.7067	1.77	0.076	–	–
Treatment Group–on	1.5570	0.8196	1.87	0.061	4.74	3.40–6.09
Wind Speed (m/sec)	0.0902	0.1034	0.86	0.388	1.15	0.98–1.31
Treatment Group–on * Wind Speed	0.0374	0.1280	0.29	0.773	1.20	0.82–1.58

[a] Treatment Group reference category = off – control, deterrents muted; on – treatment, deterrents broadcasted.

respond more effectively to the deterrents than their counterparts at the Goodnoe Hills facility occupying a temperate ridgetop/grassland landscape bordering the Columbia River in Washington. Noteworthy species-specific differences also were evident, with eagles, vultures, and buteos differing in their responses to the deterrents, especially in relation to the interactive influence of wind speed. Reasons for these differences are not well understood, but regardless of the causal factors, evidence of site- and species-specific differences in the effectiveness of DTBird warrant further consideration in the context of developing predictive models to support eagle permitting in the USA under the Bald and Golden Eagle Protection Act (e.g., see U.S. Fish and Wildlife Service 2013, Bay et al. 2016).

Most of the final multi-species and Golden Eagle models reflected noteworthy relationships between PED and wind speed. Contrary to our research hypothesis, increasing wind speeds generally resulted in higher PED for larger species such as eagles and vultures; however, smaller buteos showed the opposite, hypothesized pattern. One possible explanation is that faster-spinning turbine blades themselves function as a greater deterrent and more effectively amplify the effect of the audio deterrents for approaching larger species. Visual-acuity experiments have indicated that diurnal raptors often have difficulty visually processing low contrast, spinning turbine blades, and that sensitivity to such achromatic contrasts varies among species; however, at least one buteo species (*B. buteo*) showed a similar sensitivity profile as Golden Eagles (Blary et al. 2024). It is also possible that higher wind speeds facilitate greater maneuverability and responsiveness for larger species of soaring raptors, which are strongly dependent on the energy savings provided by wind-driven or thermal lift (Katzner et al. 2015, Duerr et al. 2019) and are likely less constrained by strong winds than smaller species such as buteos, for example (Kerlinger 1989, Hoover and Morrison 2005, Preston and Beane 2024). Thus, increasing wind speeds may be a detriment rather than a benefit for smaller buteos in influencing their ability to respond effectively to the deterrents.

In our study, larger eagles and vultures tended to be increasingly more responsive to the deterrents than smaller buteos as wind speeds increased. Further, although we were unable to track repeated responses of individual eagles in our study, studies in Scotland found that differences attributable to individual tagged Golden Eagles were the largest source of variation in eagle responses to the presence of wind turbines, often mediated by wind speed (Fielding et al. 2023, 2024). Future research incorporating individually tagged and tracked eagles could provide further insight into the individual-level responses of eagles to the DTBird audio deterrents. Such insight would, however, necessarily be limited to resident eagles known to frequent the relevant facilities for which repeated exposure to the DTBird audio deterrents is likely (also see May et al. 2012). Such an approach would not effectively capture response variation among transient eagles that are present for only brief periods and, therefore, could provide a biased perspective.

We expected responsiveness to the deterrents to be lower for raptors at low collision risk than for raptors at higher risk of exposure to the RSZ of spinning turbines, because such birds are not exposed to especially forceful deterrent broadcasts and have relatively little need to divert their flights to avoid risk. Contrary to our hypothesis, however, a dearth of significant differences in PED for raptors at moderate versus high risk, with raptors at moderate risk sometimes showing at least slightly greater PED, was unexpected. A relatively high PED for raptors at moderate risk of exposure might have reflected such birds having more time and room to maneuver effectively in response to the deterrents. In contrast, raptors at high risk of exposure might have appeared less responsive than expected because they were suddenly blasted with raucous, high-volume deterrent broadcasts and had less room to respond effectively before entering the high-risk zone.

Although we had no ability to conduct a similar control-treatment evaluation at the Manzana study site to provide comparative insight, we presume that a similar proportional effect of spinning turbines and broadcasted deterrents would apply at both study sites, but acknowledge that differences in the landscape backdrop against which the turbines are spinning could result in differential perception and responses. In contrast, we expect that higher average wind speeds should have similar effects on sound hearing/transmission and bird maneuverability at both sites.

Although based on limited observations, the Goodnoe Hills data suggested that Bald Eagles tended to be more sensitive to the deterrents than Golden Eagles. This result is consistent with Goller et al. (2022) having demonstrated that Bald Eagles were better able hear unique sounds over background noise. Alternatively, this result could have stemmed from Golden Eagles demonstrating greater achromatic contrast sensitivity than Bald Eagles (Blary et al. 2024), which might have allowed them to better perceive spinning turbines and respond less dramatically when the deterrents warned them of pending risk. Differential species-specific responses to avoiding wind turbines were also noted among White-tailed Eagles (*Haliaeetus albicilla*) and Golden Eagles in Scotland (Dahl et al. 2013, Fielding et al. 2023).

Accurately characterizing the behavioral responses of raptors to the DTBird audio deterrents was greatly confounded by two primary factors: (1) the ultra-wide-angle camera lenses (103° × 77°) designed to identify targets at greater distances produced low-resolution video recordings that frequently obscured the details of bird behaviors, such as changes in flapping rates, distinct flinches and head movements, and subtle flight path alterations; and (2) evaluating 2D renderings of 3D movement scenarios made it difficult to render insights about the degree of response, especially pertaining to measuring flight diversion angles as a relevant criteria. With this perspective in mind, if eagles and other raptors tended to respond to the deterrents less dramatically at Goodnoe Hills, then the limitations outlined above could have more easily reduced our ability to effectively discern subtler, but nonetheless effective, responses at that site. For this reason, comparing only the proportions of confirmed effective responses at the two sites could be misleading, as opposed to focusing on the combination of confirmed and potentially effective responses as a better comparative indicator of relative success. Taking this approach might have overestimated DTBird's effectiveness to some degree. We expect, however, that there is a higher likelihood of underestimating the system's effectiveness by limiting the results to confirmed effective responses, because of our limited ability to confidently discern and classify relatively subtle but nonetheless effective behavioral responses. Combining confirmed effective and potentially effective responses reduced, but did not eliminate, the indication of greater deterrence effectiveness at the Manzana facility and provided estimates of PED that exceeded 50% for both sites and for all species groups. Demonstrating deterrence effectiveness of at least 50% was a specific goal for this study to potentially stimulate the U. S. Fish and Wildlife Service to formally consider the technology as a potential measure for reducing fatalities of Golden Eagles at wind facilities in the USA (Felton et al. 2024).

We initially sought to compose generalized linear mixed-effects models (GLMMs) including Turbine ID as a random effect to address two possibilities. First, we sought to reduce the potential for nonindependence where repeated measures involving the same individual raptors was possible (i.e., potential pseudoreplication). Second, we sought to account for turbine-specific locations potentially eliciting unique responses among focal raptors given different site-specific circumstances, localized wind/weather effects, and/or the repeated presence of specific individual raptors. In all cases, however, we were unable to include Turbine ID nested within Site (multi-site models) or Turbine ID alone (Goodnoe Hills control-treatment models) as a random effect, because such attempts resulted in unacceptable singularity errors. These errors reflected limited turbine-specific sample sizes among response categories and common response patterns among turbines that resulted in over-parameterized models with near-zero variance estimates for the random effects (Bolker et al. 2008). For example, the available Golden Eagle samples ranged from 4 to 17 cases per turbine at Manzana and only 0–6 cases per turbine at Goodnoe Hills, and the problem was further exacerbated with cases separated into the binary categories used in the LGLM analyses (Table S5).

Nevertheless, although different environmental factors might have caused eagles to react less often to deterrents at certain turbines compared to others, and eagles with different behavioral traits (see Fielding et al. 2023, 2024) might have frequented certain turbines over others, our turbine-specific results provided little basis for such conclusions. All turbines with higher relative numbers of Golden Eagle visits showed a large frequency of positive responses relative to ineffective responses (Table S5). We also had no means of tracking the activities of individual raptors in our study. Therefore, we had no direct evidence that the same individuals were repeatedly sampled at the same turbines. While it is possible that some raptors were encountered multiple times, we had no basis for determining the extent of this possibility, making implementing a repeated-measures framework untenable for producing a biologically relevant analysis. Additionally, in developing multi-site models, our primary goal was to evaluate deterrence effectiveness between facilities, not within individual turbines, making modeling Site as a fixed-effect predictor, rather than only as a random effect, appropriate for our analyses.

In conclusion, despite some data limitations and analytical complications, the results of this study demonstrated that operation of the DTBird audio deterrents elicited effective avoidance responses among majorities of the Golden Eagles and other large soaring raptors observed in the specific circumstances of this study. Similar results were obtained from a previous study conducted in Norway focused on White-tailed Eagles (May et al. 2012). Our PED estimates can be combined with estimates of the probability of detection (Smith et al. 2025) to develop integrated estimates of the probability of DTBird detecting eagles and reducing the risk of their approaching the RSZ of spinning turbines (May et al. 2012, Felton et al. 2024).

Such estimates can be translated to parameters incorporated in models used to estimate the probability of eagle fatalities at wind farms (U.S. Fish and Wildlife Service 2013, Bay et al. 2016) with and without deployment of the DTBird technology. Such insight could then facilitate consideration of the technology by the U.S. Fish and Wildlife Service and other regulatory agencies as an approved avoidance, minimization, or mitigation measure for reducing collision risk for eagles at commercial wind facilities. Our results also revealed noteworthy differences in the apparent effectiveness of the DTBird deterrence system in the different landscape settings of our two study sites, and among the species groups evaluated. Therefore, we recommend further investigation to provide additional insight about the degree to which site-specific differences in factors such as species composition, foraging behaviors, landscape configuration, and wind regimes are important drivers of how large raptors such as Golden Eagles respond to audio deterrents as a means of reducing their risk of colliding with spinning wind turbines.

SUPPLEMENTAL MATERIAL (available online). Table S1. Comparison of AIC scoring, model weights, and goodness-of-fit metrics for candidate binary logistic generalized linear models and selected predictors for all large soaring raptors combined at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington. Table S2. Comparison of AICc scoring results, model weights, and goodness-of-fit metrics for candidate binary logistic generalized linear models (GLMs) portraying relationships between the DTBird probability of effective deterrence (PED) and selected predictors for Golden Eagles at the Manzana Wind Power Project in California and Goodnoe Hills Wind Farm in Washington. Table S3. Comparison of AICc scoring results, model weights, and goodness-of-fit metrics for candidate binary logistic generalized linear models (LGLMs) portraying relationships between the DTBird probability of effective deterrence (PED) given broadcasted versus muted deterrents and in relation to other selected predictors for all large soaring raptors combined at the Goodnoe Hills Wind Farm in Washington. Table S4. Comparison of AICc scoring results, model weights, and goodness-of-fit metrics for candidate binary logistic generalized linear models (LGLMs) portraying relationships between the DTBird probability of effective deterrence (PED) given broadcasted versus muted deterrents and in relation to other selected predictors for Golden Eagles at the Goodnoe Hills Wind Farm in Washington. Table S5. Distribution of deterrent-response samples among turbines at two study sites for probable Golden Eagles, reflecting sample limitations that required using simpler generalized linear models (GLMs) rather than generalized linear mixed-effects models (GLMMs) that included Site/Turbine ID (multi-site models) or Turbine ID (Goodnoe Hills control-treatment models) as random effects.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy under the Wind Energy Technologies Office Award Number DE-EE0007883. As such, this manuscript was prepared as an account of work sponsored by an agency of the United States Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U. S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U. S. Government or any agency thereof.

Other former and current H. T. Harvey & Associates staff that contributed substantively to the planning, implementation, and/or data entry work reflected herein include J. Howell, K. Lindke, K. Wolf, A. Henry, and C. Smith. Other essential collaborative, logistical, and financial support was provided by the American Wind Wildlife Institute/Renewable Energy Wildlife Institute, Washington, D.C.; Liquen Consultoría Ambiental, S.L., Madrid, Spain; Avangrid Renewables and Manzana Wind Power Project, Rosamond, CA, USA; PacifiCorp Wind Operations and Vestas–American Wind Technology, Inc. operations at the Goodnoe Hills Wind Farm, Goldendale, WA, USA; EDF Renewables, San Diego, CA, USA; Puget Sound Energy, Bellevue, WA, USA; and Portland General Electric, Portland, OR, USA. This manuscript benefited from reviews of preceding technical reports by J. Garvin, C. Hein, and M. Huso solicited by the DOE and the comments and suggestions of three independent reviewers solicited by the journal.

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Received 31 January 2025; accepted 20 March 2026
Associate Editor: Pascual López-López