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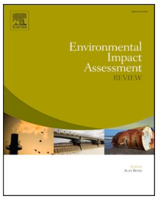

Vulnerability and behavioural avoidance of Golden Eagles near wind farms during the breeding season

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ABSTRACT

Wind energy presents a novel stressor to wildlife, sometimes resulting in habitat loss and reduced reproductive output. Vulnerability index is a powerful metric to estimate the susceptibility to harm from stressors. We aim to assess the regional-level exposure, sensitivity and vulnerability to wind farms of breeding Golden Eagles (*Aquila chrysaetos*). Our study focused on the Gaspé Peninsula (Québec, Canada), a region hosting a vulnerable population of Golden Eagles and 26 wind farms built in the last 25 years. Using nests monitoring and over 13 years of satellite tracking of eight breeding eagles, we show that eagles' exposure to wind farms increases with nest proximity, resulting in higher vulnerability for eagles nesting closer (≤20 km), especially during chick-rearing and post-fledging. Eagles nesting ≤20 km avoided wind farms, using them less than other similar areas, resulting in unused areas in the home range. Our sensitivity and vulnerability assessments revealed that wind farms are positioned in moderate to highly suitable habitats, indicating functional habitat loss. We monitored breeding before, during and after wind farm development, but reproductive outcomes did not significantly vary with development phases. However, overall breeding success in the region appeared to decline over the last two decades, possibly due to a combination of factors. Our study presents the behavioural effects of wind farms on breeding birds of prey while identifying areas most sensitive and nests most vulnerable to wind development in the region. This research underscores the need for pre-construction assessments and continued breeding monitoring for long-term assessment.

1. Introduction

Anthropogenic development potentially carries negative consequences for wildlife. To assess these impacts, vulnerability indices measure the extent to which a system may suffer harm from stressors (Turner et al., 2003). They integrate sensitivity, measuring the system's susceptibility to impact the study's species and exposure, evaluating the degree of exposition to the stressor (Costa and Kropp, 2013; Turner et al., 2003). While anthropogenic expansion keeps increasing the pressure on wildlife and ecosystems, impact assessments have become necessary to ensure the persistence of endangered species (Farmer et al., 2008; Katzner et al., 2013).

One of the most novel stressors to wildlife is wind energy and their infrastructures colonizing the aerial space (Masden and Cook, 2016). It introduces new structures that pose risks to airborne species, including birds of prey. Vulnerability of a species or individual may also vary depending on the timing and location of exposure within the species annual cycle (Barrios and Rodríguez, 2004; Devereux et al., 2008). For example, vulnerability may be important on the breeding ground due to central place foraging (Braham et al., 2015; Noguera et al., 2010), especially when wind facilities are constructed in proximity to nesting territories (Mahoney and Chalfoun, 2016). Ultimately, it may result in reduced reproductive output (Halfwerk et al., 2011; Lindsay et al., 2008).

Golden Eagles (*Aquila chrysaetos*) are large birds of prey that select habitats with rugged terrain which generates ascendant currents and

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often overlaps with wind farms (Maynard et al., 2024; Miller et al., 2014). Such preference for mountainous habitat render them vulnerable to this new development of energy production (Balotari-Chiebao et al., 2021; Noguera et al., 2010). The wariness of the species for human structures and perceived risks associated with turbines may result in macroscale avoidance (i.e. complete avoidance of the farm; May, 2015) and functional habitat loss (Therkildsen et al., 2021) i.e. loss of usable space in home range or movement corridors (Diehl, 2013). Avoidance and impacts might be enhanced during the construction phase of a farm since it implies more activity at the site and more disturbance for birds (Lemaître and Lamarre, 2020). Studies have already evaluated collision risks (Miller et al., 2014; New et al., 2015) or species-specific vulnerability (Balotari-Chiebao et al., 2021; Conkling et al., 2022) for Golden Eagles. However, regional vulnerability assessments that consider breeding stages and region-specific characteristics remain unexplored.

The Gaspé Peninsula in Québec, Canada is not only home for a Golden Eagle population of conservation concern (Équipe de Rétablissement des Oiseaux de Proie Du Québec, 2020; Katzner et al., 2020) but it is also one of the first regions in Eastern Canada to strongly develop wind farming, with some situated as close as 5 km from eagle nests (Natural Resources Canada, 2021; SOS-POP, 2022). In the region, eagles nest in low density and have wider summer home ranges than other populations (Maynard et al., 2024; Miller et al., 2017), all the conditions to exacerbate possible adverse effects from wind farms. In addition to pre-construction assessment estimating raptor passages during migration, the provincial government has implemented GPS-tracking of eagles nesting $\leq$20 km from wind farms. Some eagles nesting $>$20 km from turbines were also monitored, and regular breeding surveys are conducted yearly across the province to evaluate reproductive outcomes. This provides an opportunity to assess the impact of wind farm development on raptor movement and reproduction.

Using GPS-tracking and breeding survey data, we assessed the regional-level exposure, sensitivity, and vulnerability of breeding Golden Eagles to wind farms. The overarching objective was to develop a vulnerability and sensitivity map that aids in planning new developments to mitigate impacts on Golden Eagles. Firstly, we hypothesized that exposure would be related to wind farms' proximity to nests, whereby eagles nesting closer would have a greater overlap of their home range with the wind farm footprint. Secondly, we used two indicators of sensitivity (avoidance and reproduction) to elaborate our predictions, because these indicators could be assessed using GPS-tracking data and the breeding surveys. Thus, our second hypothesis was that there is macroscale avoidance and we predicted a lower density of GPS locations (location/km^2) within wind farm footprints as compared to reference areas of similar size and range of the nest. The third hypothesis was a shift in territory occupancy and productivity, i.e. we predicted that percent of occupied territory and the number of offspring would be lower during construction and operational phases relative to the pre-construction phase of wind farm development. Finally, we used the product of exposure and sensitivity to calculate vulnerability of each nesting territory in the region to wind farms. We identified areas where current or future wind farms could have the most significant impact on eagles, as well as optimal sites for development that minimize their impact on these birds. Our study could help land managers to plan future anthropogenic developments to mitigate impacts on local and vulnerable avian wildlife.

2. Material and methods

2.1. Study area, data and field work

Golden Eagles were monitored within the Gaspé Peninsula that comprises two administrative regions: Bas-Saint-Laurent and Gaspésie in Québec, Canada. This area encompasses 26 distinct wind farms, totaling 1420 wind turbines (Natural Resources Canada, 2021) established between 1999 and 2018, with the majority being constructed after 2007 (Fig. 1; see Supplementary Material Fig. S1 for development time line). Two additional wind farms in New Brunswick were also within reach of eagles' summer distribution with 30 (Lamèque) and 33 (Caribou) turbines, which entered in operation in 2011 and 2009, respectively (Supplementary Material Fig. S1).

Wind turbine coordinates and commissioning year were retrieved from the Canadian Wind Turbine Database (Natural Resources Canada, 2021). For this study, we defined a "wind farm" footprint as a merged 2 km buffer around wind turbines. Where multiple wind farm footprints clustered closely (less than 2 km), we merged their buffers resulting in one larger wind farm. A 2 km buffer was deemed sufficient to indicate macroscale avoidance of wind turbines (Marques et al., 2020; Tolvanen et al., 2023) and collision risks for eagles were considered negligible beyond this threshold (Eichhorn et al., 2012).

To track the movement of Golden Eagles, the Québec's Government deployed GPS/GSM telemetry units recording latitude and longitude hourly. Captures were carried out using bownets or net launchers placed near breeding territories in the early spring (February–April) and fall (August–October) 2007–2019. Sex determination was facilitated through morphometric measurements (i.e. mass, wing chord, hallux length, and head length), following Harmata and Montopoli (2013). The telemetry units were securely deployed using a 6.5 mm Teflon body harness, weighing less than 3 % of the eagle's total mass (45–75 g). Further details on field work can be found in (Maynard et al., 2022).

We obtained nest and reproduction data from the SOS-POP database, which is under the management of QuébecOiseaux (SOS-POP, 2022). This repository consolidates nesting coordinates and data derived from breeding surveys conducted by the Québec's Government (Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024), the Canadian Wildlife Service, NGOs, environmental consultants, and volunteers. The dataset starts in 1915 up to 2022. In 2010, a standardized protocol was established for wildlife biologists and technicians within the Ministère de l'Environnement, Lutte contre les Changements Climatiques, Faunes et Parcs (MELCCFP, pers. comm.) and was updated in 2021 (Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024). Notably, during the period from 2000 to 2009, monitoring activities consisted of biannual assessments conducted during the summer months. Since 2010, the practice has evolved to encompass biannual spring visits for occupancy assessment, supplemented by two additional visits aimed at ascertaining nesting success and productivity (Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024). While we included northern New Brunswick in our study area, to this day, there are no known Golden Eagle nest in New Brunswick.

We used a map of foraging probability of selection derived from a Resource Selection Function (RSF) in Maynard et al. (2024) as an indicator of habitat suitability (see Maynard et al., 2024 for details). RSFs uses an individual approach to directly assess which habitat characteristics golden eagles use or avoid within their home ranges, providing a deeper understanding of their interactions with the environment. The RSF developed by Maynard et al. (2024) is one of the most complete, robust, and exhaustive model conducted on this population. It has been peer-reviewed, making it a reliable choice for reuse in our study. Furthermore, RSFs focus on habitat selection at the scale of individual animals, which is relevant for a study with low sample size like ours. All breeding individuals and their GPS tracks from our current study were included in the RSF from Maynard et al. (2024), providing a direct linkage between the two studies. This map allowed us to estimate spatial sensitivity (see 2.2 section within material and methods). The foraging habitat selection map was created using key environmental variables (i.e., elevation, terrain ruggedness, forest cover, distance to water, average wind speed). These variables were the best to predict foraging habitat selection and concorded with other habitat studies (Singh et al., 2016; Squires et al., 2020). We summed and binned into five levels of suitability for foraging selection (1 = Low; 5 = Very High). Higher selection

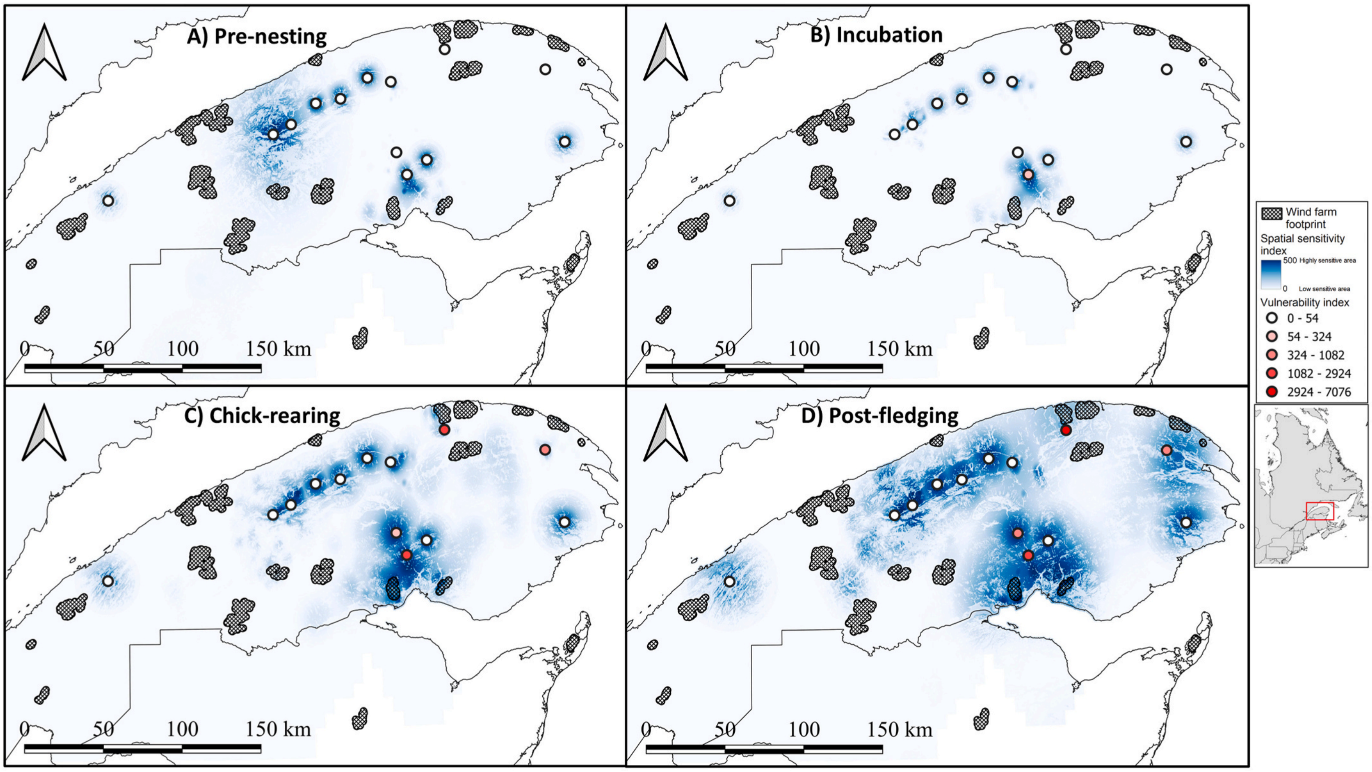

Fig. 1. Sensitive areas (gradient of blue) by breeding period and vulnerability (red gradient cercles) by Golden Eagle nest locations in the Gaspé Peninsula, Québec, Canada.

levels indicate a greater likelihood for eagles to select the location, and thus a more sensitive area if a wind turbine were to be present (Maynard et al., 2024).

2.2. Data analysis

Eleven eagles were tracked between 2007 and 2021 with eight exhibiting central place foraging from seven different nesting territories (two females, six males). The other three eagles were floaters and did not breed during the tracked summers. We considered an eagle as a 'floater' if it was either immature (<4 years of age) or exhibited irregular daily paths that deviated from consistent daily round trips to the nest resembling a central place forager pattern (Orians and Pearson, 1979), throughout the summer. Eagles were tracked from one to ten consecutive summers for a total of 50 tracked summers (Supplementary Material Table S1). Given our hypotheses focused on nesting eagles, we only present results for breeding eagle summers ($n = 36$ bird/summer; $n = 8$ individuals; $n = 7$ nesting territories).

To assess potential variations across different breeding periods, we partitioned our dataset into four stages aligned with breeding activities (Katzner et al., 2020; Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024): pre-nesting (15 March–15 April); incubating (16 April–15 May); chick-rearing (16 May–August 1); and post-fledging (August 2–31). We corroborated our incubation period with the nesting and reproduction data and by examining the GPS tracking data of two females. We had a fifth category to account for floaters/failed breeders encompassing the whole summer. The results for floaters and failed breeders are presented in Supplementary Material as it could not be linked to any metrics of a nesting pair, thus vulnerability index could not be calculated.

To examine the influence of nest proximity to wind farms on eagle summer space use (first hypothesis), we separated GPS-tracked eagles nesting ≤20 km and > 20 km of a wind farm. We selected a 20 km threshold based on regional protocols that mandate more vigilant monitoring for eagles nesting ≤20 km from wind farms due to the elevated likelihood of wind farm overlap of home range and higher collision risks (Ministère des Ressources Naturelles et de la Faune, 2008).

2.3. Wind farm exposure

For the assessment of exposure, we compared the overlap of the wind farm footprints with the home range between distance categories (20 km threshold). We initially estimated home ranges using a 95 % kernel density contour with the *adehabitatHR* in R (Calenge, 2023). These home range computations were performed across individuals, years, and breeding stages (pre-nesting, incubation, chick-rearing, and post-fledging, Supplementary Material Fig. S2). We then calculated the coverage (percentage) of the wind farm footprint over the home range (Supplementary Material Fig. S3). To identify periods with heightened overlap, we compared the coverage between distance categories to the nest (≤20 km or > 20 km) for each breeding stage. To do so, we used a generalized additive model with a beta regression. Percent coverage was the response variable while nest distance category was a fixed factor and home range superficies was a smoothed factor to account for larger home ranges. Significant variables were established based on $\alpha = 0.05$. Significant differences between group levels of interest was established with non-overlapping 95 % confidence intervals.

2.4. Sensitivity: Wind farm avoidance

For our second hypothesis, we tested whether the density of recorded eagle locations within a wind farm footprint was lower than in corresponding reference areas at similar distances from the nest (described below). To do so, we generated 100 distinct reference areas to represent a range of available areas, each mirroring the dimensions (84.95 km^2) of an average wind farm footprint in the region (Supplementary Material Fig. S3). These reference areas were randomly positioned within equivalent distances from the nest (of tracked eagles only, $n = 7$ nests; 700 total reference areas) to the nearest wind farms, ensuring they did not overlap with existing wind farm footprints. We then calculated the mean density (locations/km^2) of recorded eagle locations by areas stratified by breeding stages. We compared mean densities in reference areas with wind farms using an ANOVA with the square root of the mean density as a predictor and area (reference or wind farm) and nest distance category ($\leq$20 km or $>$ 20 km) as fixed factors and a two-way interaction. We performed one ANOVA per breeding stages. We considered a significant difference with $\alpha = 0.05$. When a variable was found significant, we used a Tukey test to determine significant differences between group levels of interest.

Within the wind farm footprints, we classified each eagle location into three categories of behaviour: resting, area-restricted search (ARS; proxy to foraging see Torres et al., 2017), and travelling, using the Residence in Space and Time method (RST; Torres et al., 2017). The RST method uses time spent in a radius (set at 5 km for this study based on scale of movements and sampling interval) to discriminate between a set of behaviours (Torres et al., 2017). To compare behaviours between areas, we calculated the mean proportion of location of the three behaviours by areas (reference or wind farm), breeding stage, individual, and year. We then compared the mean proportions of each behaviour and breeding stages using an ANOVA with the square root of the mean proportion as a predictor and area (reference or wind farm) and breeding stages as fixed factors and a two-way interaction. We made one model per behaviour using only eagles nesting $\leq$20 km from a wind farm to avoid dependence between data points created when calculating proportions and due to low to null location density in areas $>$20 km from a nest. When a variable was found significant, we used a Tukey test to determine significant difference between group levels of interest.

2.5. *Sensitivity: Effects on reproduction*

To investigate the potential impact of wind turbine construction on eagle reproductive outcomes (third hypothesis), we compared territory occupancy and productivity during the pre-construction, construction, and operation phases of wind farm development. The Gaspé Peninsula has 28 documented eagle nests across 13 breeding territories, with approximately four territories (31 %) situated $\leq$20 km of a wind farm (Fig. 1). Of the 26 wind farms in our study, seven wind farms (27 %) are situated $\leq$20 km from a one of those four territories (Supplementary Material Table S2). We established a comprehensive dataset by initially filtering for breeding surveys conducted within the year 2000s, considering the inconsistent monitoring preceding the new millennium (Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024). We calculated two different metrics: territory occupancy (percent of occupied territories) and productivity (Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024). Productivity was determined as the number of chicks per active territory seen in any monitoring event after June 15, as most chicks tend to survive until fledging after 40–45 days when growth plateaus (Katzner et al., 2020).

For each monitoring year, we assigned the developmental status of the nearest wind farm, classified as pre-construction, construction phase, and operation phase. We then calculated the mean territory occupancy and productivity across nesting territories for each wind farm status, enabling the comparison of means and associated confidence intervals. We also compared occupancy and productivity between distance categories to the nest ($\leq$20 km or $>$ 20 km). Significant differences were established between group levels based on non-overlapping 95 % confidence intervals. Because effects from overall wind energy development in the region may be cumulative and delayed, we also tested a generalized linear model with a binomial distribution (logit link) with occupancy or productivity as a predictor and year as fixed effect. The significance level for variables was set at $\alpha = 0.05$.

2.6. *Vulnerability*

Exposure, sensitivity, and vulnerability were estimated at the nest level, to identify nesting pairs that are the most vulnerable in the region. We estimated exposure as part of our first hypothesis with the mean wind farm footprint coverage of home range (%) across years for each tracked eagle. To estimate exposure of non-GPS-tracked nesting territory, we created a circular buffer of estimation of use around the non-GPS-tracked nests as wide as the mean home range surface area (km^2) for each breeding period. We then estimated coverage with nearby wind farms for untracked nests. We tested these circular potential home range against known home range of the tracked eagles and found that the circular buffers can cover from 21 to 97 % of the true home range, which should reflect some areas that are likely of importance to the nesting eagles that we did not track. Since the turbine density may differ among farms and vary the effects on eagles, we also extracted turbine density for farms that overlapped with a home range as an additional metric of exposure. If multiple wind farms were found $\leq$20 km of a nest, turbine density was averaged for the given nest.

Sensitivity was derived from our second hypothesis on wind farm avoidance (habitat loss) and our third hypothesis of reproductive outputs. Assuming our second hypothesis is true, and eagles avoided wind farms, wind farm footprints overlapping with eagle habitat results in habitat loss. We calculated the estimates of use of tracked and non-tracked nests with comparing kernel density estimates derived from GPS-tracked eagles for each breeding period. Proximity to the nest positively correlated with higher usage, signaling increased sensitivity in the presence of a wind farm (Tapia and Zuberogoitia, 2018). For tracked nests, we overlayed the rasters of the yearly estimates of use by individual eagle and chose the highest estimate per pixel to create one raster of use for all individual eagles. Similarly to exposure, we created circular buffers of estimation of use around the non-GPS-tracked nesting territory with contour estimates at each 5 % increment of use (see Supplementary Material Fig. S4). We then overlayed the kernel density estimates from GPS-tracked eagles with non-GPS-tracked nests, selecting the highest value per pixel. Finally, the spatial sensitivity per pixel was estimated with the product of estimate of use and the binned foraging level of selection (1–5) from Maynard et al. (2024). The resulting maps of sensitivity were produced for each breeding period and identified the most sensitive regions where current or future wind farms will result in habitat loss.

We used the spatial sensitivity and the reproductive output to estimate our final sensitivity index by nest. We first calculated the spatial sensitivity by wind farms by calculating the mean spatial sensitivity for pixel falling within a wind farm footprint. The value of the closest wind farm was associated with each nest. If multiple wind farms were found $\leq$20 km of a nest, spatial sensitivity of each farm was added for the given nest. For reproductive output, we calculated the differences between the mean productivities of pre-nesting and operational phase for both nests $>$20 km and $\leq$ 20 km. The final sensitivity index by nest was thus the product of the mean spatial sensitivity of the nearest wind farm and the difference between mean productivity of pre-nesting and operational phase.

Vulnerability is the product of exposure and sensitivity (Turner et al., 2003) and we expect negative effects to be aggravated by individuals' attributes and wind farm locations (Hoover and Morrison, 2005). Therefore, we calculated the vulnerability index for each nesting territory by breeding period with the product of turbine density of nearest wind farm (exposure; turbine/km2), home ranges overlap (exposure), spatial sensitivity (use and probability of selection) of the nearest wind farms and the differences in mean productivity between pre-construction and operating phases tailored to the distance category of the nest to the nearest wind farm (sensitivity; reproduction). To identify periods of elevated risk, we compared the mean vulnerability across breeding periods whereby significant differences were established based on non-overlapping 95 % confidence intervals.

All analyses were performed in R v4.2.1 (R Core Team, 2022) and QGIS (QGIS.org, 2022). Results are presented in mean ± 95 % confidence intervals (CI).

3. Results

3.1. Wind farm exposure

Home ranges expanded over the summer, with pre-nesting displaying the smallest size (153 ± 55 km^2), followed by incubation (244 ± 116 km^2), chick-rearing (1286 ± 530 km^2), then post-fledging (2652 ± 1653 km^2; Fig. 2C; Supplementary Material Fig. S2). Wind farm footprint coverage of home range varied from null to 29.10 % and was not significantly different across breeding periods ($\chi^2 = 5.07$, $p = 0.17$) but was highest during chick-rearing (5.35 ± 2.46 %), post-fledging (3.49 ± 2.03 %), incubation (1.07 ± 0.91 %) and then pre-nesting (1.00 ± 1.00 %). Wind farm footprint coverage of home range was higher for eagles nesting ≤20 km from a wind farm than for eagles nesting farther (>20 km; $\chi^2 = 30.63$, $p < 0.001$), but only during chick-rearing and post-fledging (Fig. 2A). Overlap was null or almost null for eagles nesting >20 km from wind turbines for all breeding stages.

3.2. Sensitivity: Wind farm avoidance

Eagle locations were recorded at distances ranging from 15.50 m to 95.00 km from the nearest turbine. Most locations within the wind farm footprint were recorded during the chick-rearing period (83.6 % of all locations within a wind farm footprint), followed by post-fledging season (12.0 %), incubation (2.7 %), and pre-nesting period (1.7 %). Locations recorded within the wind farm footprints were in majority ARS (92 %), then transit (7 %) and rest (1 %) and were located in habitats of very high probability of selection for foraging (mean level: 4.59 ± 0.03). The mean level of foraging habitat selection within wind farm footprints averaged 3.74 ± 0.06 (medium to high) ranging from 1.83 ± 0.55 to 4.61 ± 0.92 and 3.66 ± 0.85 for wind farms ≤20 km from a nest (Supplementary Material Table S2). In the reference areas, foraging habitat selection level averaged 3.86 ± 0.05, medium to high level. Within the wind farm footprints, habitats of high and very high probability of selection covered 10 to 90 % (mean 62± 11.%) of the surface.

When comparing the density of eagle locations in the wind farm footprint vs. the reference areas (second hypothesis; Supplementary Material Fig. S3), the ANOVAs showed that mean densities in the wind farm footprints were significantly lower than in the reference areas (Fig. 3). That result applied for each breeding stages and mostly for eagles nesting ≤20 km from a wind farm (Fig. 3). Indeed, eagles nesting ≤20 km from a wind farm all showed significantly lower location densities in the wind farm footprints than in the reference areas. For eagles nesting >20 km from a wind farm, reference areas had significantly higher densities of locations than wind farm footprints, but only during post-fledging. During pre-breeding and incubation, eagles nesting >20 km from a wind farm did not travel far enough to reach any of the closest wind farms, thus resulting in null densities (Fig. 3). For eagles nesting ≤20 km from a wind farm across all breeding stages, proportions of behaviours within wind farm footprints were not significantly higher than in reference areas for area-restricted search (78–95 %; $F = 0.56$, $p = 0.64$), transit (4–20 %; $F = 2.18$, $p = 0.09$) and rest (0–4 %; $F = 14$, $p =$

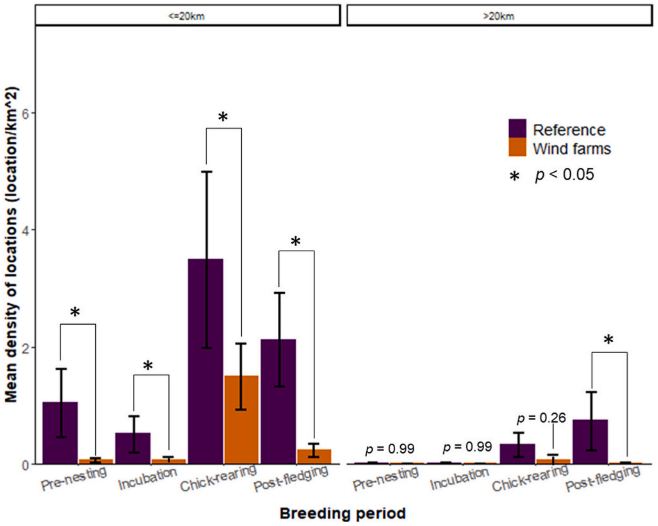

Fig. 3. Density of locations (number of GPS location/km^2) in wind farms and 100 reference areas with the same surface area and distance to nest as wind farms by breeding stage. Dots are means and error bars are 95 % confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

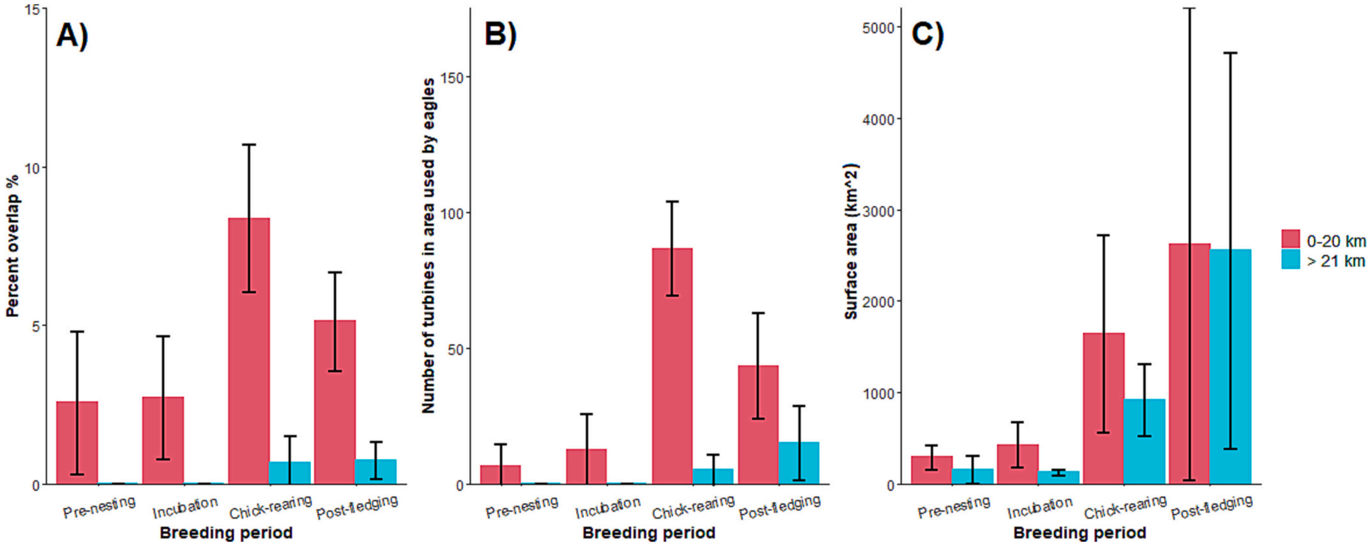

Fig. 2. Landscape use for Golden Eagles around their nest during their four breeding stages in relation to the nearest wind farm in the Gaspé Peninsula, Québec, Canada ($n = 8$ eagles; 36 bird/summers). Overlap with all wind farms and Golden Eagle home range (95 % contour; center), number of wind turbines within home range and surface area (km^2) of home ranges. Error bars are 95 % confidence intervals and overlap between levels indicate lack of significant differences.

0.93).

3.3. Sensitivity: Territory occupancy and productivity

Territories were monitored from 2000 to 2022 with one to 27 surveys done per nesting territories/year (total of 608 surveys). Territory occupancy exhibited no detectable variation among wind farm development phases or wind farm to nest distance category (Fig. 4). To test for delayed effects, a generalized linear model of territory occupancy did not show variation across years ($Z = -0.059$, $p = 0.084$) even for territories ≤20 km of wind farms (interaction: $Z = 92.275$, $p = 0.595$), but has generally been declining from ~75 % in 2000–2005 to less than 33 % in 2021–2022 (Fig. 5). Productivity showed no significant differences across distance categories (Fig. 4), but also only had one sample for the construction phase ≤20 km. According to our generalized linear model, productivity also did not change across years ($Z = -0.084$, $p = 0.504$) or with year:distance category interaction ($Z = 0.308$, $p = 0.071$) but also has been generally declining to under 50 % for territories ≤20 km from a wind farm.

3.4. Vulnerability

Given productivity was not different between development phases or across years, we removed this parameter for the calculation of vulnerability and focused on exposure and spatial sensitivity. Spatial sensitivity spanned the widest during chick-rearing and post-breeding periods (Fig. 1). Consequently, vulnerability was highest during chick-rearing and post-fledging for a few breeding territories close to wind farms (≤20 km). However, we could not find a significant difference associated with wind farm distance to nest categories as confidence intervals were very wide, and all crossed zero (Table 1).

4. Discussion

Our study reached its goal to estimate regional exposure, sensitivity, and vulnerability of breeding Golden Eagles to wind farms, using GPS-tracking data and breeding surveys. We found that eagles nesting ≤20 km from a wind farm were more exposed than those nesting >20 km from a wind farm. Exposure was greatest during chick-rearing and post-fledging periods. This result support the current eagle monitoring threshold at 20 km. These eagles nesting closer to wind farms also avoided wind farms, suggesting functional habitat loss (i.e. loss of usable space in the home range or movement corridors). Territory occupancy and productivity were, however, not significantly different between the pre-construction phase and the operation phase, suggesting that wind farm presence have not directly affected reproductive performance, even for eagles nesting ≤20 km from a wind farm. However, our sample size for nesting territories was small, which may have limited the statistical power of the results. Our result could indicate that there was no effect, or that we did not have enough data to detect one.

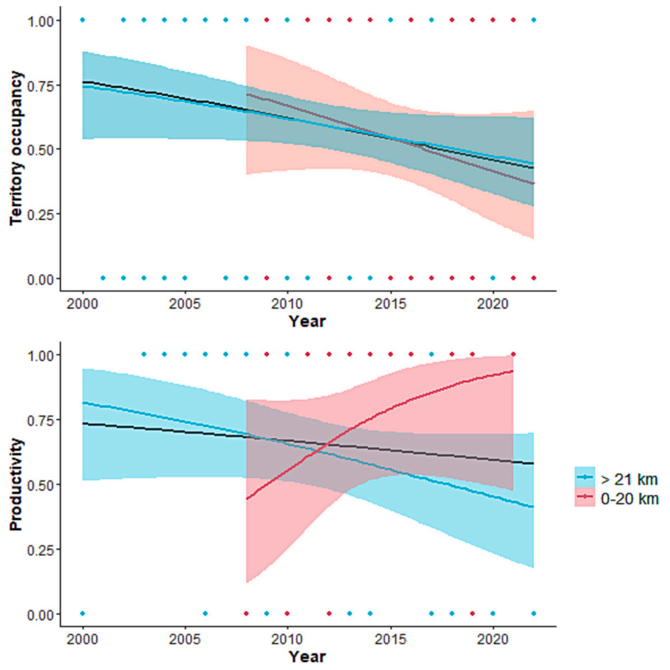

Fig. 5. Generalized linear model of territory occupancy (top) and productivity (bottom) of Golden Eagles nesting in the Gaspé Peninsula, Canada from 2000 to 2022 (n = 28 nests). Black lines indicate the general trend of all wind farm to nest distance category combined.

The apparent lack of effect on reproductive performance could be good news, given that some avian species may have significant reduction in reproductive output near wind-power facilities (Mahoney and

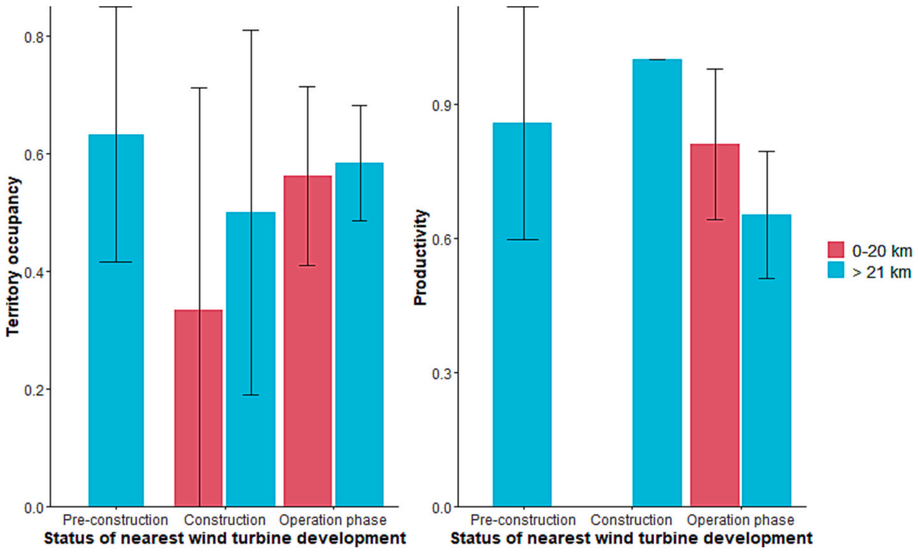

Fig. 4. Territory occupancy, i.e. number of occupied territories/number of known territories and productivity, i.e. number of chicks per territory/number of occupied nests, of Golden Eagles nesting in the Gaspé Peninsula, Canada at different stages of wind farm development ($n = 28$ nests; 22 years). Black dots and lines show the overall mean for the distance category between the nest and the nearest wind farm.

Table 1
Mean vulnerability of Golden Eagle nests with 95 % confidence interval (CI) for nests ≤20 km from a wind farm and > 20 km from a wind farm by breeding stage in Gaspé Peninsula, Canada (n = 28 nest).

Breeding stage	Vulnerability					
	≤20 km			>20 km		
	Mean	*low CI*	*high CI*	*Mean*	*low CI*	*high CI*
Pre-nesting	18.3	−6.67	43.2	0	0	0
Incubation	52.3	−50.2	155	0	0	0
Chick-rearing	1306	−3.03	2615	36	−34.5	107
Post-fledging	2324	−865	5513	126	108	361

Chalfoun, 2016). Likewise, a study in Finland found no effects on territory occupancy or post-fledging survival in White-tailed Eagles (*Haliaeetus albicilla*; Chiebáo, 2018). In addition to the lack of reported mortalities of Golden Eagles due to collision so far (MELCCFP, pers. comm.), our results tend to indicate that that the current history of wind farm implantation and operation in the Gaspé Peninsula did not significantly influence the reproductive output of this population. However, we did not estimate post-fledging survival and wind turbines may still be detrimental to post-fledglings by increasing risks for collision or reducing in available foraging habitat (Fielding et al., 2021; Watson et al., 2018).

Despite lack of significant differences across development phases, the most striking observation was the general decline in nest occupancy since the early 2000s. This result raises concern because the Gaspé Peninsula remains the southernmost nesting site for Eastern Golden Eagles. Historically, they also bred in the northeastern U.S., but known breeding locations in Maine and New York have been unoccupied since the mid-to-late 1990s, in Vermont since the 1970s, in New Hampshire since the 1960s, and in Massachusetts since the 1880s (Katzner et al., 2020).

Several other factors may have contributed to the decline in reproductive performance of the Golden Eagle in the Gaspé Peninsula, such as climate changes or lead contamination (see Katzner et al., 2023). Additionally, intensive forestry activities in the Gaspé Peninsula (Nadeau Fortin et al., 2016), may create greater functional habitat loss and affect reproductive performance (Whitfield et al., 2001). While we did not test reproductive performance against other anthropogenic development, it would be interesting to test if wind farms have a cumulative negative effect with other factors (e.g. forestry; Whitfield et al., 2001, prey conditions; Preston et al., 2017) and result in the general decline in occupancy we observed since the early 2000s.

Additionally, eagles nesting >20 km were not significantly exposed to wind farms resulting in less than half the breeding territories in the Gaspé Peninsula exposed and vulnerable to wind farming. Indeed, only the nest ≤20 km during the chick-rearing and post-fledging breeding period had high vulnerability levels. Pre-nesting and incubation require less foraging effort for the male and very little movements in females (Katzner et al., 2020), resulting in smaller home ranges and limiting potential conflict of use with turbines. Home ranges expanded with the season, and conflict may occur during the chick-rearing and post-fledging period. During early chick-rearing, males are required to feed the females, the chick and himself (Katzner et al., 2020) while still being spatially limited within daily reach of the nest to sustain viable feeding rates (Orians and Pearson, 1979). Energy requirements and increased foraging efforts explain both the wider home range and high exposure to wind farms during these later breeding periods, resulting in a high vulnerability index. This is true only for eagles nesting ≤20 km of a wind farm since eagles nesting >20 km from a wind farm did not travel far enough to be significantly exposed to wind farm most of the summer.

While exposure is significantly higher for birds nesting in proximity to a wind farm, it only becomes problematic if behavioural response is negative, as observed in our study. Eagles nesting ≤20 km from a wind farm were not found in wind farm footprints as much as the reference areas, as expected for our second hypothesis. A reduction in use of an area suggests displacement (i.e. reduced density of bird locations within the wind farm footprint; Dohm et al., 2019), or in other words, macroscale avoidance (avoidance of the wind farm footprint rather than individual turbines; May, 2015). Exact displacement distance could be estimated with GPS-tracks of higher time resolution than our study (1-h between recorded locations), that is able to follow small changes in directions. Other studies have shown that raptors can be displaced up to 5 km from the wind turbines and translates into significant habitat loss (Marques et al., 2020; Tolvanen et al., 2023). Additionally, knowing when the turbines are operating could inform on eagles' response and use of the area (Minderman et al., 2012). While our result suggest macroscale avoidance, future investigations should aspire to quantify more the displacement distance and temporal aspects of exposure with the operational states of wind turbines.

As a support to habitat loss and displacement, we found that wind farm footprints are positioned on habitat of high suitability for foraging. Indeed, foraging eagles select rugged topography of high elevations which generate ascendant currents (Duerr et al., 2019; Maynard et al., 2024), which is also the target of the wind-power industry. The few eagle locations recorded in the wind farm footprints were in majority ARS behaviour located at high to very high probability of selection for foraging, indicating that eagles wandered closer to the wind turbines to forage. Thus, we can assume that these areas would be used by eagles in the absence of wind farms and therefore, wind farming result in functional habitat loss (Fielding et al., 2023; Marques et al., 2020). Limiting foraging opportunities for breeders can increase energetic costs of foraging and reduce chances of successful breeding (Mahoney and Chalfoun, 2016; Whitfield et al., 2001, 2007). Thankfully, this does not yet seem to be the case for our population, but further stress around vulnerable nest may lead to reduced breeding performance.

Observed avoidance is likely permanent for this population as eagles are considered a wary species found to avoid human structures completely (Fielding et al., 2023; Therkildsen et al., 2021). Avian species may repopulate disturbed areas (Buchori et al., 2018; Lemaître and Lamarre, 2020) and raptors may have an upturn of abundance near the wind farm after 6–8 years (Farfán et al., 2017) but some species never return (Dohm et al., 2019). For some tracked eagles, we showed avoidance of such disturbed area even 10 years post-construction, which supports that displacement is likely lasting. In fact, eagles were likely exposed to wind farms prior to development in the region, for instance in their migration route (Miller et al., 2014). Nevertheless, a pre-construction study would have been ideal to draw definitive conclusions on behavioural adjustments.

4.1. *Management implications*

The Eastern North American Golden Eagle being of conservation concern (Équipe de Rétablissement des Oiseaux de Proie Du Québec, 2020; Katzner et al., 2020), understanding threats to its recovery is crucial to determine current and future protection measures. Here we were able to provide a map of sensitive areas to help land managers to sit future developments while mitigating habitat loss for individuals nesting in the region.

We found that nests ≤20 km of a wind farm were far more vulnerable than breeding territories farther away, and we identified territories with no to low exposition that could be protected in the future. While we used a management-based distance threshold that was already established for our study, future efforts with larger sample sizes and/or wider study regions may be able to identify a biological threshold within which eagles are more exposed and sensitive to disturbance. Our conclusions were limited by the lack of pre-construction tracking data, a common issue in environmental impact studies. Indeed, environmental assessments are often constrained by economic factors, limiting the time available for conducting thorough pre-construction studies. We echo the sentiments of New et al. (2015), emphasizing the pivotal role of pre-construction monitoring.

Incorporating such pre-emptive measures in future research endeavors will not only enrich our ecological knowledge but also aid in the development of proactive strategies for mitigating the impacts of wind energy development on avian populations well before the negative effects can happen. Finally, given some territories are already quite exposed and vulnerable to current wind farms, new technologies such as automated curtailment may improve current exposition and vulnerability of eagles nesting ≤20 km from a wind farm and would remove all chances of fatalities (Duerr et al., 2023; McClure et al., 2021). This new technology detecting avian species may be implemented in farms and avoid risks of collisions or avoidance for Golden Eagles and other avian species (McClure et al., 2018).

5. Conclusion

With our study, we assessed the effects of wind turbines on breeding birds of prey while identifying areas most sensitive and breeding territories most vulnerable to wind development in the region. We showed that wind farms contribute to habitat loss for eagles nesting ≤20 km from a wind farm. We did not find any significant effects on breeding performance; however, overall territory occupancy in the region appeared to decline, possibly due to a combination of factors. Regardless of the causes, the Gaspé Peninsula remains the last patch of southern breeding habitat for the species, and special attention should be given to its conservation. Further studies should investigate the potential cumulative effects of stressors such as lead contamination, accidental bycatch, climate changes, wind industry or forestry (Équipe de Rétablissement des Oiseaux de Proie Du Québec, 2020). Considering these findings, it is imperative for eagle conservation efforts in this region to continue breeding monitoring and conduct a long-term comprehensive assessment of the wind farming impacts on breeding performance. This is particularly significant for recovery, aligning with the overarching goal of conserving, and managing this vulnerable population. While eagles nesting in the region only represent a fraction of this vulnerable population, the cumulative effect of all the threats Golden Eagles are now facing are required in management and conservation plans since they may halt any chances at population growth and recovery.

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Ethics statement

The use of Golden Eagles for this research was approved by the MELCCFP: CPA-FAUNE 20-08; CPA-FAUNE 19-05; CPA-FAUNE 18-05; CPA-FAUNE 2017-08; CPA-FAUNE 14-35.

CRediT authorship contribution statement

Laurie D. Maynard: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Visualization. **Jérôme Lemaître:** Conceptualization, Methodology, Resources, Writing – review & editing, Funding acquisition, Supervision. **Jean-François Therrien:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Nicolas Lecomte:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107843.

Data availability

Research data is propriety of the MECCLFP at the Gouvernement du Québec and contains sensitive data on a population of conservation concern and cannot be shared.

References

Balotari-Chiebao, F., Valkama, J., Byholm, P., 2021. Assessing the vulnerability of breeding bird populations to onshore wind-energy developments in Finland. Ornis Fenn. 98 (2). https://doi.org/10.51812/of.133981.

Barrios, L., Rodríguez, A., 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. J. Appl. Ecol. 41, 72–81. https://doi.org/10.1111/j.1365-2664.2004.00876.x.

Braham, M., Miller, T., Duerr, A.E., Lanzone, M., Fesnock, A., LaPre, L., Driscoll, D., Katzner, T., 2015. Home in the heat: dramatic seasonal variation in home range of desert golden eagles informs management for renewable energy development. Biol. Conserv. 186, 225–232. https://doi.org/10.1016/j.biocon.2015.03.020.

Buchori, D., Rizali, A., Rahayu, G.A., Mansur, I., 2018. Insect diversity in post-mining areas: investigating their potential role as bioindicator of reclamation success. Biodiversitas 19, 1696–1702. https://doi.org/10.13057/biodiv/d190515.

Calenge, C., 2023. Home range estimation in R : the adehabitatHR package. https://reflector.vtti.vt.edu/cran/web/packages/adehabitatHR/vignettes/adehabitatHR.pdf.

Chiebáo, F.B., 2018. Spatial Behaviour, Habitat Use and Breeding Performance of a Long-Lived Raptor in the Context of Wind Energy (Thesis). University of Turku, Turku, Finland.

Conkling, T.J., Vander Zanden, H.B., Allison, T.D., Diffendorfer, J.E., Dietsch, T.V., Duerr, A.E., Fesnock, A.L., Hernandez, R.R., Loss, S.R., Nelson, D.M., Sanzenbacher, P.M., Yee, J.L., Katzner, T.E., 2022. Vulnerability of avian populations to renewable energy production. R. Soc. Open Sci. 9, 211558. https://doi.org/10.1098/rsos.211558.

Costa, L., Kropp, J.P., 2013. Linking components of vulnerability in theoretic frameworks and case studies. Sustain. Sci. 8, 1–9. https://doi.org/10.1007/s11625-012-0158-4.

Devereux, C.L., Denny, M.J.H., Whittingham, M.J., 2008. Minimal effects of wind turbines on the distribution of wintering farmland birds. J. Appl. Ecol. 45, 1689–1694. https://doi.org/10.1111/j.1365-2664.2008.01560.x.

Diehl, R.H., 2013. The airspace is habitat. Trends Ecol. Evol. 28, 377–379. https://doi.org/10.1016/j.tree.2013.02.015.

Dohm, R., Jennelle, C.S., Garvin, J.C., Drake, D., 2019. A long-term assessment of raptor displacement at a wind farm. Front. Ecol. Environ. 17, 433–438. https://doi.org/10.1002/fee.2089.

Duerr, A.E., Braham, M.A., Miller, T.A., Cooper, J., Anderson, J.T., Katzner, T.E., 2019. Roost- and perch-site selection by Golden eagles (*Aquila chrysaetos*) in eastern North America. Wilson J. Ornithol. 131, 310. https://doi.org/10.1676/18-38.

Duerr, A.E., Parsons, A.E., Nagy, L.R., Kuehn, M.J., Bloom, P.H., 2023. Effectiveness of an artificial intelligence-based system to curtail wind turbines to reduce eagle collisions. PLoS One 18, e0278754. https://doi.org/10.1371/journal.pone.0278754.

Eichhorn, M., Johst, K., Seppelt, R., Drechsler, M., 2012. Model-based estimation of collision risks of predatory birds with wind turbines. Ecol. Soc. 17. https://doi.org/10.5751/ES-04594-170201.

Équipe de Rétablissement des Oiseaux de Proie Du Québec, 2020. Plan de rétablissement de l'aigle royal (*Aquila chrysaetos*) au Québec — 2020-2030, produit pour le ministère des Forêts, de la Faune et des Parcs, Direction générale de la gestion de la faune et des habitats, Québec, Canada.

Farfán, M.A., Duarte, J., Real, R., Muñoz, A.R., Fa, J.E., Vargas, J.M., 2017. Differential recovery of habitat use by birds after wind farm installation: a multi-year comparison. Environ. Impact Assess. R 64, 8–15. https://doi.org/10.1016/j.eiar.2017.02.001.

Farmer, C.J., Goodrich, L.J., Ruelas, I.E., Smith, J.P., Veit, R.R., 2008. Conservation status of North America's birds of prey. In: Bildstein, K.L., Smith, J.P., Ruelas, I.E. (Eds.), State of North America's Birds of Prey. Nuttall Ornithological Club and American Ornithologists. Union Series in Ornithology, vol. 3, pp. 303–420. Cambridge, Massachusetts, and Washington, D.C.

Fielding, A.H., Anderson, D., Benn, S., Dennis, R., Geary, M., Weston, E., Whitfield, D.P., 2021. Non-territorial GPS-tagged golden eagles *Aquila chrysaetos* at two Scottish wind farms: avoidance influenced by preferred habitat distribution, wind speed and blade motion status. PLoS One 16, e0254159. https://doi.org/10.1371/journal.pone.0254159.

Fielding, A.H., Anderson, D., Benn, S., Taylor, J., Tingay, R., Weston, E.D., Whitfield, D. P., 2023. Responses of GPS-tagged territorial Golden eagles *Aquila chrysaetos* to wind turbines in Scotland. Diversity 15, 917. https://doi.org/10.3390/d15080917.

Halfwerk, W., Holleman, L.J.M., Lessells, C.M., Slabbekoorn, H., 2011. Negative impact of traffic noise on avian reproductive success: traffic noise and avian reproductive success. J. Appl. Ecol. 48, 210–219. https://doi.org/10.1111/j.1365-2664.2010.01914.x.

Harmata, A., Montopoli, G., 2013. Morphometric sex determination of North American Golden Eagles. J. Raptor Res. 47, 108–116. https://doi.org/10.3356/JRR-12-28.1.

Hoover, S.L., Morrison, M.L., 2005. Behavior of red-tailed hawks in a wind turbine development. J. Wildl. Manag. 69, 150–159. https://doi.org/10.2193/0022-541x(2005)069<0150:borhia>2.0.co;2.

Katzner, T., Johnson, J.A., Evans, D.M., Garner, T.W.J., Gompper, M.E., Altwegg, R., Branch, T.A., Gordon, I.J., Pettorelli, N., 2013. Challenges and opportunities for animal conservation from renewable energy development. Anim. Conserv. 16, 367–369. https://doi.org/10.1111/acv.12067.

Katzner, T.E., Kochert, M.N., Steenhof, K., McIntyre, C.L., Craig, E.H., Miller, T.A., 2020. Golden eagle (*Aquila chrysaetos*). In: Rodewald, P.G., Keeney, B.K. (Eds.), Birds of the World. Cornell Lab of Ornithology. https://doi.org/10.2173/bow.goleag.02.

Katzner, T.E., Miller, T., Dennhardt, A.J., Field, M., Wittig, T., Mojica, E., Lanzone, M., Martell, M., Bailey, R., Berry, A., Dillard, R., Brandes, D., Brinker, D.F., Brown, B., Call, E., Cooper, J.L., Duerr, A.E., Farmer, C.J., Felton, S.K., Garvin, J., Gubler, R., Harding, S., Jones, M., Kelly, C., Kern, H., Kiogima, N., Koppie, C., Lemaître, J., Maddox, M., Mehus, S., Merriman, J., Mitchell, A., Parsons, B., Pennarola, N., Rheude, M., Rucker, C., Rush, S., Schmitz, R., Seltzer, H., Slabe, V.A., Soehren, E., Wills, J., 2023. Conservation Plan for Golden Eagles in Eastern North America. Eastern Golden Eagle Working Group, p. 81. https://egewg.org/conservation-plan.

Lemaître, J., Lamarre, V., 2020. Effects of wind energy production on a threatened species, the Bicknell's thrush *Catharus bicknelli*, with and without mitigation. Bird Conserv. Int. 30, 194–209. https://doi.org/10.1017/S095927092000012X.

Lindsay, K., Craig, J., Low, M., 2008. Tourism and conservation: the effects of track proximity on avian reproductive success and nest selection in an open sanctuary. Tour. Manag. 29, 730–739. https://doi.org/10.1016/j.tourman.2007.08.001.

Mahoney, A., Chalfoun, A.D., 2016. Reproductive success of horned lark and McCown's longspur in relation to wind energy infrastructure. Condor 118, 360–375. https://doi.org/10.1650/CONDOR-15-25.1.

Marques, A.T., Santos, C.D., Hanssen, F., Muñoz, A., Onrubia, A., Wikelski, M., Moreira, F., Palmeirim, J.M., Silva, J.P., 2020. Wind turbines cause functional habitat loss for migratory soaring birds. J. Anim. Ecol. 89, 93–103. https://doi.org/10.1111/1365-2656.12961.

Masden, E.A., Cook, A.S.C.P., 2016. Avian collision risk models for wind energy impact assessments. Environ. Impact Assess. R 56, 43–49. https://doi.org/10.1016/j.eiar.2015.09.001.

May, R.F., 2015. A unifying framework for the underlying mechanisms of avian avoidance of wind turbines. Biol. Conserv. 190, 179–187. https://doi.org/10.1016/j.biocon.2015.06.004.

Maynard, L.D., Therrien, J.-F., Lemaître, J., Booms, T., Katzner, T., Somershoe, S., Cooper, J., Sargent, R., Lecomte, N., 2022. Interannual consistency of migration phenology is season- and breeding region-specific in North American Golden Eagles. Ornithology 139, 1–18. https://doi.org/10.1093/ornithology/ukac029.

Maynard, L.D., Lemaître, J., Therrien, J.-F., Miller, T.A., Katzner, T., Somershoe, S., Cooper, J., Sargent, R., Lecomte, N., 2024. Key habitats and breeding zones of threatened golden eagles in eastern North America identified by multi-level habitat selection study. Landsc. Ecol. https://doi.org/10.21203/rs.3.rs-1935603/v1.

McClure, C.J.W., Westrip, J.R.S., Johnson, J.A., Schulwitz, S.E., Virani, M.Z., Davies, R., Symes, A., Wheatley, H., Thorstrom, R., Amar, A., Buij, R., Jones, V.R., Williams, N. P., Buechley, E.R., Butchart, S.H.M., 2018. State of the world's raptors: distributions, threats, and conservation recommendations. Biol. Conserv. 227, 390–402. https://doi.org/10.1016/j.biocon.2018.08.012.

McClure, C.J.W., Rolek, B.W., Dunn, L., McCabe, J.D., Martinson, L., Katzner, T., 2021. Eagle fatalities are reduced by automated curtailment of wind turbines. J. Appl. Ecol. 58, 446–452. https://doi.org/10.1111/1365-2664.13831.

Miller, T.A., Brooks, R.P., Lanzone, M., Brandes, D., Cooper, J., Malley, K.O., Maisonneuve, C., Tremblay, J., Duerr, A., Katzner, T., 2014. Assessing risk to birds from industrial wind energy development via paired resource selection models. Conserv. Biol. 28, 745–755. https://doi.org/10.1111/cobi.12227.

Miller, T.A., Brooks, R.P., Lanzone, M.J., Cooper, J., O'Malley, K., Brandes, D., Duerr, A., Katzner, T.E., 2017. Summer and winter space use and home range characteristics of Golden eagles (*Aquila chrysaetos*) in eastern North America. Condor 119, 697–719. https://doi.org/10.1650/condor-16-154.1.

Minderman, J., Pendlebury, C.J., Pearce-Higgins, J.W., Park, K.J., 2012. Experimental evidence for the effect of small wind turbine proximity and operation on bird and bat activity. PLoS One 7, e41177. https://doi.org/10.1371/journal.pone.0041177.

Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs, 2024. Recueil des protocoles standardisés pour le suivi de la nidification et de la productivité de l'aigle royal au Québec. Gouvernement du Québec, Québec, Canada.

Ministère des Ressources Naturelles et de la Faune, 2008. Protocole d'inventaires d'oiseaux de proie dans le cadres de projets d'implantation d'éoliennes au Québec. Gouvernement du Québec, Québec, Canada.

Nadeau Fortin, M.-A., Sirois, L., St-Laurent, M.-H., 2016. Extensive forest management contributes to maintain suitable habitat characteristics for the endangered Atlantic-Gaspésie caribou. Can. J. For. Res. 46 (7), 933–942. https://doi.org/10.1139/cjfr-2016-0038.

Natural Resources Canada, 2021. Canadian Wind Turbine Database [Dataset].

New, L., Bjerre, E., Millsap, B., Otto, M.C., Runge, M.C., 2015. A collision risk model to predict avian fatalities at wind facilities: an example using Golden Eagles, *Aquila chrysaetos*. PLoS One 10, e0130978. https://doi.org/10.1371/journal.pone.0130978.

Noguera, J.C., Pérez, I., Mínguez, E., 2010. Impact of terrestrial wind farms on diurnal raptors: developing a spatial vulnerability index and potential vulnerability maps. Ardeola 57, 41–53.

Orians, G.H., Pearson, N.E., 1979. On the theory of central place foraging. In: Horn, D., Mitchell, R., Straits, G. (Eds.), Analysis of Ecological Systems. Ohio University Press, Athens, OH, pp. 154–177.

Preston, C.R., Jones, R.E., Horton, N.S., Reston, C.H.R.P., 2017. Golden Eagle diet breadth and reproduction in relation to fluctuations in primary prey abundance in Wyoming's Bighorn Basin. J. Raptor Res. 51, 334–346. https://doi.org/10.3356/JRR-16-39.1.

QGIS.org, 2022. QGIS Geographic Information System. QGIS Association [Software]. http://www.qgis.org.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria v4.2.1 (Version 4.2.1) [software]. https://www.R-project.org/.

Singh, N.J., Moss, E., Hipkiss, T., Ecke, F., Dettki, H., Sandström, P., Bloom, P., Kidd, J., Thomas, S., Hörnfeldt, B., 2016. Habitat selection by adult Golden eagles *Aquila chrysaetos* during the breeding season and implications for wind farm establishment. Bird Study 63 (2), 233–240. https://doi.org/10.1080/00063657.2016.1183110.

SOS-POP, 2022. Banque de données sur les populations d'oiseaux en situation précaire au Québec. Regroupement Québec Oiseaux, Montréal, Québec, Canada [Dataset].

Squires, J.R., Olson, L.E., Wallace, Z.P., Oakleaf, R.J., Kennedy, P.L., 2020. Resource selection of apex raptors: implications for siting energy development in sagebrush and prairie ecosystems. Ecosphere 11 (8). https://doi.org/10.1002/ecs2.3204.

Tapia, L., Zuberogoitia, I., 2018. Breeding and nesting biology in raptors. In: Sarasola, J. H., Grande, J.M., Negro, J.J. (Eds.), Birds of Prey. Springer International Publishing, Cham, pp. 63–94.

Therkildsen, O.R., Balsby, T.J.S., Kjeldsen, J.P., Nielsen, R.D., Bladt, J., Fox, A.D., 2021. Changes in flight paths of large-bodied birds after construction of large terrestrial wind turbines. J. Environ. Manag. 290. https://doi.org/10.1016/j.jenvman.2021.112647.

Tolvanen, A., Routavaara, H., Jokikokko, M., Rana, P., 2023. How far are birds, bats, and terrestrial mammals displaced from onshore wind power development? – a systematic review. Biol. Conserv. 288, 110382. https://doi.org/10.1016/j.biocon.2023.110382.

Torres, L.G., Orben, R.A., Tolkova, I., Thompson, D.R., 2017. Classification of animal movement behavior through residence in space and time. PLoS One 12, 1–18. https://doi.org/10.1371/journal.pone.0168513.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. USA 100, 8074–8079. https://doi.org/10.1073/pnas.1231335100.

Watson, R.T., Kolar, P.S., Ferrer, M., Nygård, T., Johnston, N., Hunt, W.G., Smit-Robinson, H.A., Farmer, C.J., Huso, M., Katzner, T.E., 2018. Raptor interactions with wind energy: case studies from around the world. J. Raptor Res. 52, 1–18. https://doi.org/10.3356/JRR-16-100.1.

Whitfield, D.P., McLeod, D.R.A., Fielding, A.H., Broad, R.A., Evans, R.J., Haworth, P.F., 2001. The effects of forestry on golden eagles on the island of Mull, western Scotland. J. Appl. Ecol. 38, 1208–1220. https://doi.org/10.1046/j.0021-8901.2001.00675.x.

Whitfield, D.P., Fielding, A.H., Mcleod, D.R.A., Morton, K., Stirling-Aird, P., Eaton, M.A., 2007. Factors constraining the distribution of Golden eagles *Aquila chrysaetos* in Scotland. Bird Study 54, 199–211. https://doi.org/10.1080/00063650709461476.