The impact of wind turbines on the distribution of wintering and migrating raptors

By

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Abstract

Renewable energy sources, including wind power, are rapidly expanding as governments aim to fight climate change. However, wind turbines may negatively affect surrounding wildlife. Raptors are birds of prey and are potentially susceptible to being negatively affected by wind turbines. Raptor collisions with wind turbines are well-studied, but the potential for their spatial displacement due to wind turbines has received less attention. Understanding both collisions and displacement is necessary to comprehend the overall effects of wind turbines on raptors. Amherst Island, Ontario, Canada is renowned for its number and diversity of wintering raptors. Wind turbines were built on the island in 2018. In this study, we used standardized surveys to record the presence, number, and precise location of raptors on Amherst Island during winter and spring migration for three years before (2015, 2016, 2017) and three years after (2019, 2022, 2023) the windfarm was built. We recorded 3,277 observations of raptors which we used to test whether the turbines affected raptor distributions, incorporating both spatial and temporal controls. We found no evidence that any of our six focal raptor species – Northern Harrier (*Circus hudsonicus*), Bald Eagle (*Haliaeetus leucocephalus*), Red-tailed Hawk (*Buteo jamaicensis*), Rough-legged Hawk (*Buteo lagopus*), Snowy Owl (*Bubo scandiacus*), or American Kestrel (*Falco sparverius*) – changed their distributions in response to wind turbines. Similarly, we found no evidence of changes in the distributions of different age classes of Bald Eagle in response to wind turbines. Changes in overall population sizes on Amherst Island for our six focal species, as well as for Short-eared Owl (*Asio flammeus*) and Northern Shrike (*Lanius borealis*), mirrored regional trends in abundance, suggesting no impacts of wind turbines on raptor abundance. Overall, despite some collisions between raptors and wind turbines recorded in monitoring studies, we found no evidence of negative impacts of wind turbines on how our focal

species use Amherst Island during winter and spring migration. As the need for renewable energy grows, using strong methods to study potential effects of wind turbines on surrounding wildlife will help ensure appropriate sites are chosen for future windfarms.

Co-Authorship

The work presented in Chapter 2 was completed with co-author Paul R. Martin. KEM and PRM conceived and designed the study. PRM collected field data. KEM completed analyses with input from PRM. KEM wrote the manuscript with edits from PRM.

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Indigenous sources, listen to Indigenous voices, and actively support and uplift Indigenous initiatives.

I would like to further acknowledge the environmental impact of my project. The most environmentally impactful component of this study was travel to, from, and around our study site and the fuels used to power the vehicle. To mitigate the related carbon emissions, we avoided unnecessary travel by ensuring all the trips taken to Amherst Island were critical for data collection and by only driving the necessary route for data collection.

Supplemental CBC Data are provided by National Audubon Society (www.audubon.org, www.christmasbirdcount.org and www.bsc-eoc.org) and through the generous efforts of Bird Studies Canada and countless volunteers across the Western Hemisphere.

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List of Abbreviations

"kW" – Kilowatt

"BACI study" – Before-After Control-Impact study

"km" – Kilometers

"m" – Meters

"AIC" – Akaike's Information Criterion

"ANOVA" – Analysis of Variance Analysis

"glmm" – Generalized linear mixed models

"GPS" – Global Positioning System

Chapter 1: Introduction

Renewable energy sources are important for mitigating climate change; however, these energy sources can harm local biodiversity. Global renewable energy output is expected to rise more than 60% between 2020 and 2026 as many governments work toward reducing carbon emissions (International Energy Agency 2021). These rapidly expanding sources of renewable energy (i.e., hydro, wind, and solar power sources) may negatively impact their surrounding environments. For example, the growth of hydropower in the early 1990s in North America and Europe involved the building of hydroelectric dams that interrupted fish migration, reducing the survival and reproductive success of migratory fish (Ruggles et al. 1993, Ward 1989). Efforts to address the negative effects of hydroelectric dams on fish, including developing new technologies like fish ladders and other safe fish passage systems, have helped to improve migration success and reduce mortality (Larinier 2001, Scruton et al. 2008). As with hydroelectricity, identifying the negative impacts of any new power source is critical to ensure steps are taken to minimize any environmental impacts that may result.

Wind turbines are an increasingly important source of renewable energy; however, we still do not fully understand how they affect nearby ecosystems. Collisions are the most direct and simple of these negative effects to measure. For example, bats are often negatively affected by collisions, with approximately 16 bats killed per turbine per year in Canada, with long-distance migratory species, such as the Silver-haired Bat (*Lasionycteris noctivagans*), accounting for most mortalities (Zimmerling and Francis 2016). Other more subtle, but nonetheless important, effects of wind turbines can also occur. For example, land mammals such as European Badgers (*Meles meles*) living near wind turbine sites were found to have higher hair cortisol levels when compared to those living at control sites (Agnew et al. 2016). Other organisms, such as the European Golden Plover (*Pluvialis apricaria*), may be displaced from turbine sites during operation (Sansom et al. 2016), and thus turbines may alter their local habitat use and distributions.

Although many different organisms can be affected by wind turbines, raptors may be particularly impacted. Raptors are carnivorous bird species that include top predators and are important for ecosystem function (Alkama et al. 2005, Whelan et al. 2008). Many raptors soar, allowing them to travel long distances, or hunt, while using less energy (Duriez et al. 2014). Soaring relies on updrafts, therefore soaring birds tend to move along areas with high updraft potential (Brandes and Ombalski 2004, Dennhardt et al. 2015). Soaring raptors and all turbines require strong winds, the former to save energy and the latter to create it, therefore they are often found in the same areas (Martín et al. 2018), increasing the risks of collisions. Collisions have been well-documented and researched, and multiple factors (e.g., poor visibility, wind turbine design, habituation to wind turbines, and temporal fluctuations) may increase the number of raptor fatalities due to collisions (Barrios and Rodriguez 2004, Linder et al. 2022, Orloff and Flannery 1992, Osborn et al. 2000, Smallwood and Thelander 2008, Winkelman 1985).

The spatial displacement of raptors due to wind turbines has been given less attention by researchers and policy makers than collisions. For example, all wind farms in Ontario with a capacity of 50 kW or greater are required to perform at least 3 years of post-turbine construction bird mortality surveys, with raptors as a distinct category; however, there is no requirement to document the displacement of birds from their habitats unless a wind farm is located within 120 meters of a significant wildlife habitat for birds (Ontario Ministry of Natural Resources 2011). Yet examining both displacement and collisions is necessary to fully understand the effects of wind turbines on raptors. For example, wind turbines could negatively impact raptor populations through displacement, while simultaneously reducing collisions (De Lucas et al. 2004). Further, few studies examine raptor activity both before and after turbine construction, despite before-after controls being important for accurate tests of wind turbine impacts (Dahl et al. 2012, De Lucas et al. 2004). In addition, most studies of raptor displacement only seek to understand deviations in flight and migration patterns (Dahl et al. 2012, De Lucas et al. 2004, Pearce-Higgins et al. 2009, Villegas-Patraca et al. 2014). Little is known about how wind turbines affect the fine-scale distribution or activity of raptors, particularly in important areas for foraging during winter and migration.

Wintering and migrating raptors on Amherst Island, Canada, are an ideal system in which to examine wind turbine effects on fine-scale raptor distributions and activity. Amherst Island is located in southeastern Ontario, in the northeast corner of Lake Ontario. The small island is internationally recognized as an Important Bird Area by BirdLife International and renowned for its high concentrations of wintering and migrating raptors, notably owls and hawks, that hunt dense, cyclic populations of Eastern Meadow Voles (*Microtus pennsylvanicus*) (Bird Studies Canada n.d., Bell et al. 1979, Martin 2015, Phelan 1976, Phelan and Robertson 1978, Quilliam 1965, Weir 2008). Amherst Island and nearby Wolfe Island have hosted some of the largest concentrations of wintering raptors in North America, with notable numbers of some arctic species, such as Snowy Owls (*Bubo scandiacus*) (Bell et al. 1979, Quilliam 1965, Weir 1973, 2008). Cyclical raptor population densities occur on the island corresponding to years of high vole populations and irruption years, when large numbers of raptors migrate south (Bell et al. 1979, Leonard 2015, Martin 2015). For example, an irruption year on Amherst Island in 1979 included 10 different owl species with an estimated 160 different owls using the island throughout the winter, alongside at least 230 other non-owl raptors (Bell et al. 1979). In a more recent irruption year (winter/spring 2015), Amherst Island hosted over 40 different Snowy Owls on peak days (Martin 2015). Amherst Island is thus an important wintering and migration stopover location for raptors.

The position of Amherst Island on the northeast side of Lake Ontario has also made the island an ideal site for persistent and predictable winds, leading to the installation of 26 wind turbines in 2018 (Windlectric LLC. 2023). These turbines were placed across the island but restricted to open patches of private land where landowners granted permission. Given the large populations of raptors using Amherst Island, the wind turbine project was controversial, but managers lacked adequate data on the effects of wind turbines on raptors in similar settings. For example, wind turbines installed on nearby Wolfe Island in 2009 did not include well-designed studies of habitat use before and after turbine construction, and thus any potential repercussions on raptor habitat use by turbines were difficult to identify. The large natural fluctuations in raptor numbers on both Wolfe and Amherst islands also made identifying effects of turbines on raptors challenging. The construction of wind turbines on Amherst Island presented a new opportunity to test for the potential impacts of turbines on raptor habitat use at a site that is important for feeding raptors, particularly during winter and migration. Evidence of important negative effects on Amherst Island raptors would also allow managers to implement mitigation measures in the future.

In this study, we test the hypothesis that wind turbines on Amherst Island affect the distribution of wintering and migrating raptors using a before-after control-impact (BACI) study design (i.e., a design with both temporal and spatial controls). We used standardized surveys to record the presence, number, and location of wintering (January-February) and migrating (March-April) raptors on or near the island for 3 years before and 3 years after the wind turbines were built. If wind turbines repel raptors (H_1), then we predicted that raptors would be distributed further from wind turbine sites after construction. If wind turbines attract raptors (H_2; e.g. to feed on carrion below the turbines), then we predicted that raptors would be distributed closer to wind turbine sites after the wind turbines were built. If wind turbines do not impact raptor distributions (H_0), then we predicted no change in raptor distribution on Amherst Island pre- and post-turbines. We tested among these alternative hypotheses using data on six species of raptors, representing three families of birds: Accipitridae: Northern Harrier (*Circus hudsonicus*), Bald Eagle (*Haliaeetus leucocephalus*), Red-tailed Hawk (*Buteo jamaicensis*), Rough-legged Hawk (*Buteo lagopus*); Strigidae: Snowy Owl; and Falconidae: American Kestrel (*Falco sparverius*). To these focal species, we added analyses of abundance before and after turbine construction for 2 additional species that were too uncommon to test our main distributional hypotheses: Strigidae: Short-eared Owl (*Asio flammeus*) and Laniidae: Northern Shrike (*Lanius borealis*). Our surveys covered a time span of nine years (2015-2023), and included 3,277 observations of raptors, providing a large sample with which to test our predictions.

Chapter 2: Methods

Study Site

We conducted this study on Amherst Island (44°14'N, 76°30'W), near Kingston, Ontario, Canada. The island is 67 km^2 and is situated in the northeastern region of Lake Ontario. Much of the island was historically cleared for pasture and croplands, resulting in mostly flat, open habitat with patches of mixed or deciduous forest and wetland (Phelan and Robertson 1978). The human population on Amherst Island is approximately 400 people (Statistics Canada 2001) and linked to the mainland by ferry. The onshore wind farm consists of twenty-six 3.2-megawatt Siemens SWT-3.2-113 turbines (hub height = 99.5 m, blade length = 55 m) (Fig. 1, Power Technology 2023, Siemens 2015). The installation of the wind turbines took place in winter 2018, with power generation commencing in June 2018 (Windlectric LLC. 2023).

Raptors are often reported as at risk for collisions with wind turbines (Barrios and Rodriguez 2004, Orloff and Flannery 1992, Osborn et al. 2000, Smallwood and Thelander 2008, Winkelman 1985); however, our study did not assess the collision risk to raptors. Collision mortality data, however, were collected by environmental consultants on Amherst Island as mandated by the government of Ontario (Natural Resource Solutions 2020, 2021, 2022, Ontario Ministry of Natural Resources 2011). Raptors killed per year across all 26 turbines during mortality surveys were: three in 2019, three in 2020, and nine in 2021 (Natural Resource Solutions 2020, 2021, 2022). Raptor mortality was slightly higher than the provincial threshold of 0.2 raptors killed/turbine/year for 2020 (0.32) and 2021 (0.65), leading to implementation of anti-collision mitigation strategies (Natural Resource Solutions 2021, 2022).

Study species

We collected intensive data on six species of wintering and migratory raptors: Northern Harrier, Bald Eagle, Red-tailed Hawk, Rough-legged Hawk, Snowy Owl, and American Kestrel. We recorded other raptor species during our surveys, but in insufficient numbers for some of our analyses. We include these species [Great Horned Owl (*Bubo virginianus*), Red-shouldered Hawk (*Buteo lineatus*), Merlin (*Falco columbarius*), Peregrine Falcon (*Falco peregrinus*), Golden Eagle (*Aquila chrysaetos*), Osprey (*Pandion haliaetus*), and Cooper's Hawk (*Accipiter cooperii*)] in our dataset, and present abundance data for species we sometimes recorded in high numbers (Short-eared Owl) or recorded regularly in low numbers (Northern Shrike). Although we collected data for Turkey Vultures (*Cathartes aura*), they are mainly a transient migrant or an occasional winter straggler, only rarely feeding on voles (Black and Roy 2010) and thus were not included in our analysis.

Migrant raptors typically use Amherst Island as a stopover site for foraging during migration; few were observed in the act of active migration (i.e., actively moving across the island, heading north in spring). The island raptor population is dynamic within and between years, responding to the availability of food. Even within a winter, the numbers of raptors fluctuate depending on vole numbers, depth of snow, temperature, and other factors that influence the accessibility of food (e.g., ice covered snow that can make snow difficult to penetrate) (Phelan 1976, Phelan and Robertson 1978). Nonetheless, in good vole years, some species defend winter territories (e.g., Snowy Owl) and can be present in consistent numbers throughout the season (e.g., Martin 2015).

Survey Methods

We conducted surveys between mid January and early April for three years before (2015, 2016, 2017) and three years after (2019, 2022, 2023) the wind turbines were built and became operational (2018). We did not conduct surveys in 2018 because of disruption from heavy construction, and we did not conduct surveys in 2020 or 2021 due to COVID-19 pandemic restrictions on field research. We included three years before and after turbine construction to attempt to capture natural fluctuations in raptor abundance in both pre- and post-construction samples. Each survey year we conducted a minimum of 6 and a maximum of 10 surveys.

We conducted our surveys along a consistent route around the island, covering all passable public roads; we alternated which side of the island we visited first (east or west side first), but maintained the same routes for each of these two options (Fig. 1). We drove a vehicle along the designated route and scanned both sides of the road for the presence of raptors. When we sighted a bird, we stopped the vehicle and identified it using binoculars (10 x 50, Leica, Wetzlar, Germany) or a tripod-mounted telescope (20 x to 60x, Swarovski, Wattens, Austria). We designated certain locations along the route as 'regular scanning stations', offering good, long-range visibility. We made complete stops at regular scanning stations and made a 360^{o} scan using binoculars and telescope. One person (PRM) conducted all surveys to control for interobserver bias. Each survey required an average of 7 hours and 45 minutes to complete and covered an average distance of 79.9 km.

When we identified a raptor, we recorded the species, time (to the nearest minute), and estimated location on previously prepared maps of the island (satellite map data: Google, TerraMetrics, and NOAA). After surveys, we used the same satellite maps online to convert the locations from our printed maps to latitude and longitude for each raptor. For some species, we also identified the morph (Rough-legged Hawk), and estimated the age (Bald Eagle), and sex (American Kestrel) of each raptor when possible. We originally estimated the sex and age of Snowy Owls based on methods described by Josephson (1980); however, more recent research found these methods to be unreliable (Bortolotti and Stoffel 2012), and thus we did not include Snowy Owl sex or age estimates in our analyses. We did not record the age and sex of all raptor species that could be distinguished due to time constraints during surveys.

To minimize counting the same individuals more than once, we identified specific characteristics and the direction of movement of each raptor when possible (especially for Snowy Owls and Bald Eagles); the large numbers of *Buteo* hawks during some surveys made identifying individuals more difficult.

Control Sites

We created control sites (i.e., locations with no wind turbines) on Amherst Island to act as spatial controls for the presence of wind turbines. We measured the distance between turbines on Amherst Island, and the distance of turbines from Lake Ontario, dense forest, non-turbine structures, and public roads. We then used the smallest of each measurement to establish rules for designating our control sites; thus, control sites were similar to turbine sites to minimize confounding factors such as roads and power lines (Colman et al 2017, Marques et al. 2021, Walters et al 2014).

To generate control sites, we used Google Maps (map data ©2023 Google) to locate the most northward, southward, eastward, and westward coordinates of Amherst Island. We then created random points within these four coordinates using the runif and cbind functions in R, version 4.2.2 (R Core Team 2022). We removed points located off Amherst Island and then measured each point on the island against our set of rules. We removed any control sites found within 616 m from Lake Ontario, 93 m from public roads, 474 m from non-turbine structures, and 124 m from forested areas. We defined a forested area as anywhere with trees close enough together to obscure the ground between them on Google Maps. We removed any sites encircled by forest on all sides. We also ensured control sites were the same minimum distance from one-another as true wind turbine sites are from one-another, removing any control sites located less than 405 meters from another control site (the site removed chosen by randomized selection). Finally, to ensure the wind turbines did not affect birds at control sites, we removed any control points less than 810 m (double the minimum distance between wind turbines) from a wind turbine. We created 26 control sites to match the number of wind turbines (Fig. 1).

Figure 1. Map of Amherst Island with turbine sites, control sites, and our survey route. Surveys alternated between starting on the east or west side of the island and covered the entire route.

Statistical Analysis

We conducted our plotting and statistical analyses in R (version 4.2.2, R Core Team 2022). R code and the full data set have been deposited in Open Science Framework at the following link: (https://osf.io/f5s6a/?view_only=29c3bea19f314246b91eaaa258188900).

Distribution of Raptors on Amherst Island

Our data set included 3,277 observations representing 16 raptor species. For our analysis of distribution, we removed any species with fewer than 20 records before and 20 records after turbine construction, leaving us with 6 focal species (Northern Harrier, Bald Eagle, Red-tailed Hawk, Rough-legged Hawk, American Kestrel, and Snowy Owl).

We tested the hypothesis that wind turbines on Amherst Island affect the distribution of wintering and migrating raptors with linear mixed effects and least squares models using the *nlme* package; (version 3.1-160, Pinheiro et al. 2023). We used shortest distance from a turbine or control site as the response variable (cube-root transformed to improve normality of model residuals) because we were most interested in the short-range effects of turbines on raptors. We created one predictor variable (Site Type and Turbine Presence) with four levels: wind turbine site before construction, wind turbine site after construction, control site before construction, control site after construction, where 'construction' refers to the year wind turbines were installed on the island (2018). Thus, these four levels incorporated both spatial (wind turbines versus control sites) and temporal (before and after turbine installation) controls.

We ran separate models for each focal species. For each species, we compared models incorporating each observation as a random factor with models without a random factor (both models using restricted maximum likelihood methods). We included observation as a random factor because each observation was associated with two values: a distance to a wind turbine and to a control site, and if a raptor is observed in a location far away from wind turbines, they are likely to also be found further away from control sites. We compared model performance of the linear mixed effects and least squares models using Akaike Information Criterion (AIC) values, with the best-performing model having the lowest AIC value. We then ran the best performing model and checked model fit following Zuur et al. (2009), by plotting fitted values versus standardised residuals between factor levels using plots and Bartlett's tests of homogeneity of variances, examining histograms of model residuals, and assessing Cook's distance values. If the models showed significant differences in variance structure among 'Site Type and Turbine Presence' levels, then we moved to a revised model that allowed us to incorporate the different variance structures across the levels by specifying weights = varIdent (form = ∼1| Site Type and Turbine Presence) and reassessed model fit (Zuur et al., 2009).

We used the analysis of variance (ANOVA) function to determine whether distance of raptors from focal sites differed among predictor levels overall. We then compared pairwise differences among the four levels using Tukey tests in the R package *emmeans* (version 1.8.4-1, Lenth 2021).

If wind turbines impacted the spatial use of Amherst Island for our focal raptor species, then we predicted they would be found further from (H_1) or nearer to (H_2) turbine sites post-construction. We also predicted that raptor distances from control sites pre- and post-construction would not differ.

Distribution Based on Age

For analyses of distribution based on age, we included species with at least 20 adult records and 20 immature records, excluding Snowy Owls due to the potential for error in ageing (Bortolotti and Stoffel 2012). Our focal species for distribution based on age was the Bald Eagle, where we separated individuals into two age classes: immature (juvenile to basic IV plumage) and adult (definitive basic plumage) following McCollough (1989).

We tested the hypothesis that wind turbines on Amherst Island affect the distribution of wintering and migrating Bald Eagles based on age with general linear mixed effects and least squares models using the *nlme* package; (version 3.1-160, Pinheiro et al. 2023). We used the same response variable and predictor variable as we used above for the overall distribution. We also included age as a second predictor variable with two levels: adult and immature. We compared models incorporating observation number as a random factor with models without a random factor (both models using restricted maximum likelihood methods). We then also compared models without an interaction term, with an interaction term between 'Site Type and Turbine Presence' and age, without age included, and with just the intercept. We compared model performance as described above for overall distribution.

We used the ANOVA function to determine whether Bald Eagles differed in their distance from focal sites among predictor levels based on age. We compared pairwise differences among the four levels to identify which levels differed from each other using Tukey tests in the R package *emmeans* (version 1.8.4-1, Lenth 2021).

If wind turbines impacted the spatial use of Amherst Island by Bald Eagles based on age, then we predicted that one of the age classes (adults or immatures) would be found further from turbine sites post-construction compared with pre-construction, with no differences for control sites pre- versus post-turbine construction.

Abundance

For our abundance analyses we included any species with at least 20 individuals recorded on our surveys overall, leaving us with eight focal species: Northern Harrier, Bald Eagle, Red-tailed Hawk, Rough-legged Hawk, American Kestrel, Snowy Owl, Short-eared Owl, and Northern Shrike. We included season (two levels: winter and spring) as a random factor in our models to control for potential seasonal differences in abundance.

To assess abundance trends of wintering and migrating raptors on Amherst Island, we ran generalized linear mixed-effects models with raptor count (i.e., number of birds of a focal species recorded on each complete survey) as the response variable. We had one predictor variable with two levels: pre-turbine construction, and post-turbine construction.

We first ran models with a Poisson distribution using the *glmer* function in the *lme4* package (version 1.1-33, Bates et al. 2015). We ran the full model and examined its fit by plotting standardized residuals against fitted values and all predictors, testing for overall deviations from expected distributions and linearity by running tests for correct distribution (Kolmogorov-Smirnov test), dispersion, and outliers using the *DHARMa* package (version 0.4.6, Florian Hartig 2022). We then tested the homogeneity in variance of residuals for each predictor using plots and Levene tests for homogeneity of variance and tested for zero-inflation using the *DHARMa* package. We also ran the full model for each response variable and random factor independently and examined its fit by plotting standardized residuals against fitted values and all predictors, tested the homogeneity in variance of residuals for each predictor using plots and Levene tests for homogeneity of variance.

If the first Poisson model did not meet assumptions, we then ran further models: a Poisson model with a dispersion parameter, a negative binomial model, a Poisson zero-inflated model, and a negative binomial zero-inflated model. If we encountered a singular fit in our model, then we removed season as a random effect from the model to allow the variance-covariance matrices to be estimated precisely enough to avoid singularity (Matuschek et al. 2017). We identified the best-fitting model as the simplest model to fit all model assumptions and present the results of these best-fitting models.

Short-eared Owl counts included many zeros and occasionally high numbers, creating challenges for model fitting. Thus, we also ran binomial models where the response variable was simplified to the presence or absence of Short-eared Owls on a survey. We used the same predictor variable as in previous abundance models and included season as a random factor. We examined model fit as explained above.

We also compiled and plotted abundance data from the Lake Ontario Region for comparison. We assessed trends in abundance across the Lake Ontario Region using Christmas Bird Count data (National Audubon Society 2015-2023) for our focal survey years (i.e., for the same winter season as our winter surveys) compiled from 22 different count locations conducted on Lake Ontario (New York, Ontario) and at the headwaters of the St. Lawrence River near Amherst Island (Gananoque, Thousand Islands).

We plotted the results of all our analyses using the R package *ggplot2* (version 3.4.0, Wickham, 2016).

Chapter 3: Results

Distribution of Raptors on Amherst Island

We found no evidence that our focal raptor species altered their distributions on Amherst Island in response to wind turbines (Table S1, Fig. 2).

Northern Harrier

Habitat use by the Northern Harrier did not change following turbine construction, but Northern Harriers tended toward occurring closer to control sites than turbine sites across all years (Fig. 2a, ANOVA, $F_{3,826} = 2.273$, $p = 0.079$). We found no difference in the distance of Northern Harriers to wind turbine sites before versus after construction (Tukey test, $p = 1.0$); Northern Harriers also did not differ in their distance to control sites before versus after turbine construction (Tukey test, $p = 0.97$).

Bald Eagle

Habitat use by the Bald Eagle did not change following turbine construction, but Bald Eagles occurred closer to control sites than turbine sites across all years (ANOVA $F_{3,276} = 18.409$, $p = <0.0001$), particularly on the west end of the island (Fig. 2b). We found no difference in the distance of Bald Eagles to wind turbine sites before versus after construction (Tukey test, $p = 1.0$); Bald Eagles also did not differ in their distance to control sites before versus after turbine construction (Tukey test, $p = 1.0$).

Red-tailed Hawk

Habitat use by the Red-tailed Hawk did not change following turbine construction, but Red-tailed Hawks tended toward occurring closer to control sites than turbine sites across all years (Fig. 2c, ANOVA, $F_{3,1560} = 2.405$, $p =0.066$). We found no difference in the distance of Red-tailed

Hawks to wind turbine sites before versus after construction (Tukey test, $p = 0.09$); Red-tailed Hawks also did not differ in their distance to control sites before versus after turbine construction (Tukey test, $p = 0.55$).

Rough-legged Hawk

Habitat use by the Rough-legged Hawk did not change following turbine construction, neither at control nor turbine sites (ANOVA, $F_{3,2256} = 1.17$, $p = 0.32$), and Rough-legged Hawks showed no evidence of avoiding wind turbines (Fig. 2d).

American Kestrel

Habitat use by the American Kestrel did not change following turbine construction, neither at control nor turbine sites (ANOVA, $F_{3,206} = 1.797$, $p = 0.15$), and American Kestrels showed no evidence of avoiding wind turbines (Fig. 2e).

Snowy Owl

Habitat use by the Snowy Owl did not change following turbine construction, neither at control nor turbine sites (ANOVA, $F_{3,367} = 1.474$, $p = 0.22$), and Snowy Owls showed no evidence of avoiding wind turbines (Fig. 2f).

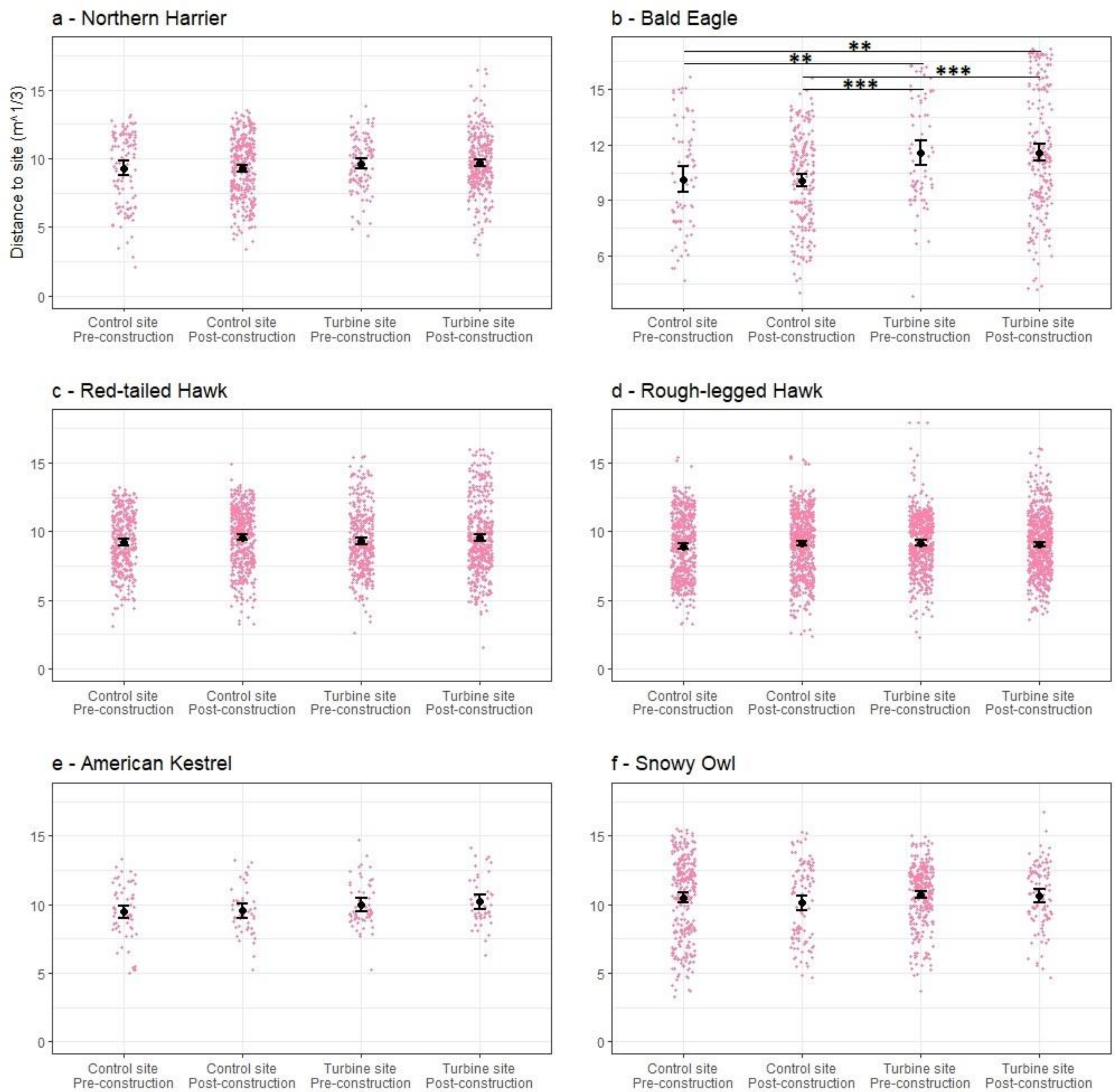

Figure 2. Distance (m^1/3) from control sites and wind turbine sites before and after turbine construction for 6 focal raptor species. Black points represent model-predicted mean values with 95% confidence limits as error bars. Pink points represent raw data points for each raptor species. Raptors were observed on Amherst Island during winter and spring (January-April) before (2015, 2016, 2017) and after (2019, 2022, 2023) wind turbine construction. Asterisks indicate significance (*p < 0.05; **p < 0.01; ***p<0.001) between locations and times (ANOVA followed by Tukey HSD tests). Sample sizes are given in Table 1.

Table 1. Sample sizes for each focal species before and after wind turbine construction.

Species	Pre-construction	Post-construction
Northern Harrier	109	306
Bald Eagle	73	206
Red-tailed Hawk	350	432
Rough-legged Hawk	528	602
American Kestrel	58	47
Snowy Owl	270	100
Short-eared Owl	2	76
Northern Shrike	6	17

Distribution Based on Age

Bald Eagles of different age classes did not differ in their distances to control and turbine sites (ANOVA, $F_{1,273} = 0.28$, $p = 0.60$, Fig. 3).

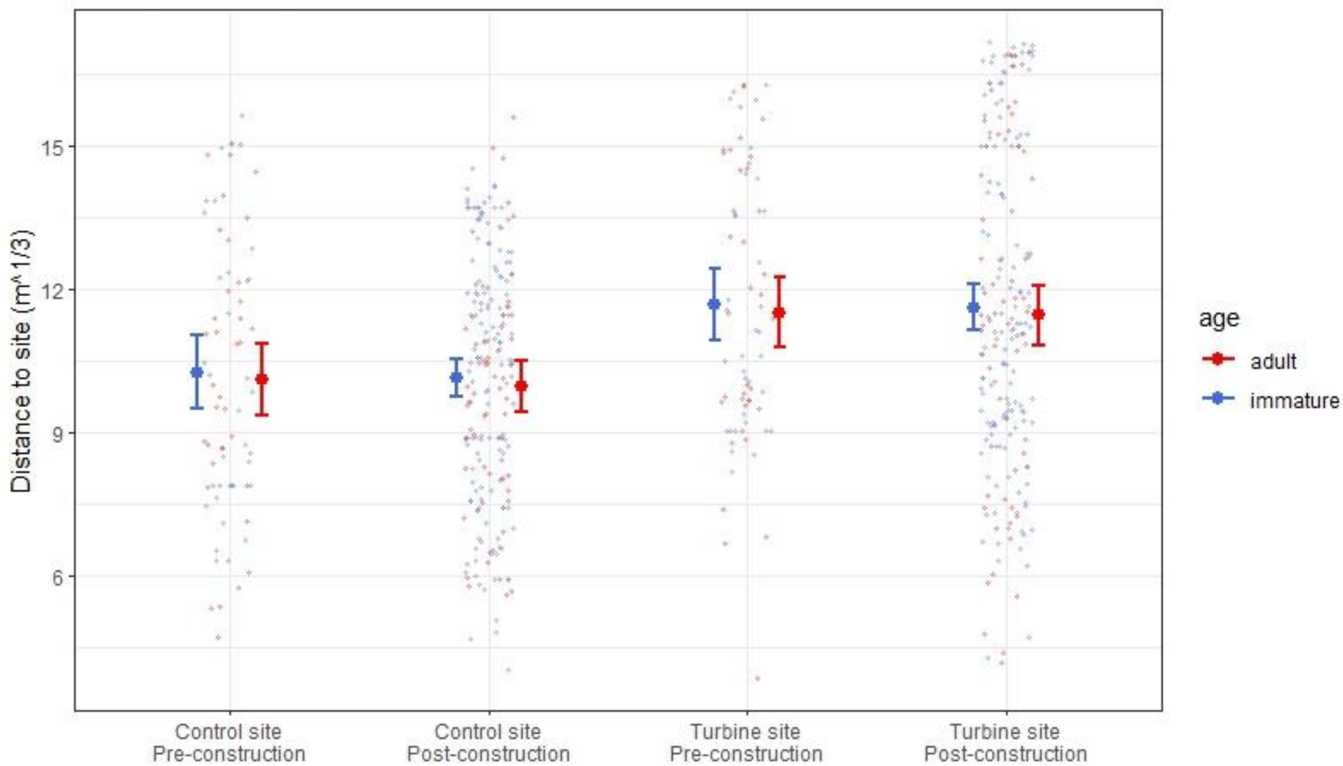

Figure 3. Distance (m^1/3) from control sites and wind turbine sites before and after turbine construction for adult (n = 97) and immature (n = 178) Bald Eagles. Blue and red points represent mean values with 95% confidence limits as error bars. Light blue and light red points represent raw data points for Bald Eagles of different age classes. Bald Eagles were observed on Amherst Island during winter and spring (January-April) before (2015, 2016, 2017) and after (2019, 2022, 2023) wind turbine construction.

Abundance

We found that some raptor species on Amherst Island changed in abundance between the periods before versus after wind turbine construction (Table S5, Fig. 4). Three species showed higher abundances and one species showed lower abundances after wind turbine construction (Fig. 4). One other species showed a higher incidence of occurrence post-turbine construction. In general, trends in abundance between pre- and post-turbine construction periods matched the regional trends in abundance for our focal species from across the Lake Ontario region (Fig. 4).

Northern Harrier

Northern Harrier abundance was significantly higher after turbine construction than before turbine construction (Poisson glmm, $z = -3.76$, $p = 0.0002$, Fig. 4a).

Bald eagle

Bald Eagle abundance was significantly higher after turbine construction than before turbine construction (Poisson glmm, $z = -5.04$, $p = 4.63e-07$, Fig. 4b).

Red-tailed Hawk

Red-tailed Hawk abundance was significantly higher after turbine construction than before turbine construction (Poisson glmm, $z = -2.01$, $p = 0.04$, Fig. 4c).

Rough-legged Hawk

Rough-legged Hawk abundance did not change after turbine construction (Poisson zero-inflated glmm, $z = -0.12$, $p = 0.90$, Fig. 4d).

American Kestrel

American Kestrel abundance did not change after turbine construction (Poisson glmm, $z = -0.10$, $p = 0.92$, Fig. 4e)

Snowy Owl

Snowy Owl abundance was significantly lower after turbine construction than before turbine construction (Poisson glmm, $z = 2.06$, $p = 0.04$, Fig. 4f).

Short-eared Owl

Short-eared Owl abundance did not change after turbine construction (Poisson glmm, $z = -1.39$, $p = 0.16$, Fig. 4g); however, the likelihood of Short-eared Owl occurrence was significantly higher after turbine construction compared with before turbine construction (Binomial glmm, $z = -2.25$, $p = 0.02$).

Northern Shrike

Northern Shrike abundance did not change significantly after turbine construction (Poisson glmm, $z = -1.96$, $p = 0.05$, Fig. 4h), although it approached significance, with higher counts after turbine construction (Fig. 4h).

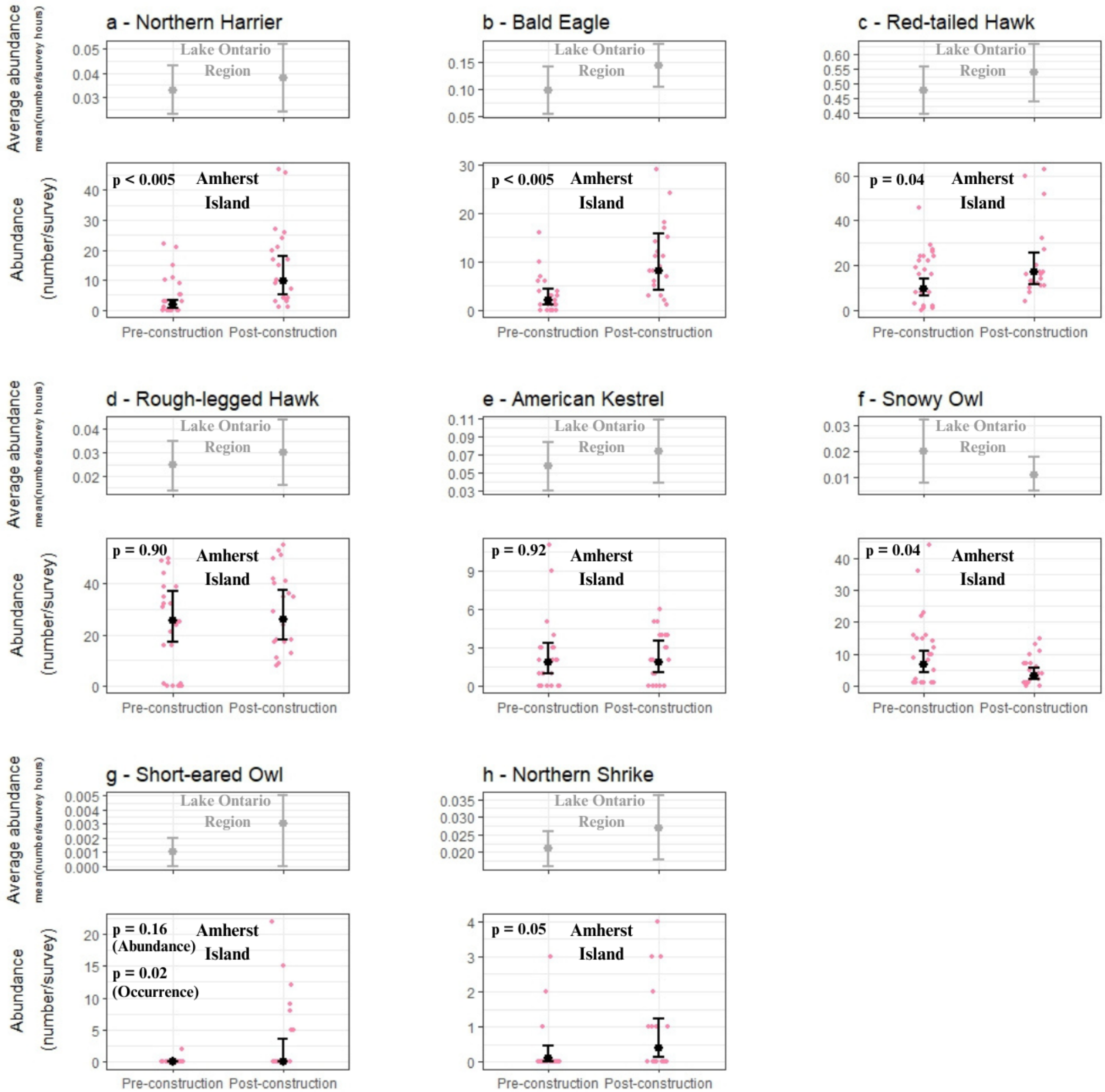

Figure 4. The abundance of raptor species in the Lake Ontario Region (mean number/survey hour) and on Amherst Island (number/survey) for the periods before and after turbine construction. Black points are model-predicted means and 95% confidence limits as error bars; grey points are the Lake Ontario Regional means and 95% confidence limits across 22 different Christmas Bird Count locations. Pink points represent raw data points for each raptor species. Raptors on Amherst Island were observed during winter and spring (January-April) before (2015, 2016, 2017) and after (2019, 2022, 2023) wind turbine construction. Raptor data for the Lake Ontario Region are provided by the National Audubon Society (2015-2023). Sample sizes for raptors on Amherst Island are given in Table 1. Y-axes have different scales.

Chapter 4: Discussion

To examine whether wind turbines affect the distribution of wintering and migrating raptors, we conducted standardized field surveys three years before (2015, 2016, 2017) and three years after (2019, 2022, 2023) turbine installation on Amherst Island, Ontario. Our six focal species were Northern Harrier, Bald Eagle, Red-tailed Hawk, Rough-legged Hawk, American Kestrel, and Snowy Owl. We found no evidence that any focal species changed its distribution in response to wind turbines during the period of our study.

Negative effects of wind turbines on the abundance and distribution of raptors have been found in some previous studies (Campedelli et al. 2014, Garvin et al. 2011, Marques et al. 2020). For example, Black Kites (*Milvus migrans*) fitted with GPS trackers used areas around wind turbines less often than expected given the uplift potential (Marques et al. 2020). Raptors have also been found to change their flight direction and behaviour to avoid turbine blades, especially when turbine blades are spinning (De Lucas et al. 2004, Garvin et al. 2011). In other studies, raptor observations decreased near turbines (Campedelli et al. 2014, Pearce-Higgins et al. 2009). For example, one study found breeding raptor abundance was reduced post-turbine construction, with Red-tailed Hawks, Turkey Vultures, and American Kestrels declining the most (Garvin et al. 2011). However, in a different study, Turkey Vulture and Red-tailed Hawk numbers near wind turbines experienced an initial decline immediately post-construction and then rebounded in the following years, although American Kestrel numbers showed sustained declines near turbines after turbine construction (Dohm et al. 2019).

These previous studies may have found results that differed from ours because of differences in wind farm and habitat characteristics between study sites. Habitat loss is higher at wind farms with large clusters of turbines compared with smaller clusters and lines of turbines (Larsen and Madsen 2000) that better characterize the Amherst Island wind farm (Fig. 1). In addition, smaller wind farms, such as Amherst Island (26 wind turbines), may cause weaker or no declines in species' densities compared with larger wind farms (Fernández-Bellon et al. 2019). Further, the Amherst Island wind farm is located on previously disturbed land – farmland historically cleared for pasture and croplands (Phelan and Robertson 1978). Previous studies have shown that managed forests or areas with high degradation due to human interference tend to show reduced changes in bird populations post-wind turbine construction, possibly because species that are sensitive to anthropogenic change have already been lost (Rehling et al. 2023). Finally, differences between some previous studies and ours may result from differences in the focal raptor species studied, with evidence for species-specific effects in previous work (Dohm et al. 2019).

Our findings are consistent with some other studies that have found no significant effects of wind turbines on raptor habitat use (Dahl et al. 2013, Hernández-Pliego et al. 2015). For example, studies on White-tailed Eagles (*Haliaeetus albicilla*) found no evidence of turbine avoidance overall (Dahl et al. 2013, May et al. 2013). Further, White-tailed Eagles continued to breed in similar locations before and after wind turbine construction, although breeding success may have declined near wind turbines due to adults' vulnerability to being killed in collisions with wind turbines (Balotari-Chiebao et al. 2016). Studies on Montagu's Harrier (*Circus pygargus*) nests and colonies and other raptor populations found no change in abundance after turbine construction (De Lucas et al. 2004, Hernández-Pliego et al. 2015). Finally, other studies argue that while raptor abundance may initially decline post-turbine construction, some raptors, such as *Accipiter* hawks, Turkey Vultures and Red-tailed Hawks, may habituate and return to their pre-turbine abundance six or more years after construction (Dohm et al 2019, Farfán et al. 2017).

Our study also addressed whether wind turbines differentially affect the distribution of Bald Eagles on Amherst Island based on age classes. We found that adult and immature Bald Eagles did not differ in their response to wind turbines, unlike what we might have expected if turbines reduced habitat quality. This result contrasts with previous research on the closely related White-tailed Eagle that found evidence that adults may avoid turbine sites more than immatures (Dahl et al. 2013).

While our study was not designed to test for population-level responses, we collected and analyzed raptor abundance data that covered both high and low vole abundance years before and after turbine construction. We found that populations on Amherst Island generally mirrored regional population trends around Lake Ontario, with populations of some species remaining relatively stable in pre- versus post-turbine survey years (Rough-legged Hawk, American Kestrel, Northern Shrike), some species increasing in abundance or occurrence in post-turbine construction years (Northern Harrier, Bald Eagle, Red-tailed Hawk, Short-eared Owl), and one species decreasing in abundance in post-turbine construction years (Snowy Owl). Given the similar trends for the populations of our focal species in the Lake Ontario region generally, and thus not associated with wind turbine construction, these population fluctuations are unlikely to reflect specific responses to turbines on Amherst Island. For example, Bald Eagle populations are rebounding in the Lake Ontario region after the ban of dichlorodiphenyltrichloroethane (DDT) and a reduction in persecution by humans (Eakle et al. 2015, Grier 1982, U.S. Fish and Wildlife Service 2020). Similarly, a decrease in snow cover in southern Ontario after 2018 created easier hunting conditions for species like Northern Harriers and Short-eared Owls (Environment and

Climate Change Canada 2022, Sonerud 1986), which could explain their general increases on Amherst Island and across the Lake Ontario region. The higher abundance of Snowy Owls during pre-turbine years is also associated with an unusually large southward irruption of this species across eastern North America in the winter of 2015 (Therrien et al., 2017).

Previous studies varied in the strength of their study design, which may explain the variation in reported evidence for impact of turbines on raptors. When strong study designs were used, such as pre- and post- turbine data collection with spatial controls, they typically found little effect of wind turbines on raptor abundance or found initial declines in raptors followed by a return to pre-turbine abundance levels after several years (Farfán et al. 2017, Hernández-Pliego et al. 2015). Occasionally, studies with robust designs have also found species-specific effects of wind turbines on raptor abundance (Dohm et al. 2019) or lower raptor abundance and breeding success post-wind turbine construction (Dahl et al. 2012, Garvin et al. 2011). When stronger methods were not used, however, studies have generally reported evidence for raptor avoidance (Marques et al. 2020, Walker et al. 2005, Pearce-Higgins et al. 2009). Before-and-after turbine construction study designs with spatial controls are important for accurate results (Christie et al. 2019, Dahl et al. 2012); however, few studies use these sampling designs to test for wind turbine effects on raptors (Conkling et al. 2022, Marques et al. 2021).

We used multiple years of surveys, spatial and temporal controls, and a large number of observations, which gives us confidence in our results. The before and after turbine construction and spatial control approach allowed us to account for natural, pre-existing differences between sites, and control for other confounding variables. For example, had we not included data from before turbine construction, we may have misinterpreted our Bald Eagle distribution results - where Bald Eagle occurred further from turbine sites than control. However, pre-turbine construction temporal controls demonstrate that these differences were not caused by wind turbines, but instead by pre-existing differences in habitat use by Bald Eagles. Our study took place over a span of nine years, with data collection occurring during three years before and three years after turbine construction, allowing us to account for natural raptor population fluctuations; our surveys also included years of high and low meadow vole numbers in the survey years both before and after turbine construction, and included 3,277 raptors in total.

Our results demonstrate that foraging raptors continue to use Amherst Island as they did before the wind turbines were built, suggesting no functional habitat loss or shifts in prey availability for wintering and migrating raptors. If prey availability had shifted or habitat loss occurred, we would expect raptors to have changed their use of the island because wintering and migrating raptors select habitat containing high prey densities and move to follow resources (Johnson and Sherry 2001, Marzluff et al. 1997, Shepard et al. 2013). Our results demonstrate that, despite some collisions with turbines (Natural Resource Solutions 2020, 2021, 2022), wintering and migrating raptors have not changed their spatial distributions in response to wind turbines. Overall, we found no evidence of negative impacts of wind turbines on the ecology and health of raptor populations, mediated by habitat use, on Amherst Island, Ontario.

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Appendix A: Supplementary Results

Overall Distribution

Table S1. ANOVA results testing the importance of treatment in our statistical models for each raptor species. Distance to site was the response variable in all models; treatment was the sole predictor and included four levels: control site before turbine construction, control site after turbine construction, wind turbine site before turbine construction, wind turbine site after turbine construction. Asterisks indicate significance: *p < 0.05; **p < 0.01; ***p<0.001. Tukey tests (Table S2) tested for differences between levels within Treatment.

Species	F-Value	P-Value
Northern Harrier	2.27	0.079
Bald Eagle	18.41	<0.0001***
Red-tailed Hawk	2.41	0.066
Rough-legged Hawk	1.17	0.32
American Kestrel	1.80	0.15
Snowy Owl	1.47	0.22

Table S2. Results of Tukey tests for pairwise comparisons for all focal species. Asterisks indicate significance: *p < 0.05; **p < 0.01; ***p<0.001.

Northern Harrier

Contrast	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction Control site ~ Post-construction control site	0.030	0.288	163	0.11	1.00
Pre-construction control site ~ Pre-construction wind-turbine site	-0.303	0.319	193	-0.95	0.78
Pre-construction control site ~ Post-construction wind-turbine site	-0.397	0.286	158	-1.39	0.51
Post-construction control site ~ Pre-construction wind-turbine site	-0.333	0.226	207	-1.48	0.45
Post-construction control site ~ Post-construction wind-turbine site	-0.427	0.175	601	-2.43	0.072
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	-0.094	0.222	198	-0.42	0.97

Bald Eagle

Contrast	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction control site ~ Post-construction control site	0.054	0.392	276	0.14	1.00
Pre-construction control site ~ Pre-construction wind-turbine site	-1.418	0.392	276	-3.61	0.002 **
Pre-construction control site ~ Post-construction wind-turbine site	-1.439	0.421	276	-3.42	0.004 **
Post-construction control site ~ Pre-construction wind-turbine site	-1.472	0.385	276	-3.83	0.0009 ***
Post-construction control site ~ Post-construction wind-turbine site	-1.493	0.233	276	-6.40	<.0001 ***
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	-0.021	0.414	276	-0.05	1.00

Red-tailed Hawk

Contrast	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction control site ~ Post-construction control site	-0.352	0.152	761	-2.32	0.094
Pre-construction control site ~ Pre-construction wind-turbine site	-0.104	0.167	689	-0.62	0.92
Pre-construction control site ~ Post-construction wind-turbine site	-0.336	0.166	785	-2.02	0.18
Post-construction control site ~ Pre-construction wind-turbine site	0.249	0.162	720	1.54	0.42
Post-construction control site ~ Post-construction wind-turbine site	0.017	0.162	834	0.10	1.00
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	-0.232	0.176	776	-1.32	0.55

Rough-legged Hawk

Contrast	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction control site ~ Post-construction control site	-0.192	0.134	2256	-1.44	0.48
Pre-construction control site ~ Pre-construction wind-turbine site	-0.242	0.138	2256	-1.75	0.30
Pre-construction control site ~ Post-construction wind-turbine site	-0.125	0.134	2256	-0.94	0.79
Post-construction control site ~ Pre-construction wind-turbine site	-0.050	0.134	2256	-0.37	0.98
Post-construction control site ~ Post-construction wind-turbine site	0.067	0.129	2256	0.52	0.95
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	0.118	0.134	2256	0.87	0.82

American Kestrel

Contrast	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction control site ~ Post-construction control site	-0.080	0.360	206	-0.22	1.00
Pre-construction control site ~ Pre-construction wind-turbine site	-0.493	0.340	206	-1.45	0.47
Pre-construction control site ~ Post-construction wind-turbine site	-0.726	0.360	206	-2.02	0.19
Post-construction control site ~ Pre-construction wind-turbine site	-0.413	0.360	206	-1.15	0.66
Post-construction control site ~ Post-construction wind-turbine site	-0.646	0.378	206	-1.71	0.32
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	-0.233	0.360	206	-0.65	0.92

Snowy Owl

Contrast	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction control site ~ Post-construction control site	0.402	0.338	367	1.19	0.64
Pre-construction control site ~ Pre-construction wind-turbine site	-0.225	0.217	367	-1.04	0.73
Pre-construction control site ~ Post-construction wind-turbine site	-0.121	0.298	367	-0.41	0.98
Post-construction control site ~ Pre-construction wind-turbine site	-0.627	0.316	367	-1.99	0.20
Post-construction control site ~ Post-construction wind-turbine site	-0.523	0.350	367	-1.50	0.44
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	0.104	0.272	367	0.38	0.98

Distribution Based on Age

Table S3. ANOVA results testing the importance of treatment in our statistical models for Bald Eagle. Distance to site was the response variable in all models. Our predictor variables included treatment (Site Type and Turbine Presence) which included four levels: control site before turbine construction, control site after turbine construction, wind turbine site before turbine construction, wind turbine site after turbine construction; and age (two levels: adult and immature). Asterisks indicate significance: *$p < 0.05$; **$p < 0.01$; ***$p<0.001$. Tukey tests (Table S4) tested for differences between levels within Treatment.

Contrast	F-Value	P-Value
Site Type and Turbine Presence	18.05	<0.0001***
Age	0.28	0.60
Site Type and Turbine Presence ~ Age	0.17	0.92

Table S4. Results of Tukey tests for pairwise comparisons of Bald Eagles of different age classes. Asterisks indicate significance: *p < 0.05; **p < 0.01; ***p<0.001.

Contrast	Age	Estimate	Standard Error	Degrees of Freedom	T-Ratio	P-Value
Pre-construction control site ~ Post-construction control site	Adult	0.39	0.48	363	0.80	0.85
Pre-construction control site ~ Pre-construction wind-turbine site	Adult	-1.12	0.32	363	-3.55	0.003**
Pre-construction control site ~ Post-construction wind-turbine site	Adult	-0.66	0.43	363	-1.52	0.43
Post-construction control site ~ Pre-construction wind-turbine site	Adult	-1.51	0.45	363	-3.35	0.005**
Post-construction control site ~ Post-construction wind-turbine site	Adult	-1.05	0.50	363	-2.11	0.15
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	Adult	0.46	0.40	363	1.16	0.65
Pre-construction control site ~ Post-construction control site	Immature	0.28	0.46	363	0.61	0.93
Pre-construction control site ~ Pre-construction wind-turbine site	Immature	0.51	0.29	363	1.79	0.28
Pre-construction control site ~ Post-construction wind-turbine site	Immature	0.28	0.41	363	0.68	0.91
Post-construction control site ~ Pre-construction wind-turbine site	Immature	0.23	0.43	363	0.54	0.95
Post-construction control site ~ Post-construction wind-turbine site	Immature	-0.004	0.48	363	-0.01	1.00
Pre-construction wind-turbine site ~ Post-construction wind-turbine site	Immature	-0.24	0.38	363	-0.62	0.92

Abundance

Table S5. GLMM results testing the importance of treatment in our statistical models for each raptor species. Abundance (count of the number of individuals recorded on each complete survey) was the response variable in all models; treatment was the sole predictor and included two levels: pre-wind turbine construction and post-wind turbine construction. The Estimate reflects the pre-turbine abundance relative to the post-turbine abundance. Asterisks indicate significance: *p < 0.05; **p < 0.01; ***p<0.001.

Species	Estimate	Standard Error	Z-Value	P-Value
Northern Harrier	-1.78	0.47	-3.76	1.71e-4***
Bald Eagle	-1.34	0.27	-5.04	4.63e-07***
Red-tailed Hawk	-0.57	0.28	-2.01	0.04*
Rough-legged Hawk	-0.03	0.21	-0.12	0.90
American Kestrel	-0.03	0.27	-0.10	0.92
Snowy Owl	0.72	0.35	2.06	0.04*
Short-eared Owl	-3.23	2.31	-1.39	0.16
Northern Shrike	-1.43	0.73	-1.96	0.05

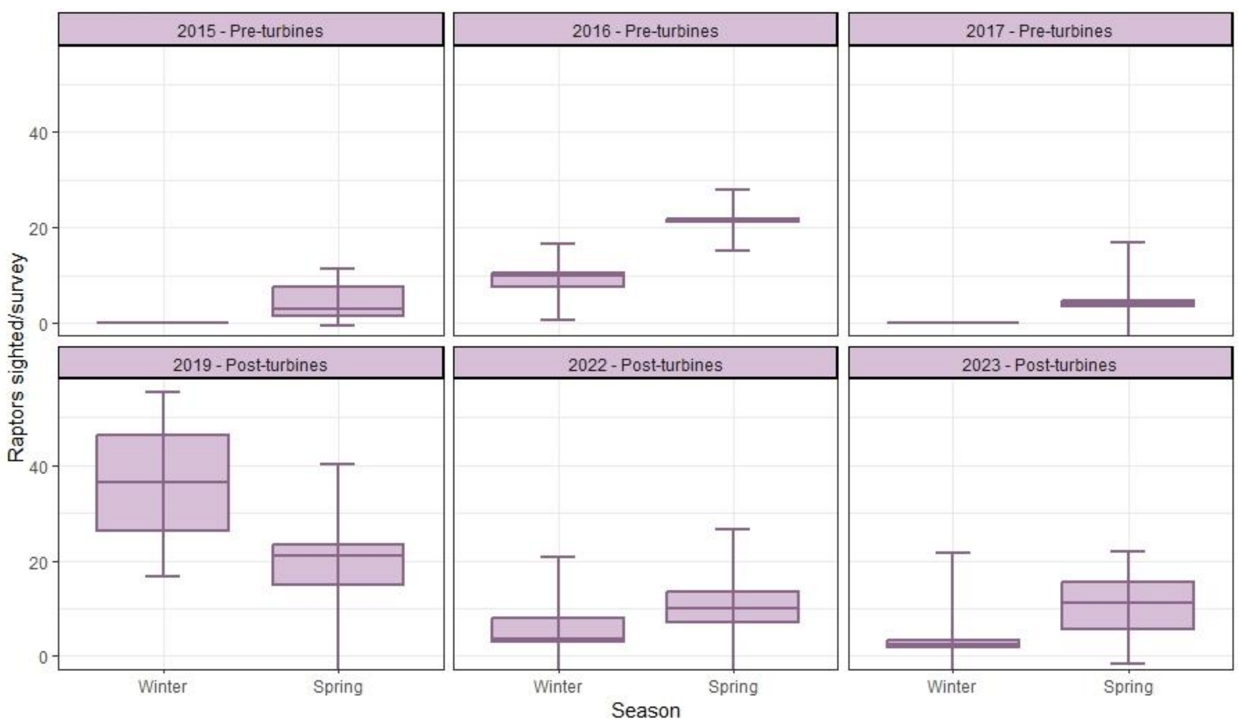

Figure S1. Boxplot of Northern Harrier abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

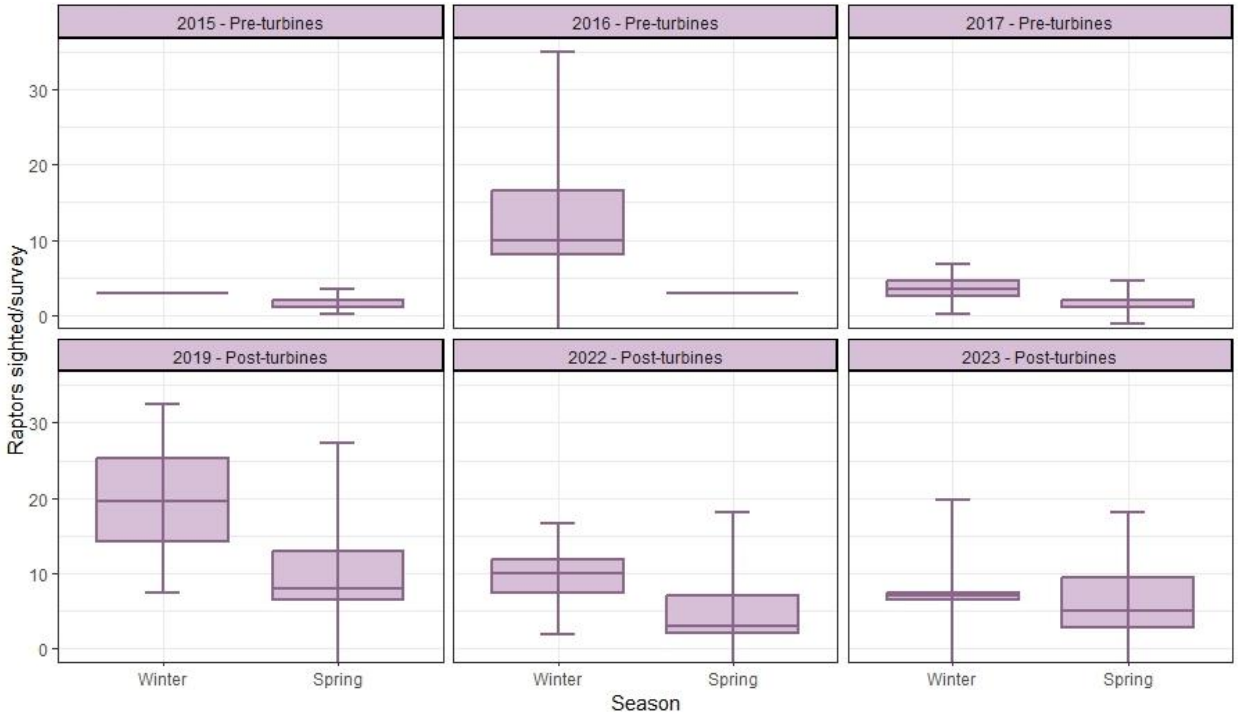

Figure S2. Boxplot of Bald Eagle abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

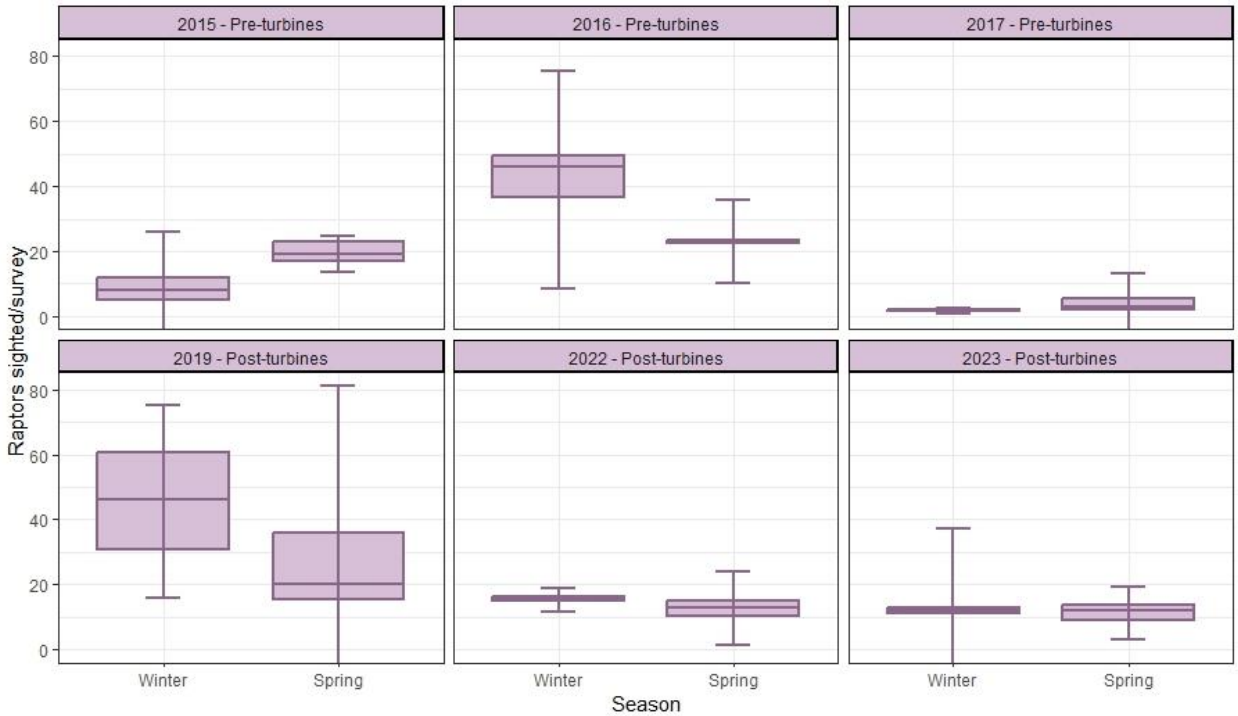

Figure S3. Boxplot of Red-tailed hawk abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

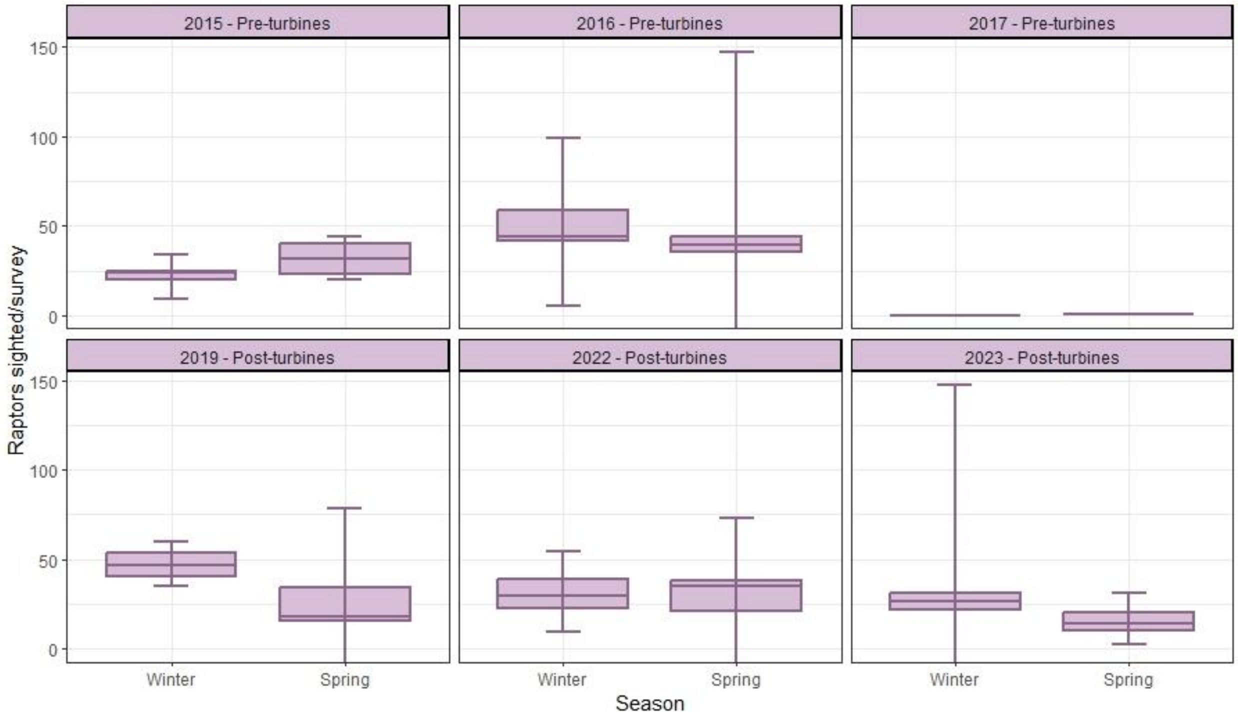

Figure S4. Boxplot of Rough-legged Hawk abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

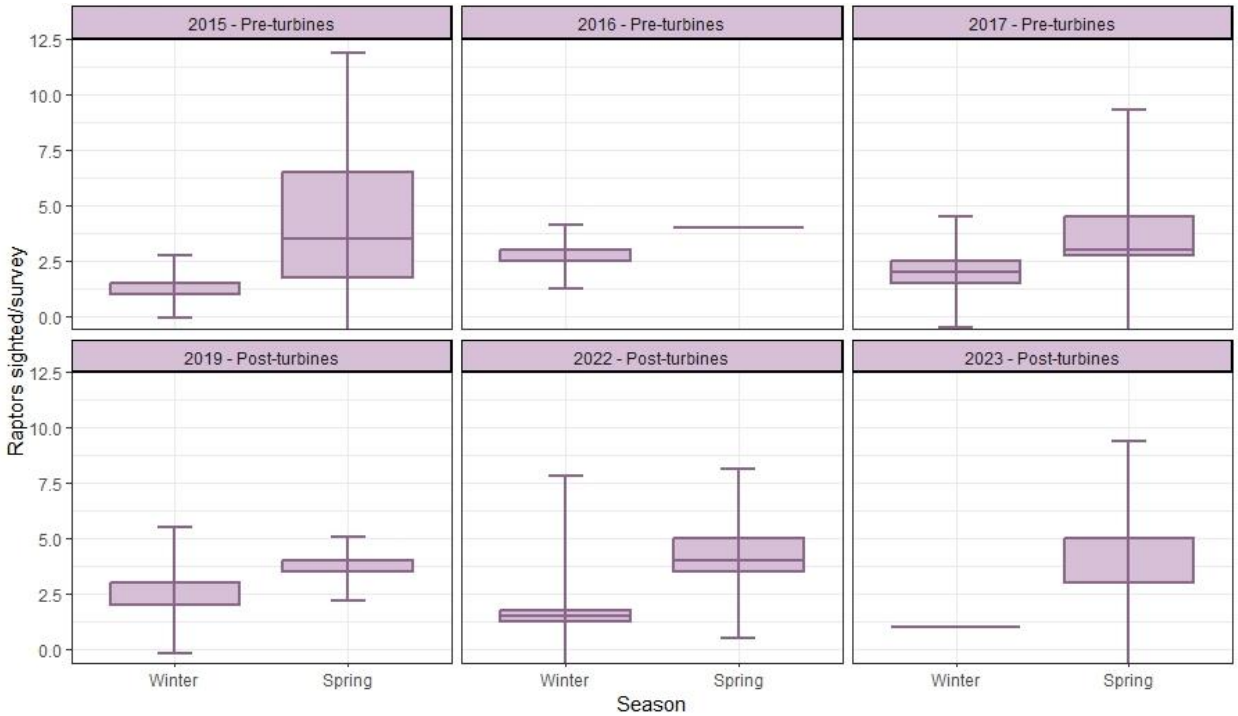

Figure S5. Boxplot of American Kestrel abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

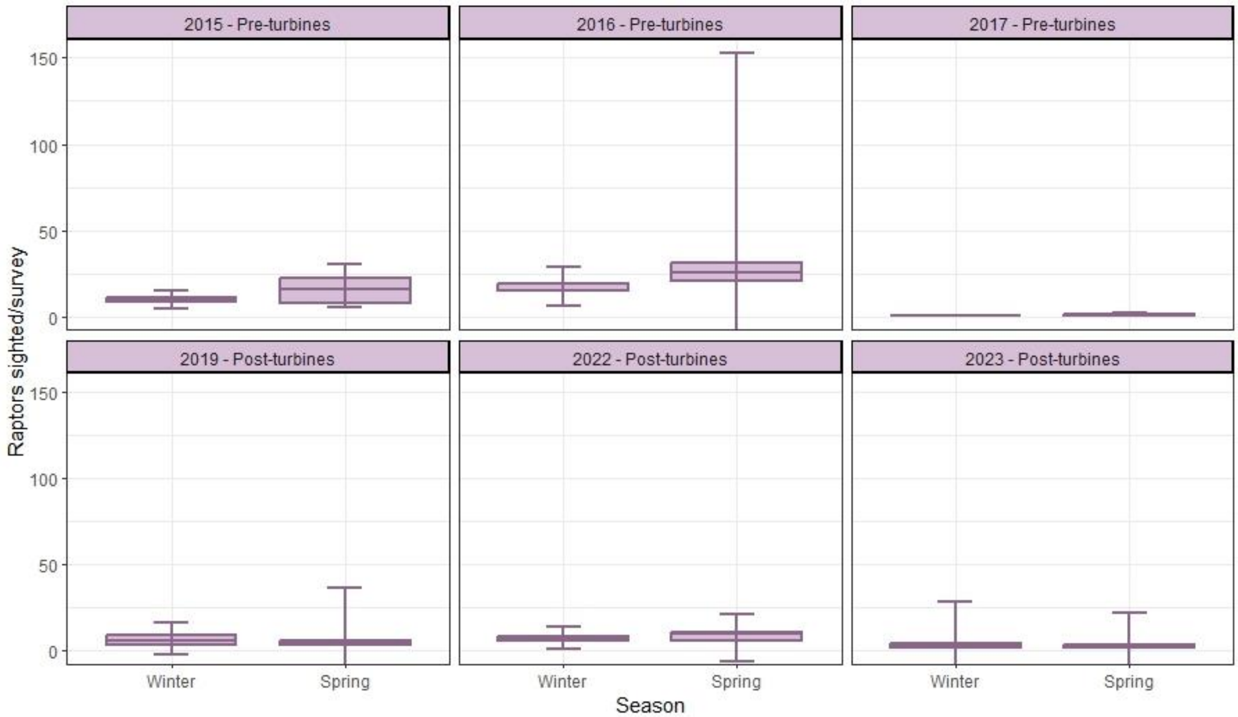

Figure S6. Boxplot of Snowy Owl abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

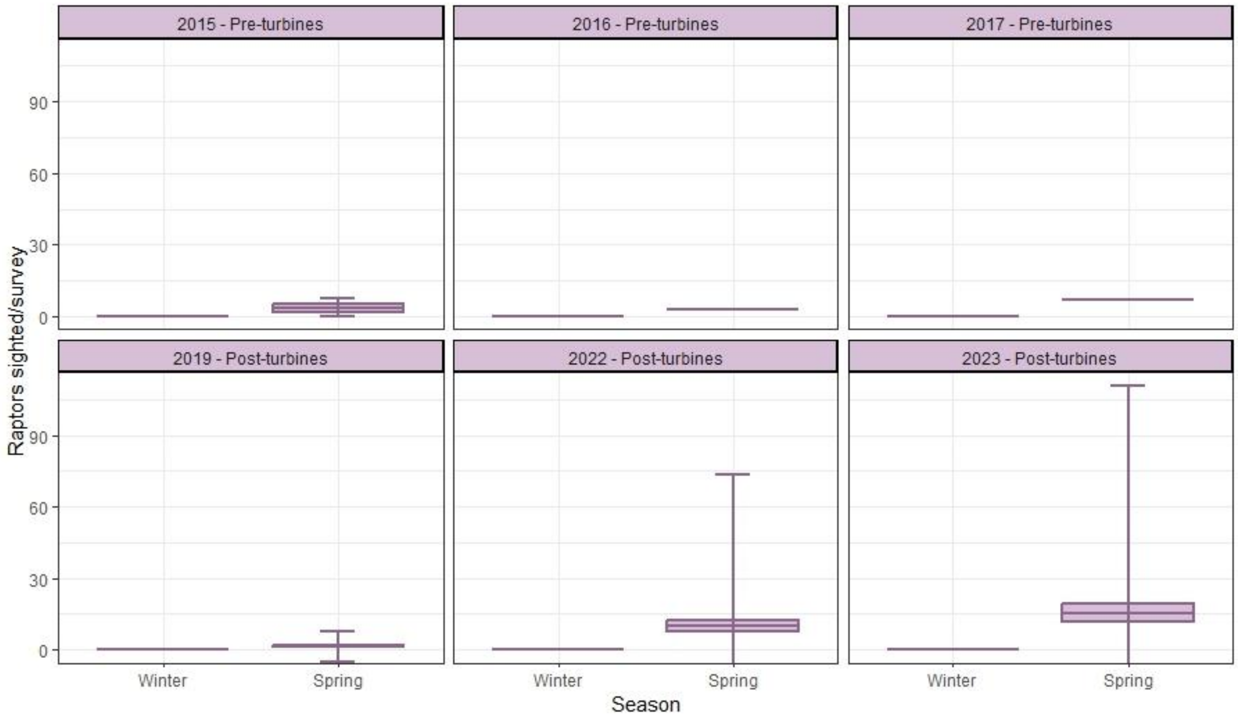

Figure S7. Boxplot of Turkey Vulture abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

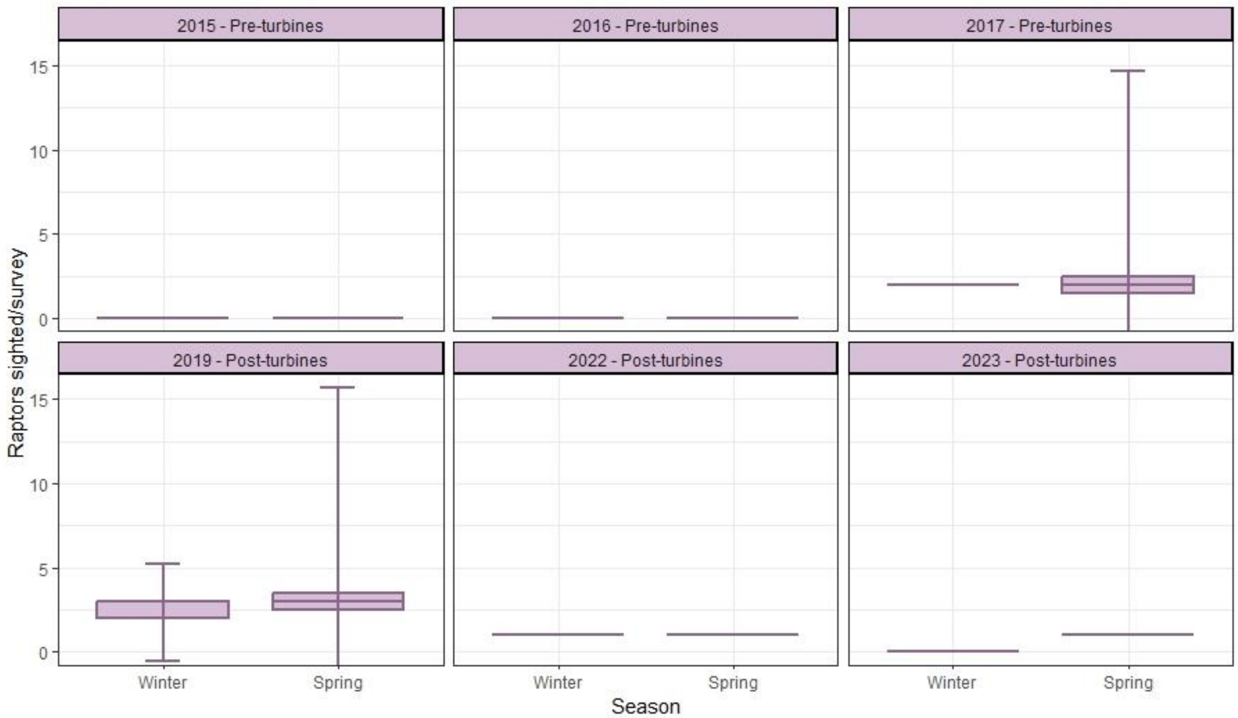

Figure S8. Boxplot of Northern Shrike abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

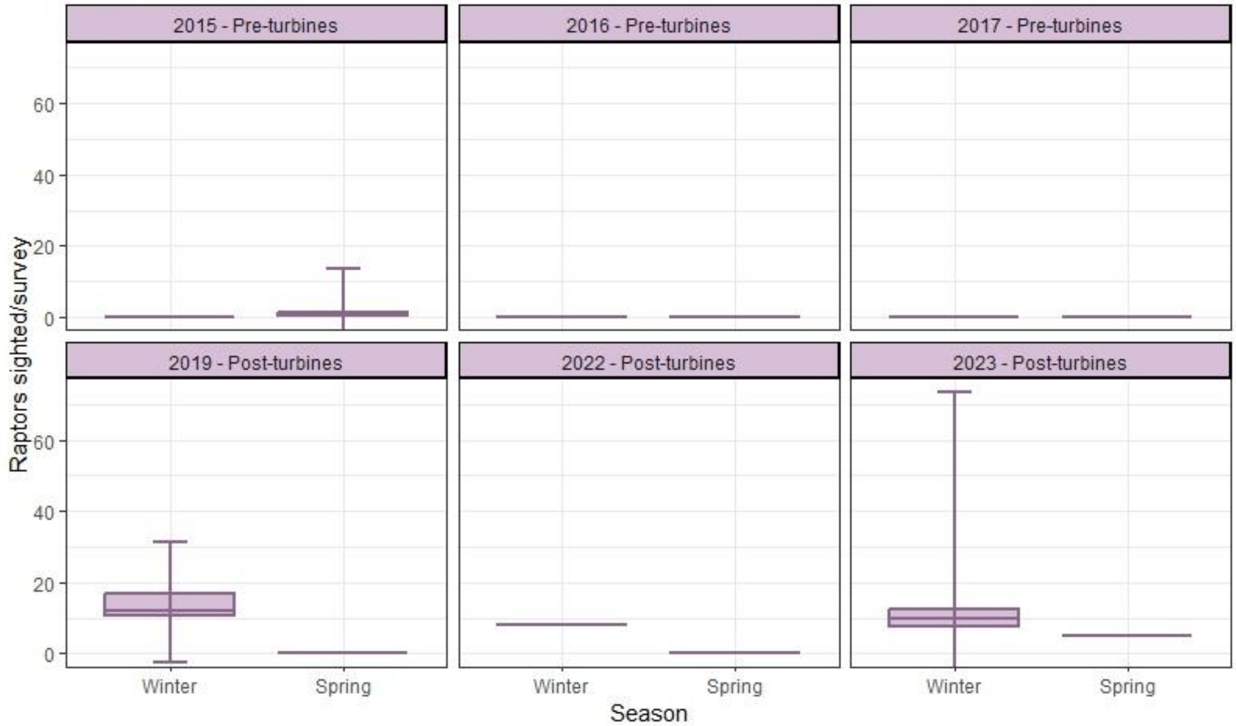

Figure S9. Boxplot of Short-eared Owl abundance on Amherst Island during winter (January and February) and spring (March and April) pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. The center line represents the median abundance, boxes encompass the interquartile range, error bars encompass 95% confidence limits.

Appendix B: Supplementary Maps

Figure S10. Maps of Amherst Island with each American Kestrel observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

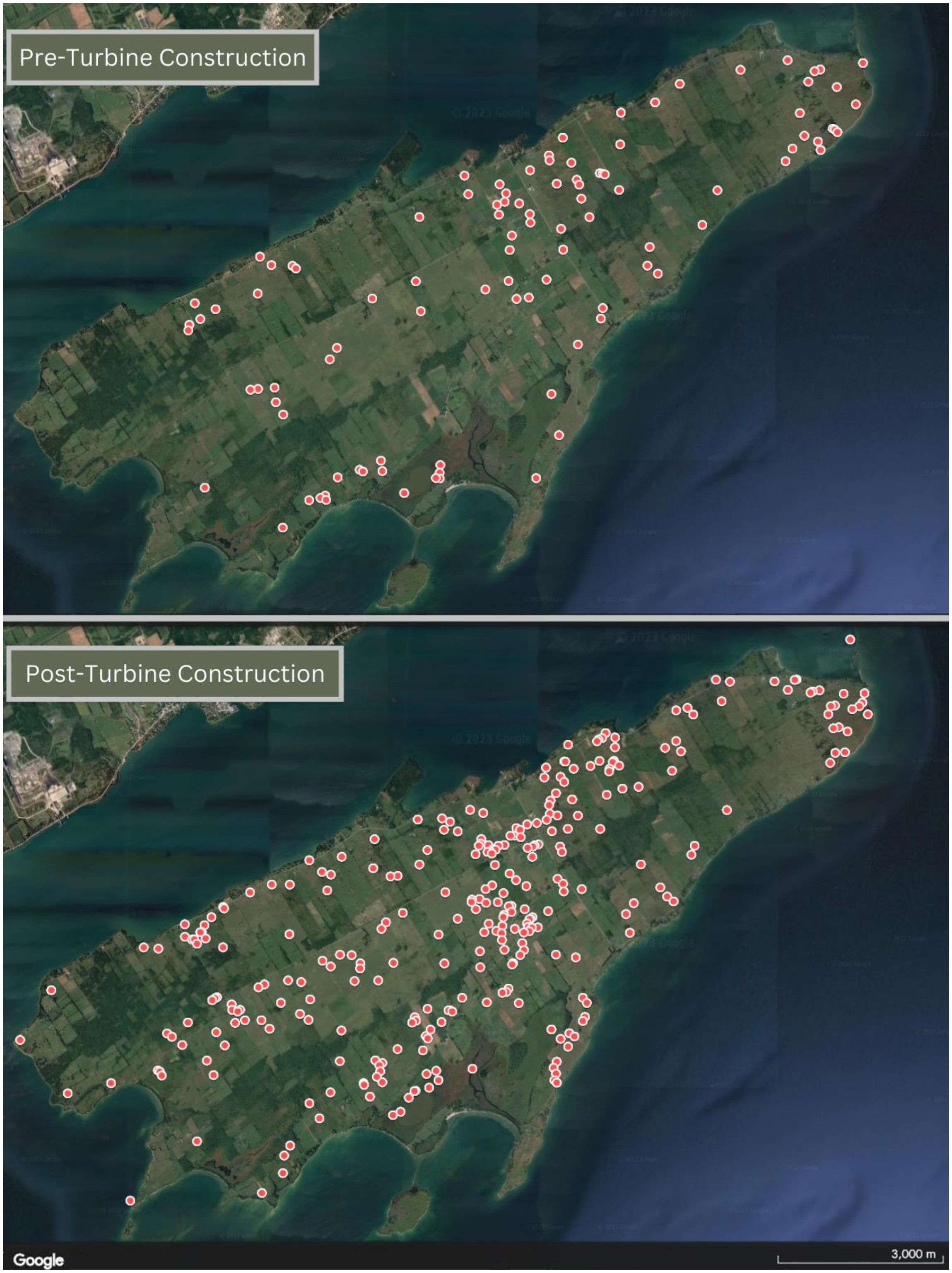

Figure S11. Maps of Amherst Island with each Northern Harrier observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

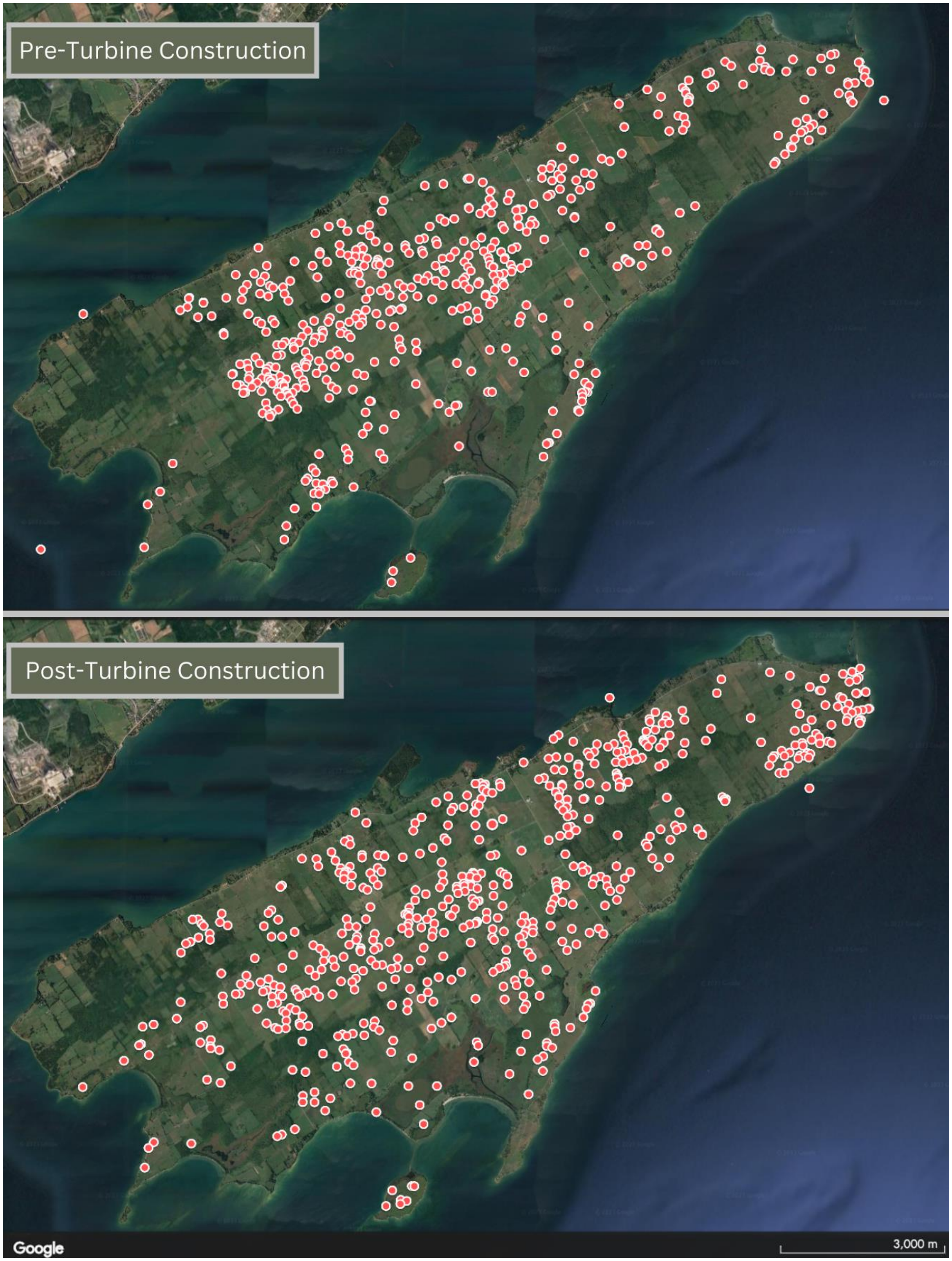

Figure S12. Maps of Amherst Island with each Rough-legged Hawk observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

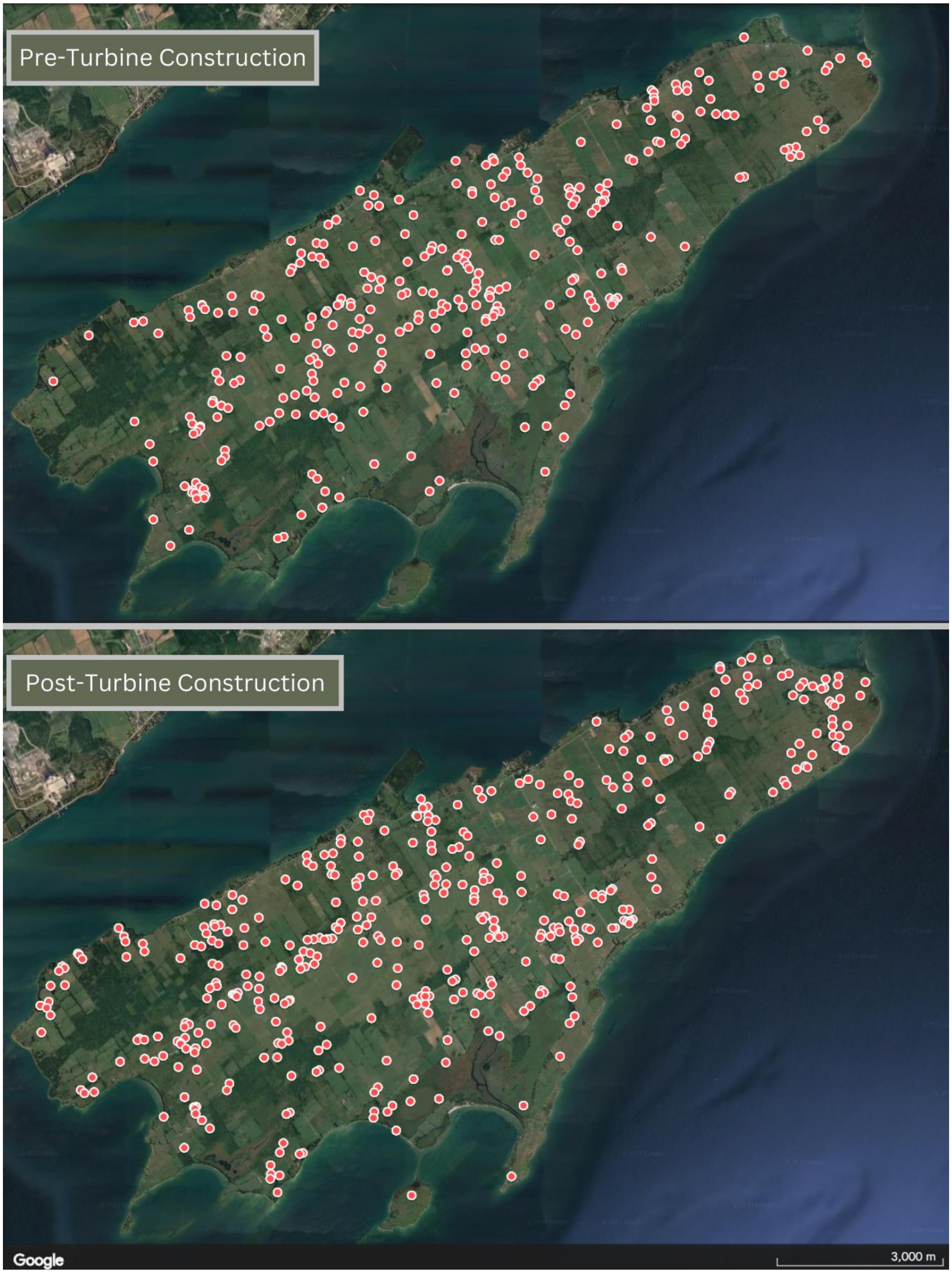

Figure S13. Maps of Amherst Island with each Red-tailed Hawk observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

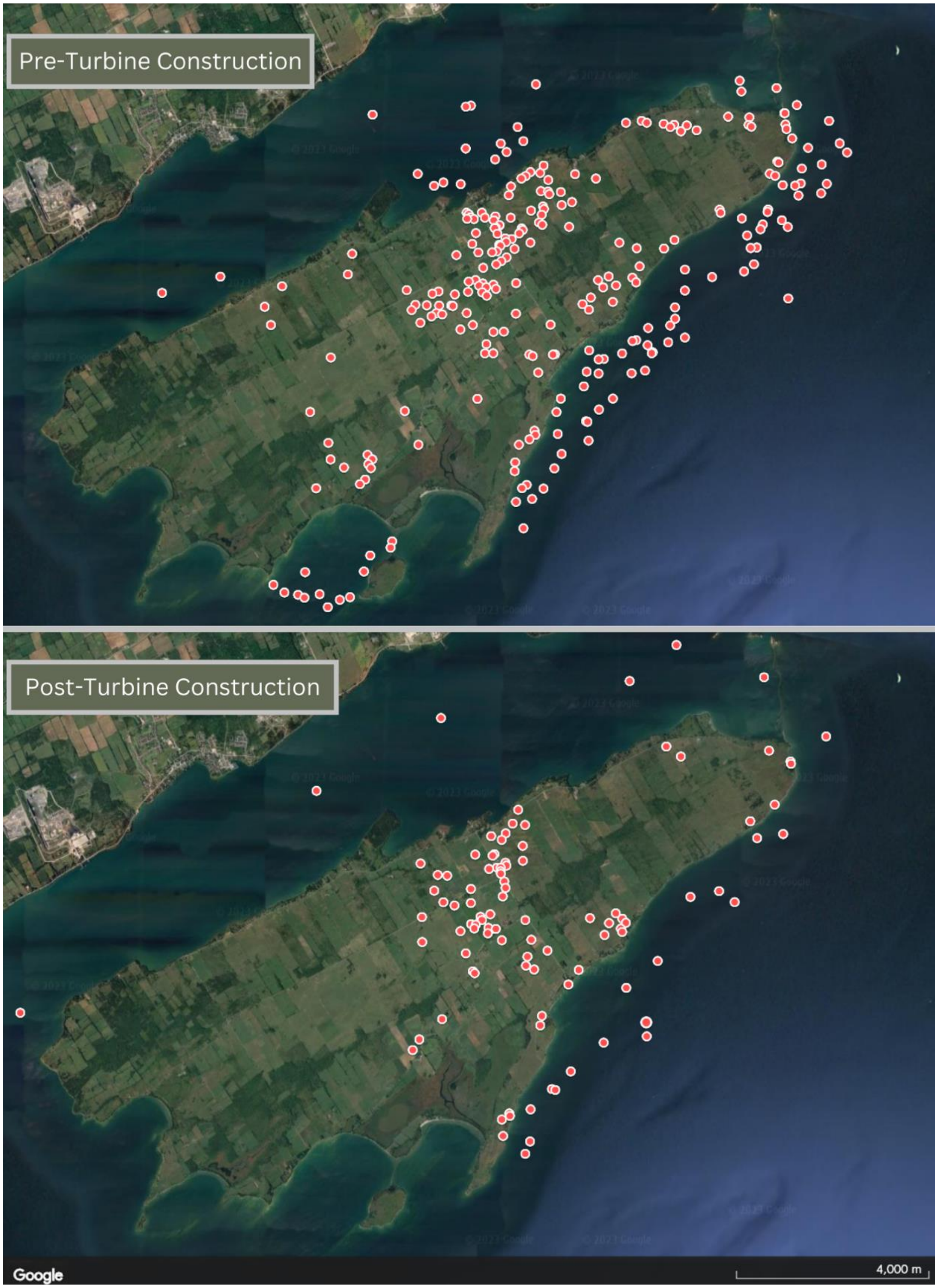

Figure S14. Maps of Amherst Island with each Snowy Owl observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

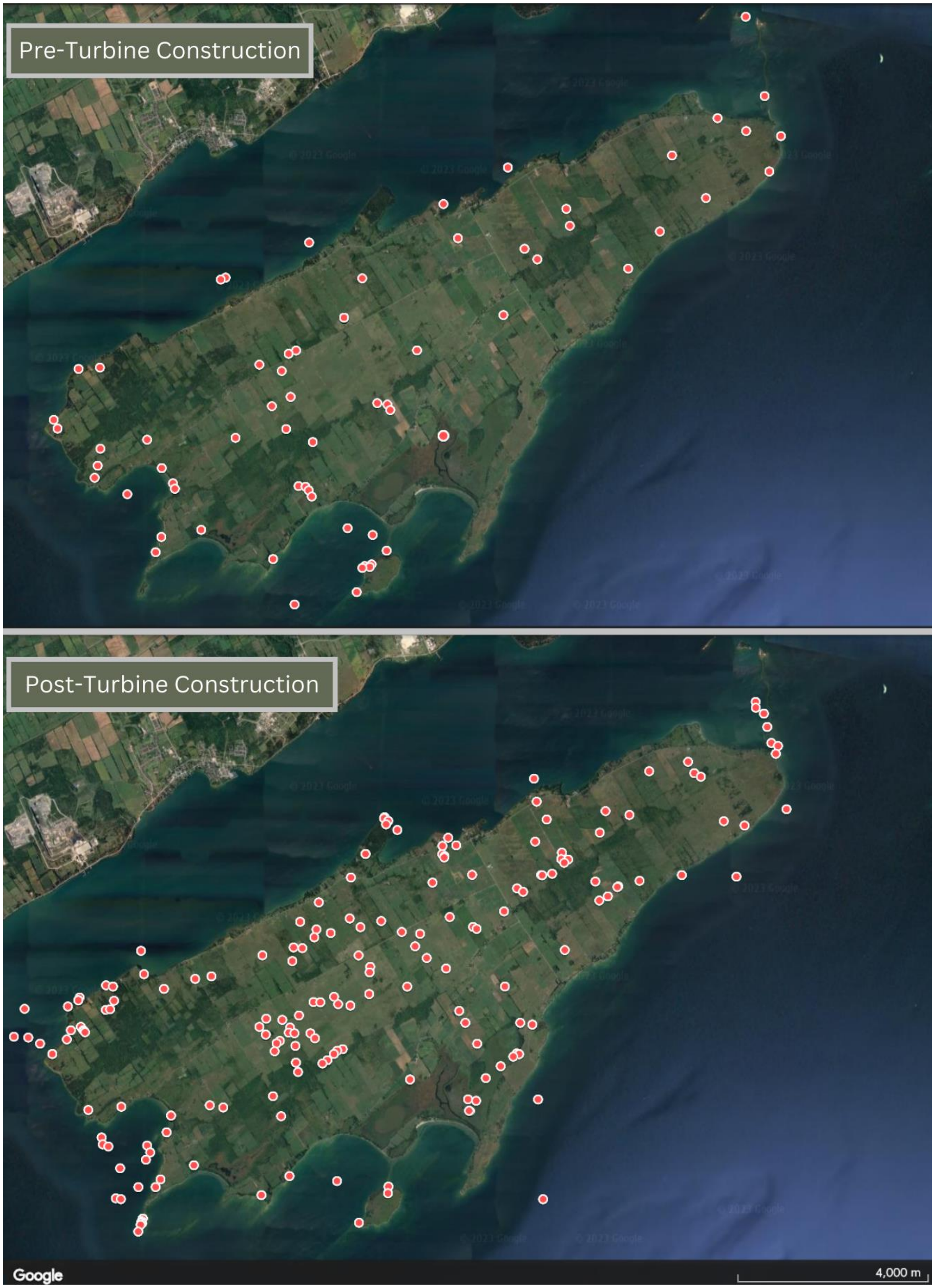

Figure S15. Maps of Amherst Island with each Bald Eagle observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S16. Maps of Amherst Island with each Turkey Vulture observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S17. Maps of Amherst Island with each Osprey observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S18. Maps of Amherst Island with each Merlin observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S19. Maps of Amherst Island with each Great-horned Owl observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S20. Maps of Amherst Island with each Northern Shrike observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S21. Maps of Amherst Island with each Short-eared Owl observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S22. Maps of Amherst Island with each Peregrine Falcon observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S23. Maps of Amherst Island with each Cooper's Hawk observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S24. Maps of Amherst Island with each Red-shouldered Hawk observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.

Figure S25. Maps of Amherst Island with each Golden Eagle observation made during surveys pre- (2015, 2016, 2017) and post- (2019, 2022, 2023) wind turbine construction. Each point represents a single raptor observation.