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Long-Term Changes in Nesting Raptor Communities After Construction of Wind Power Projects

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ABSTRACT.—We evaluated changes in communities of nesting raptors and Common Ravens (*Corvus corax*) in the upper Columbia Basin of the Pacific Northwest, USA, at wind power projects 1–18 yr post-construction. Relative abundance of nests for anthropogenically sensitive species, including Golden Eagles (*Aquila chrysaetos*), Ferruginous Hawks (*Buteo regalis*), and Prairie Falcons (*Falco mexicanus*), declined on project sites ($n = 18$), whereas Common Ravens increased on project sites and reference sites ($n = 4$). We used a Bayesian approach to understand community shifts as driving declines and to determine the effect of wind power vs. other factors on species composition. Golden Eagles, Ferruginous Hawks, and Prairie Falcons each experienced twofold decreases in their proportions in the raptor communities on wind project sites compared to reference sites. Declines on reference sites were consistent with decreasing populations of these species on the larger landscape due to multiple environmental factors. Case histories of territory occupancy for Ferruginous Hawks and Golden Eagles documented over multiple years during the study showed that adult turbine-strike mortality and repeated mortality of replacement adults created localized population sinks. We believe compositional shifts in the nesting guild were also facilitated by increases in competing and/or predatory species more adapted to nesting in altered habitats, principally Common Ravens and Great Horned Owls (*Bubo virginianus*). Commitment to long-term monitoring and establishment of control sites would improve our understanding of the contribution of wind power development to population declines for nesting species that are less tolerant of anthropogenic activities and habitat alterations across landscapes.

KEY WORDS: *community composition*; *population-level effects*; *territory occupancy*; *wind power development*; *wind turbine collision.*

CAMBIOS A LARGO PLAZO EN COMUNIDADES DE RAPACES NIDIFICANTES TRAS LA CONSTRUCCIÓN DE PROYECTOS DE ENERGÍA EÓLICA

RESUMEN.—Evaluamos los cambios en las comunidades de rapaces nidificantes y en *Corvus corax* en la cuenca superior de Columbia, en el noroeste del Pacífico, EEUU, en proyectos de energía eólica de 1 a 18 años después de su construcción. La abundancia relativa de nidos de especies sensibles a las actividades humanas, como *Aquila chrysaetos*, *Buteo regalis* y *Falco mexicanus*, disminuyó en los lugares de los proyectos ($n = 18$), mientras que *C. corax* aumentó tanto en los lugares de los proyectos como en los lugares de referencia ($n = 4$). Utilizamos un enfoque bayesiano para entender los cambios en la comunidad como causantes de las disminuciones y para determinar el efecto de la energía eólica en comparación con otros factores en la composición de especies. Los individuos de *A. chrysaetos*, *B. regalis* y

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F. mexicanus experimentaron una disminución dos veces mayor en sus proporciones en las comunidades de rapaces en los lugares de proyectos eólicos en comparación con los lugares de referencia. Las disminuciones en los lugares de referencia fueron consistentes con la disminución de las poblaciones de estas especies en el paisaje más amplio debido a múltiples factores ambientales. Los historiales de ocupación de los territorios de *B. regalis* y *A. chrysaetos*, documentados a lo largo de varios años durante el estudio, mostraron que la mortalidad de adultos por colisiones con turbinas y la mortalidad repetida de adultos de reemplazo crearon sumideros poblacionales localizados. Creemos que los cambios en la composición del gremio de nidificación también fueron facilitados por el aumento de especies competidoras y/o depredadoras más adaptadas a anidar en hábitats alterados, principalmente *C. corax* y *Bubo virginianus*. El compromiso con el seguimiento a largo plazo y el establecimiento de lugares de control mejoraría nuestra comprensión de la contribución del desarrollo de energía eólica a la disminución de las poblaciones de especies nidificantes que son menos tolerantes a las actividades antropogénicas y a las alteraciones del hábitat en los paisajes.

[Traducción del equipo editorial]

INTRODUCTION

Understanding the impacts of wind energy projects on raptor populations is a topic of global concern (De Lucas and Perrow 2017, Bullock et al. 2024). Raptor research in the context of wind energy impacts has largely emphasized estimating fatalities from turbine strikes (Huso et al. 2016, Hallingstad et al. 2023), improving turbine siting (Smallwood et al. 2017), and identifying tools to reduce collisions (May et al. 2020, McClure et al. 2022). More recently, there has been a recognized need to better understand cumulative and population-scale effects (May et al. 2019, Diffendorfer et al. 2021). An overarching requirement to better understand and remedy all impacts is to improve monitoring methods (Smallwood 2017).

The standard method used to monitor impacts of wind power projects on raptors is to estimate potential mortality of each species using pre-construction surveys and evaluate actual mortality from post-construction surveys conducted a minimum of 1 yr after project completion (US Fish and Wildlife Service 2012). Turbine fatalities are assessed at a confined spatial scale in proximity to turbines (e.g., within 200 m). Fatality thresholds derived during pre-construction are presumed to be appropriate throughout the life of the project (e.g., 30 yr). Mitigation methods are identified and implemented, and if predicted mortality thresholds are exceeded, additional mitigation measures are triggered to reduce mortality or compensate for it.

Although fatality monitoring and subsequent mitigation are vital to address impacts on raptors, this standard approach may have limitations. First, mortalities are rarely differentiated by breeding and migratory status (e.g., local breeders, local nonbreeders, or migrants) unless individuals have been previously marked or telemetered (Hunt et al. 2017). Feather isotope analysis has also been used to determine migratory status of raptors killed in turbine strikes (Katzner et al. 2016, Vander Zanden et al. 2024). This characterization is important if a disproportionate number of local breeding adults are among wind turbine fatalities because resulting mitigation measures may be best directed to maintain the regional nesting population rather than applied to the broader ecoregion. Also, when fatalities can be linked to breeding raptors that have been tracked through marking or telemetry, the mortality data may illuminate the impacts of turbine strikes on local territory occupancy (Hunt et al. 2017, Watson et al. 2018).

A second limitation of fatality monitoring is that it does not address indirect displacement of raptors from project sites. Displacement is difficult to predict before projects are developed and may take several years to assess. For nesting pairs, displacement may occur outright when projects are constructed (i.e., macro- or meso-avoidance; e.g., Walker et al. 2005), or may be manifested over several years depending on the strength of a pair's fidelity to their home range and the attractiveness of the location to new recruits (Farfán et al. 2017, Watson et al. 2018, Crouch et al. 2019). Displacement may result from disturbance, but causes may be unclear (Hötker 2017). Although displacement results in fewer fatal turbine collisions it may also reduce the number of nesting raptors on a project, potentially impacting declining species, and making it important to consider numbers of nests and proportions of species in raptor communities before and after projects are constructed.

Understanding the effects of wind power on long-term changes in populations of raptors necessitates evaluating the degree to which other factors may affect the same populations. Broader declines (or increases) of a species in the landscape due to all sources, and the magnitude of those effects, may

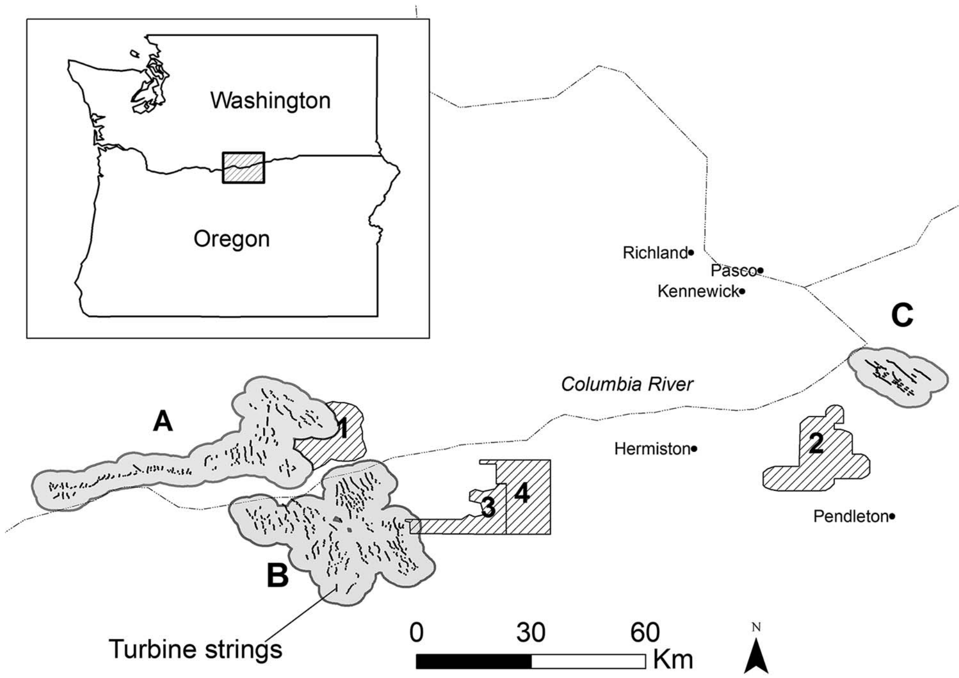

Figure 1. Locations of wind power development areas A, B, and C, encompassing 18 project sites along the Columbia River in Washington and Oregon (USA) where long-term changes in raptor nest use were assessed. Undeveloped (stippled) areas 1, 2, 3, and 4 identify reference sites that provided baseline nest information where raptor nest use was monitored incidentally to the study.

or may not be the same as effects attributed to wind power development. Concurrent monitoring of raptors on wind power developments and reference areas may provide this comparative information. At least four studies have evaluated changes in the number of raptors counted near turbines up to 10 yr post-construction, but none reported nesting trends at comparable reference areas (Farfán et al. 2009, Garvin et al. 2011, Campedelli et al. 2013, Dohm et al. 2019).

We evaluated raptor and Common Raven (*Corvus corax,* hereafter raven) nest use in a raptor guild along the Washington-Oregon border in the western USA in 18 closely associated wind development projects 1–18 yr after construction. We included ravens because they can compete with raptors for nest structures (Steenhof et al. 1993, Sullivan et al. 2011), consume raptor eggs or small young (Brambilla et al. 2004), or kleptoparasitize raptor nests (Simes et al. 2017). Our objectives were to: (1) document changes in the relative abundance of occupied nests for each species among all projects between pre-construction surveys and surveys in 2020 and 2021; and (2) evaluate the direction and magnitude of change in the proportion of each species within the raptor communities attributed to both wind power and other sources by studying reference sites. We augment analysis of trends in nest use with case histories of territory occupancy in the study area where adults suffered turbine fatality possibly leading to changes in species use or vacancy. We were particularly interested in evaluating potential changes in nesting populations of Ferruginous Hawks (*Buteo regalis*), state-listed as endangered in Washington and critically sensitive in Oregon, and Golden Eagles (*Aquila chrysaetos*), designated a species of greatest conservation need in Washington and protected in Oregon.

METHODS

Study Area. We studied raptors near the mid-Columbia River in southern Washington and northern Oregon, USA (Fig. 1). The study area consisted of three areas of development <40 km from the Columbia River: area A in Washington contained eight project sites, area B in Oregon contained nine project sites, and area C contained one project site. Wind power projects began operation in the study

Table 1. Characteristics of wind power project sites and reference sites near the Columbia River where raptor nests were surveyed to assess long-term changes in species use.

Site	Name	State	Area[a] (km^2)	First[b] Survey Year	Second[c] Survey Year	Year Project Site Operational	No. Turbines	Rated Capacity (MW)
Project	Bighorn I	WA	176	2003	2020	2007	133	200
	Bighorn II	WA	106	2003	2020	2011	25	50
	Juniper Canyon I	WA	153	2007	2020	2010	63	151
	Goodenoe Hills	WA	101	2007	2021	2008	47	94
	Windy Point I	WA	161	2007	2021	2009	82	137
	Windy Point II	WA	93	2009	2021	2009	37	85
	Harvest Wind	WA	137	2007	2021	2009	43	99
	White Creek	WA	147	2004	2021	2007	89	205
	Stateline	WA/OR	185	2001	2021	2003	452	307
	Rattlesnake	OR	105	2007	2021	2008	49	103
	Willow Creek	OR	76	2007	2021	2009	48	72
	Wheatfield	OR	89	2007	2021	2009	46	97
	Montague	OR	153	2017	2021	2019	56	201
	Leaning Juniper I	OR	129	2005	2021	2006	67	101
	Leaning Juniper IIa	OR	159	2005	2021	2011	43	90
	Leaning Juniper IIb	OR	124	2009	2021	2011	74	111
	Pebble Springs	OR	138	2006	2021	2009	47	99
	Shepherd's Flat[d]	OR	522	2003	2021	2012	338	845
Reference	Area 1	WA	118	2007	2020	NA	NA	NA
	Area 2	OR	232	2001	2021	NA	NA	NA
	Area 3	OR	114	2001	2019	NA	NA	NA
	Area 4	OR	151	1995	2022	NA	NA	NA

[a] Extent of project sites used to define area was 3.2 km from the outermost turbines.
[b] First surveys were pre-construction surveys at project sites, and initial surveys at reference sites.
[c] Second surveys were post-construction surveys at project sites, and final surveys at reference sites.
[d] North, central, and south Shepard's Flat project sites combined.

area as early as 2003. In 2021 the 18 project sites occupied 1682 km^2 and supported 1723 turbines that generated a maximum output of 3047 MW (Table 1). Individual project site boundaries extended 3.2 km from the outermost turbines, so some sites overlapped. Habitat alterations within project sites included strings of turbines often situated along ridgelines or elevated ground, graded turbine pads and gravel access roads, and electrical infrastructure. Potential disturbances and impacts within sites were mainly rotating turbine blades, low-intensity vehicle traffic, and human presence associated with turbine maintenance. We identified, post hoc, four undeveloped reference sites collectively in proximity to project sites where raptor nest use was monitored throughout the study (Fig. 1). These reference sites provided a baseline for changes in nest use comparable to project sites.

Topography in this portion of the Columbia River Basin ranged up to 700 masl in elevation and included large, sloping hillsides along the river and smaller valleys and draws that bisected more level uplands. This portion of the basin was in the rain shadow of the Cascade Mountain Range resulting in hot and dry summers and cold, overcast winters. Dry-land and irrigated agriculture were interspersed with rangeland used primarily for cattle and sheep grazing. Few vegetation communities remained undisturbed throughout the study area. Sagebrush (*Artemisia* spp.) and rabbitbrush (*Ericameria nauseosa*) were mixed among annual grasses or in remnant patches along with areas of lithosol soil. Cheatgrass (*Bromus tectorum*) was prevalent in heavily grazed pastures and intensively burned areas.

Diurnal raptors nested throughout the study area on cliffsides as well as in trees including black cottonwood (*Populus trichocarpa*), western juniper (*Juniperus occidentalis*), and Douglas fir (*Pseudotsuga menziesii*). Ferruginous Hawks were most often associated with shrub-steppe habitats or native grasslands found on talus slopes and hills that were too steep to cultivate.

Golden Eagles built nests on cliffs or large trees in the same habitats. Both species also used nests in relatively level landscapes in between valleys but nests were typically in more isolated areas devoid of human activity. Scrapes of Prairie Falcons (*Falco mexicanus*) and Peregrine Falcons (*F. peregrinus*) were found on prominent cliffs or talus slopes where Barn Owl (*Tyto alba*; recently reclassified as American Barn Owl [*Tyto furcata*] by the American Ornithological Society) nest cavities were also located. Red-tailed Hawks (*Buteo jamaicensis*) and ravens used cliffs for nesting structure, but also nested on windbreak trees and transmission towers in mixed cropland and native habitats. Swainson's Hawks (*B. swainsoni*) and Great Horned Owls (*Bubo virginianus*) frequently nested in old raptor nests in exotic or native homestead trees adjacent to agricultural land. Bald Eagles (*Haliaetus leucocephalus*) and Osprey (*Pandion haliaetus*) nested in dominant trees or snags in proximity to the Columbia River.

Project Sites. *Pre-construction surveys.* We compiled pre-construction raptor nest use information from unpublished reports and internal documents provided by developers or consultants to county or state permit offices that evaluated projects when they were proposed. Essential information in reports included survey dates and times, nest locations, species using each nest, and nest status as unused or used (defined by the presence of a perched adult, incubating adult, eggs, or young), with some reports providing information on type of nest substrate (e.g., tree, cliff, power pole). Most projects included exact geographic coordinates of nests. For other projects, we used report maps to digitize locations. Accuracy of digitized locations was adequate for temporal analyses because it did not require that we revisit prior nest locations. The probability of detecting nests was not determined during any pre-construction surveys. However, we estimated probability of nest detection during post-construction surveys (described below) that confirmed a very high degree of reliability in counts of nests using the same methodology. Thus, for our analyses, we assumed a high rate of detection during pre-construction surveys. We gathered additional information for project sites including initiation dates for construction and operation, the total number of turbines, and the total power output for each project from direct communication with project owners, public reports, or press releases (Table 1).

Pre-construction survey protocols were the same or very similar among projects because they were directed by state and federal guidelines provided to developers and were often conducted by the same consultants. For a few projects, consultants conducted pre-construction surveys to gather baseline information over large survey areas that were not project-specific followed by project-specific surveys. In those cases, we used the project-specific survey information that was also closer to time of project construction ($\bar{x}$ interval = 3 ± 2 [SD] yr). Most surveys were conducted during one breeding season, by helicopter, with the intent to record all observed raptor nests, used and unused, within the 3.2-km project boundary. Additional data recorded for each nest included nesting species and evidence confirming nest use (see above definition). There were two notable exceptions: the Goodenoe Hills project site in area A (Fig. 1) where consultants surveyed with a 1.6-km buffer that was supplemented out to 3.2 km with Washington Department of Fish and Wildlife survey information; and the Shepherd's Flat project site in area B that was surveyed from the ground. We conducted a sensitivity analysis before including the latter project to confirm that significance ($\alpha = 0.05$) of results did not change for any of the monitored species.

Pre-construction surveys were scheduled after most raptors finished incubating eggs or brooding young but prior to the onset of leaf out to increase visibility of nestlings in nests (15 April–15 May). This scheduling was intended to maximize the accurate assessment of nest use for the most species. There was potential underestimation of nest use, albeit likely small, for the adults that were absent at any failed nests for the earliest nesting species (e.g., Great Horned Owl, Golden Eagle, and Red-tailed Hawk), or at any nests that had not yet been initiated for later nesting species (e.g., Swainson's Hawk). Searches included areas with natural and artificial elevated structures such as cliffs and talus along valleys, tree stands, lone trees, transmission towers, and windmills.

Post-construction surveys. We conducted post-construction surveys in 2020 and 2021 following the protocols used during pre-construction surveys. That included helicopter surveys to locate used and unused nests within 3.2-km of project buffers, conducted during the same survey months, and documenting the same nest information without prior knowledge of nest locations. Each of our surveys were conducted by the same observer working with the same assistant to be able to estimate probability of detection of a nest using the double-observer approach (Nichols et al. 2000). The pilot was directed to fly to all areas with elevated structures and the two observers independently searched for nests during each helicopter pass. When the primary observer located a nest, he marked the waypoint. At the end of the pass, he inquired and recorded whether the secondary observer, observing from the same field of view, saw the nest or conversely, whether there were nests he did not see but were seen by the secondary observer. The pilot was then instructed to repeat the pass if a nest was only seen by one observer.

Between pre-construction and post-construction surveys from 1999 to 2014 we conducted annual territory occupancy surveys at Ferruginous Hawk and Golden Eagle territories in the study area as part of other investigations (Watson et al. 2014, 2018, R. Gerhardt unpubl. data). During this period, we also recorded mortality of breeding adults on these territories as reported by raptor rehabilitation facilities, biologists, and wind power companies. We summarize case histories on these territories to provide a qualitative perspective on the evolution of nest use leading to territory vacancy or species replacement.

Reference Sites. Four undeveloped reference sites in proximity to project areas provided baseline raptor and raven nest use data for qualitative comparisons of nest counts (Fig. 1, Table 1). Reference sites were inappropriate for use as controls in a Before-After Control-Impact design because they were only identified post construction, were surveyed with varied survey protocols, and were not paired with projects. Two reference sites were slated for wind power development so were surveyed at the same time nearby projects were surveyed during pre-construction. During post-construction, we resurveyed these two areas using the same protocols that we used on developed areas. These areas were under private ownership and not restricted from other uses. The first area (area 1) was first surveyed in 2007 (Northwest Wildlife Consultants Inc., internal document, 2008) and we resurveyed it in 2020. The second area (area 2) was surveyed in 2001 (FPL Energy, Ch2M Hill, internal document 2000) and we resurveyed it in 2021. The other two reference sites were the Boardman Conservation Area (area 3), that was surveyed annually by ground by The Nature Conservancy from 2001 through 2019 (Langevin and Wallis 2020), and The Naval Weapons Systems Training Facility Boardman (area 4) that was surveyed periodically by ground by the US Department of Defense from 1995 through 2022 (J. Phillips, Dept. of Defense, unpubl. data). Areas 3 and 4 had controlled access. We used the first and last survey years on these two reference sites to derive changes in the number of nests for each species during the post-construction period.

Analysis. *Change in nest counts.* For each species, we tabulated pre- and post-construction nest counts for project sites and initial and final nest counts for reference sites. A few nests, found during both pre- and post-construction, were located within overlapping project boundaries. We assigned these nests to the project that was constructed first, recognizing use of these nests was influenced by more than one project but the effect on modeled outcome was minor. For nine projects surveyed in both 2020 and 2021, we used the larger of the two counts in this analysis.

We analyzed change in nest counts by species between first and last surveys for project and reference sites using generalized linear mixed-effects models (PROC MIXED, SAS 9.4 SAS Institute, Cary, NC, USA). We modeled species as a main effect, with an intercept term for each project site as a cross-species random effect. Due to comparatively small sample sizes, and their shared sensitivity to wind-power development (Diffendorfer et al. 2021), we pooled counts of Ferruginous Hawks, Golden Eagles, and Prairie Falcons into one group (i.e., sensitive species) for these analyses.

Change in species composition. To identify compositional shift in the raptor and raven communities between pre- and post-construction periods we considered the number of nests for each species as a proportion of the total nests used across all species and modeled the difference in species composition at the site level (site = project site or reference site) using a Bayesian approach. We computed the 95% highest posterior density (HPD) intervals for each estimated proportion (Hyndman 1996) and effect size probabilistically, based on the mass of the posterior distribution (Ellison 1996). We chose this modeling approach to improve the precision of estimates due to relatively small datasets by borrowing strength across study areas and time periods. We compared proportions of species between pre-construction and post-construction periods independently for project and reference sites to determine the effect of wind power vs. other factors on species composition. The number of nests belonging to species i at site j in period k (pre vs. post) was considered a count from a multinomial distribution of the total number of nests at the site for that period (Eq. 1). The 22 sites were further split to 18 project sites and four reference sites such that:

$$Y_{ij(k)} \sim Multi\left(\theta_k, \sum Y_{j(k)}\right) \text{ where } \sum \theta_{ij(k)} = 1_{j(k)}$$
$$\text{and } k \in \{pre4, pre18, post4, post18\} \qquad \text{(Eq. 1)}$$

and placed a noninformative canonical Dirichlet prior for θ_k with an equal weight of 1 for all species or species groups.

We used JAGS 4.3.1 for Markov Chain Monte Carlo sampling (Plummer 2003) called from R-

4.2.2.patched with the *rjags* package (Plummer 2022, R Core Team 2023). After a burn-in period of 1000 iterations, we ran three chains with independent starting values for 75,000 iterations at a thinning rate of 150 for an effective sample of approximately 1500 independent draws from the joint posterior. We determined convergence through inspecting trace plots, ensuring $\hat{R}$ was less than 1.1 (Gelman and Rubin 1992) and having no within-chain auto correlation.

Detection probability. For both survey years, we used program PRESENCE to model a single-season, two-survey model with removal (MacKenzie et al. 2006) to compute the mean probability of detecting a nest during post-construction surveys with 95% confidence intervals. The model used the maximum likelihood estimator without the need for parameterizing temporal variation between surveys, and we assumed each observer (same observers across all surveys) was equally proficient. We planned to reduce bias of naïve nest counts in post-construction by adjusting them through detection probability prior to temporal and spatial analyses, but very high detection rates (e.g., 98%) provided no added benefit to raw counts for making inferences across time periods.

RESULTS

Relative Abundance. During pre-construction surveys, biologists recorded 140 used raptor and raven nests at the 18 project sites (Fig. 2A). During post-construction surveys, we recorded 444 used raptor and raven nests. At four reference sites, we recorded 55 and 157 used raptor and raven nests during initial and final surveys, respectively. The probability of detecting nests via helicopter was very high in both 2020 ($\hat{p} = 0.988$; 0.973–0.994) and 2021 ($\hat{p} = 0.981$; 0.967–0.990). Due to the very high probability of detecting nests, we used raw counts to estimate relative abundance and determine species composition.

Relative abundance of most species changed significantly on wind power projects over time with ravens experiencing the largest positive increases in the number of nests, followed by Swainson's Hawks and Red-tailed Hawks (Table 2). The number of Great Horned Owl nests tended to increase (Table 2). In contrast, sensitive species collectively decreased significantly on wind project sites. On reference sites, all species experienced the same directional changes in nest numbers compared to wind project sites, but the only significant change over time was increased nesting by ravens (Table. 2).

Species Composition. The proportion of nests for most species within communities increased or decreased over time consistently on both project sites and reference sites (Fig. 2B). Golden Eagles experienced the greatest magnitude of change within communities (Table 3) declining proportionally on both project sites (13×) and reference sites (6×), followed by declines of Ferruginous Hawks (8× and 4×, respectively) and Prairie Falcons (4× and 1×, respectively). Thus, the magnitude of decline for each of the sensitive species within communities on projects was over twice the magnitude of decline on reference sites. Although HPD intervals overlapped zero for Golden Eagles and Prairie Falcons, reflecting uncertainty associated with the low number of reference sites in our sample, the mass of the posterior distributions was less than zero suggesting some level of decline rather than no change (Table 3). Red-tailed Hawks and Swainson's Hawks were the only species with apparent proportional decreases in nesting on project sites but increases on reference sites over time (Fig. 2B). However, the magnitude of proportional changes was small (i.e., 1×) compared to other species, and except for declines of Red-tailed Hawks on projects, there was no support for any one direction of change (Table 3). The magnitude of proportional increases in nesting Great Horned Owls tended to be higher, especially on reference sites (3×), and ravens increased similarly on project sites (4×) and reference sites (3×). Comparative changes in other species were substantially different between project and reference sites, largely reflecting increased nesting by Peregrine Falcons, Bald Eagles, Osprey, and Barn Owls on project sites adjacent to the Columbia River.

Case Histories. On seven Ferruginous Hawk territories within the study area where adults suffered turbine-strike fatality, in the next generation two nest trees were used by Great Horned Owls, two nest trees were vacant, one tree was used by ravens, one nest tree was used by Swainson's Hawks and Ferruginous Hawks in alternate years of our study, and one nest tree continued to be used by Ferruginous Hawks. On four Golden Eagle territories where at least one adult suffered turbine strike fatality, we documented no nesting activity in 2020–2021 (J. Watson unpubl. data). On one of these unoccupied territories, there was a repeated pattern of replacement of adult eagles in years prior to vacancy: first, an adult male was shot in 2007, then a replacement male was hit by a turbine blade in 2011, and after that a replacement male died from unknown causes but <600 m from a turbine in

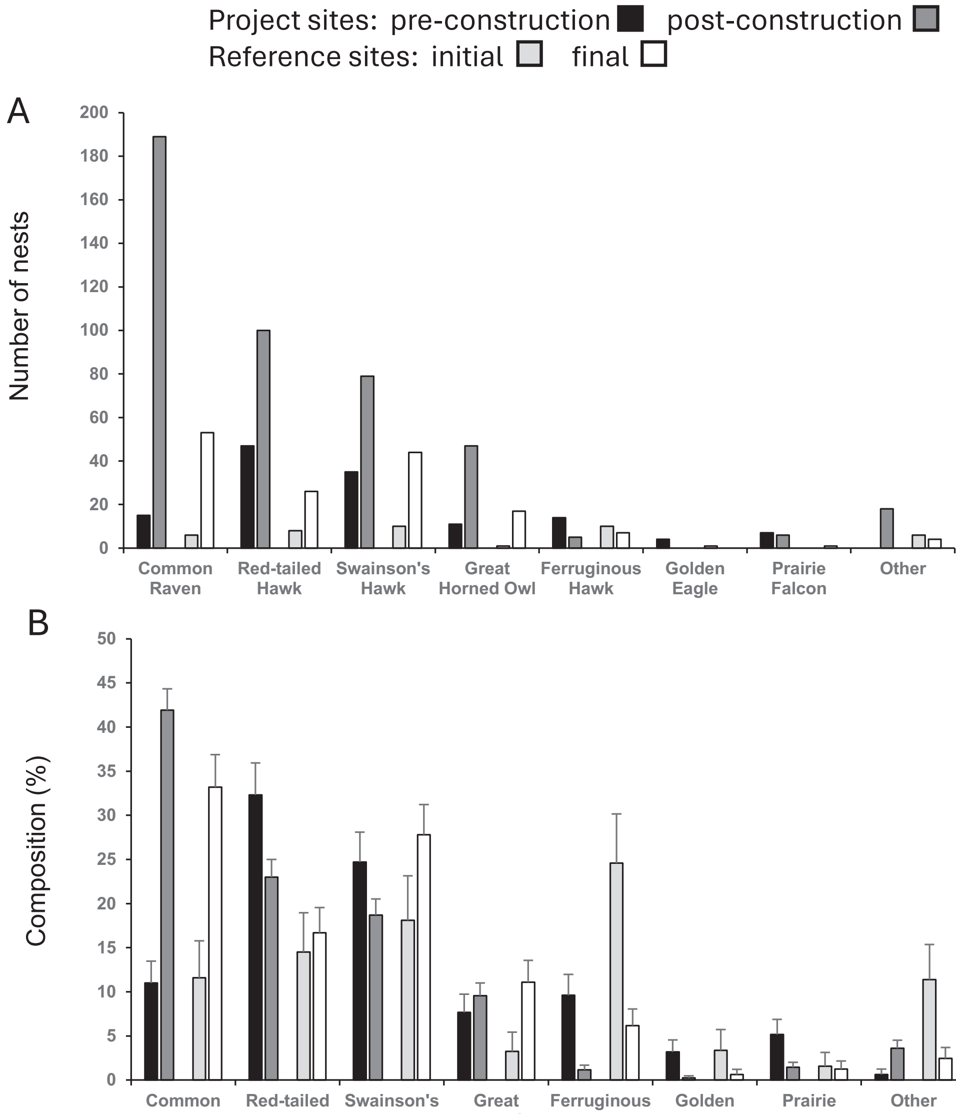

Figure 2. Pooled counts of raptor and raven nests recorded during four types of surveys (A) and proportion of nests among all species represented by posterior means (%) and SDs (B). Nests were studied at 18 wind power project sites and four reference sites with pre-construction and post-construction surveys separated by ≤18 yr. Other species included Peregrine Falcon, Bald Eagle, Osprey, and Barn Owl.

2014. A similar pattern of progressive turbine-strike fatalities of three adults was noted within another territory on the study area in 2011 and 2012. Overall, mortality from turbine strikes was recorded for at least one individual of ravens and the six raptor species on at least one of the 18 projects we studied.

DISCUSSION

Stewart et al. (2007) emphasized the need for better evidence-based assessments of negative impacts of windfarms on bird populations. To that end, our study demonstrates the need for (1) long-term monitoring of nesting populations on wind

Table 2. Changes in relative abundance of raptor and raven nests on 18 wind power project sites and at four reference sites near the Columbia River. The interval between pre-construction and post-construction periods was ≤18 yr. Parameter estimates were derived from general linear mixed models with project modeled as a random effect. Statistically significant results are given in bold.

	Project Site				Reference Site			
Species	Estimate	SE	*t*	*P*	Estimate	SE	*t*	*P*
Common Raven	10.12	1.06	9.50	**<0.0001**	10.50	4.28	2.45	**0.032**
Red-tailed Hawk	2.90	1.04	2.79	**0.007**	4.80	4.88	0.98	0.347
Swainson's Hawk	2.80	1.13	2.47	**0.016**	8.25	4.28	1.93	0.080
Great Horned Owl	2.09	1.13	1.85	0.069	4.14	4.88	0.85	0.416
Sensitive[a]	−6.71	2.60	2.58	**0.012**	−1.00	4.28	0.23	0.819
Other[b]	2.30	1.46	1.57	0.120	−0.67	5.91	0.12	0.908

[a] Raptors associated with native shrub-steppe ecosystems and documented sensitivity to anthropogenic impacts including Ferruginous Hawk, Golden Eagle, and Prairie Falcon.

[b] Peregrine Falcon, Bald Eagle, Osprey, and Barn Owl.

projects, (2) concurrent monitoring of reference sites, and (3) analysis of the shifting compositions of raptor communities.

Long-term Monitoring. Changing relative abundances of the species we studied reflected a range of adaptability to and tolerance of anthropogenic change manifest over several nesting seasons. At one extreme we documented reduced relative abundance of nesting Ferruginous Hawk, Golden Eagle, and Prairie Falcon and reaffirmed that these species are at increased risk for long-term declines in nesting from wind power development (Beston et al. 2016, May et al. 2019, Diffendorfer et al. 2021). Declining numbers of nesting pairs of Ferruginous Hawks and extirpation of nesting Golden Eagles on project sites was striking and reflected the documented susceptibility of these species to anthropogenic disturbance in native habitats (Bechard et al. 1990, Steenhof et al. 1999, Watson et al. 2014, Kolar and Bechard 2016, Spaul and Heath 2017).

Next, we found moderate changes in nesting by Great Horned Owl, Red-tailed Hawk, and Swainson's Hawk. Although these species experienced wind turbine mortality (J. Watson, unpubl data), they likely benefited from associated landscape changes that mitigated loss of individuals. The number of nesting Great Horned Owls increased on both project and reference sites; this species has a comparatively lower potential for population impacts from wind power development (Diffendorfer et al. 2021). They make regular use of human structures for nesting (Olendorff 1973, Bohm 1977, Steenhof et al. 1993, Stout et al. 1996, Howe et al. 2014), and like Red-tailed Hawk and Swainson's Hawk, Great Horned Owls have generalized diets (Sherrod 1978) that contribute to their adaptability. The latter two species may be susceptible to population impacts from wind power development (Diffendorfer et al. 2021). However, the smaller magnitude of change in the number of nests of both species on our project sites, and increases on reference areas demonstrated their anthropogenic tolerance (Schmutz 1984, Schmutz 1987, Knight and Kawashima 1993, Berry et al. 1998, Coates et al. 2014, White et al. 2017, Boal 2018).

At the other extreme, the substantial increase in the number of ravens nesting reflected the nature of a synanthropic species that is not just more tolerant of anthropogenic change, but directly benefits from it (Marzluff and Neatherlin 2006, Webb et al. 2011). Recent proliferation of this species is in part due to its ability to adapt and thrive in human-altered habitats (Boarman et al. 2006, Harju et al. 2021), including areas with energy infrastructure that provide nest structures (Marzluff and Neatherlin 2006, Bui et al. 2010, Coates et al. 2014) and anthropogenic food sources like landfills (Restani et al. 2001). Two landfills within our study area and a proliferation of electrical infrastructure likely contributed to the raven population growth we observed.

These results affirm that monitoring of wind development impacts should include multi-generational assessment of sensitive species not provided through short-term (e.g., 1 yr) fatality monitoring. Case histories of Ferruginous Hawk and Golden Eagle territories suggest potential recruits to disturbed territories may avoid the area and the territory may become vacant over multiple years. Alternatively, if the perceived risk by new recruits is low but the actual risk high, the result may be progressive loss of adults due to turbine strikes and the creation of an ecological trap/sink. Eventually, these territories may be occupied by more adaptable species, resulting in a

Table 3. Magnitude and direction of long-term changes in the composition of the avian community accounted for by individual species nesting on wind power project sites and reference sites. Intervals in bold indicate highest certainty in trend.

	Project Site		Reference Site	
Species	Magnitude[a]	95% HPD[c]	Magnitude[b]	95% HPD[c]
Golden Eagle	−12.76	**−infinity, −3.37**	−5.45	−infinity, 1.28
Ferruginous Hawk	−8.23	**−38.86, −3.87**	−3.98	**−10.27, −2.17**
Prairie Falcon	−3.57	**−16.44, −1.56**	−1.27	−84.83, 14.07
Red-tailed Hawk	−1.40	**−1.83, −1.08**	1.15	−1.89, 2.27
Swainson's Hawk	−1.32	−1.82, 1.05	1.54	−1.25, 2.79
Great Horned Owl	1.25	−1.68, 2.23	3.43	−1.80, 20.06
Common Raven	3.82	**2.28, 5.97**	2.86	**1.28, 6.05**
Other[d]	5.70	−1.35, 101.04	−4.65	**−35.58, −1.76**

[a] Pre-construction posterior $\bar{x}$ %/post-construction posterior $\bar{x}$ %.
[b] Initial survey posterior $\bar{x}$ %/final survey posterior $\bar{x}$ %.
[c] Bayesian highest posterior density interval.
[d] Peregrine Falcon, Bald Eagle, Osprey, and Barn Owl.

shift in nesting populations. We cannot discount the potential for generational habituation to counter territory loss over time through increased tolerance of fledglings that survive and eventually nest on disturbed habitats, but this hypothesis is untested (Guinn 2013).

Reference Sites. Nesting data from reference sites in the surrounding landscape allowed us to document a twofold negative effect of wind power on sensitive species compared to other unknown causes. Reference sites provided a baseline for interpreting changes in nest use in the larger landscape that are potentially masked when only examining footprints of wind power projects. Ferruginous Hawks and Golden Eagles are impacted by wind power development in the Columbia Basin (Watson et al. 2014, 2018, 2020, Kolar and Bechard 2016), yet declines in their nesting populations in Washington have also resulted from loss of prey populations, habitat conversion, and lead contamination (Watson and Davies 2015a, 2015b, Watson et al. 2023). The collective result has been a decades-long decline in territory occupancy and nesting success of the Golden Eagle population in Washington (Watson et al. 2020) and Oregon (Isaacs 2021), and the recent uplisting of Ferruginous Hawks to endangered status in Washington (Hayes and Watson 2021). Prairie Falcon territory occupancy has also declined significantly statewide in the past 40 yr (J. Watson, unpubl. data).

Community Composition. Analysis of changing composition of the raptor and raven communities allowed us to determine the magnitude of wind power effect on species and highlighted the potential for increasing presence of synanthropic species to negatively affect sensitive species. Studies of long-term dynamics of raptor communities and invasion ecology largely attribute changing community composition to differences in anthropogenic sensitivity among species (Coates et al. 2014, Carlisle and Sanders 2018, Cooper et al. 2020). The well-studied shift in the forest owl communities in the Pacific Northwest, USA, from northern Spotted Owls (*Strix occidentalis*) to Barred Owls (*S. varia*) is an example of invasion ecology on a larger geographic scale (Buchanan et al. 2007). The synanthropic nature of Barred Owls promotes increased nesting in altered and old-growth forests that is enhanced by larger clutch sizes, smaller home ranges, generalized diets, and interference competition and aggressive interactions (Gutiérrez et al. 2007). Likewise, changing composition of the raptor communities we studied favored species (i.e., ravens and Great Horned Owls) that are also behaviorally dominant through agonism, depredation of eggs or young, and competition for nest structure (Brambilla et al. 2004, Cianfaglione 2007, Nordell et al. 2017, Morton and Pereyra 2008, Simes et al. 2017), potentially leading to further reductions in nest use by sensitive species. Buteo species compete against each other for nest structures (Thurow and White 1983, Janes 1994). Great Horned Owls do not build their own nests and compete with other species for nests (Thurow and White 1983, Janes 1994, Langley 2013), and they have a competitive advantage for nest selection because they are nonmigratory and commence nesting earlier than other raptors (Artuso et al. 2022).

In conclusion, we ascribe long-term shifts in the nesting communities we studied on wind projects to loss of adults through turbine strikes, differences in anthropogenic tolerance of individual species that influenced recruitment onto territories with altered habitats, and possibly to changing levels of intraspecific predation and competition among species as community composition changed. As such, mitigation that is focused solely on reducing turbine collision fatality (e.g., real-time curtailment) will not address long-term changes in altered habitats that affect generational recruitment and species interactions within nesting communities. Preconstruction surveys should use protocols to estimate probability of detection and identify control areas to provide for systematic surveys of long-term changes in species (Sutherland et al. 2004, Ferraro and Pattanayak 2006, Brunk et al. 2021). We also recommend including Burrowing Owls (*Athene cunicularia*) in future long-term evaluations of post-construction effects that were not considered in this study because nest burrows are detected through ground survey protocols. We suspect, based on recent anecdotal observations (R. Gerhardt unpubl. data) there were dramatic long-term declines in nesting Burrowing Owls during our study.

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