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# Limited rigor in studies of raptor mortality and mitigation at wind power facilities

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ABSTRACT

Wind power is an expanding source of renewable energy. However, there are ecological challenges related to wind energy generation, including collisions of wildlife with turbines. Lack of rigor, and variation in study design, together limit efforts to understand the broad-scale effects of wind power infrastructure on wildlife populations. It is not clear, however, whether these types of limitations apply to groups of birds such as raptors that are particularly vulnerable to negative effects of wind energy. We reviewed 672 peer-reviewed publications, unpublished reports, and citations from 321 wind facilities in 12 countries to evaluate methods used to monitor and mitigate for wind facility impacts on raptors. Most reports that included raptor monitoring (86 %, $n = 461$) only conducted post-construction monitoring for raptor fatalities, while few (12 %; $n = 65$) estimated pre-construction raptor use. Only 27 % of facilities ($n = 62$) provided estimates of fatalities or raptor use across multiple construction phases, and the percentage of facilities with data available from multiple construction periods has not changed over time. A formal experimental study design was incorporated into surveys at only 29 % of facilities. Finally, mitigation practices to reduce impacts on raptors were only reported at 23 % of facilities. Our results suggest that rigorous data collection on wind energy impacts to raptors is rare, and that mitigation of detrimental effects is seldom reported. Expanding the use of rigorous research approaches and increasing data availability would improve understanding of the regional and global effects of wind energy on raptor populations.

## 1. Introduction

Wind power is a major and increasingly used source of renewable energy (Energy Information Administration, 2021). However, there are ecological challenges associated with energy generation via wind power, including collisions of wildlife with turbine rotors and towers (Katzner et al., 2019; Stokke et al., 2020). Indeed, hundreds of thousands of birds and bats are killed annually at wind power facilities in the United States alone (Hayes, 2013; Loss et al., 2013; Smallwood, 2013).

It is difficult to understand the total number and cumulative impacts of wildlife fatalities across wind power facilities, or the changes in wildlife use of habitat pre- vs post- construction within a given facility. Such difficulty arises because of the methodological heterogeneity and lack of rigor in studies evaluating effects of wind power infrastructure on wildlife. Conkling et al. (2020) reviewed 628 reports of wildlife surveys at renewable energy facilities across North America, finding that pre- and post-construction surveys and survey methods were rarely comparable, detection rates were seldom calculated for habitat-use surveys, and few studies incorporated elements of experimental design. The results of Conkling et al. (2020) hold generally for birds and bats, and similar conclusions have also been emphasized elsewhere (Huso et al., 2016; Kuvlesky et al., 2007). Yet, it is possible that certain taxa, such as uncommon, declining, or otherwise sensitive species groups, have been the subject of more rigorous research (McClure et al., 2021).

The group of birds called ‘raptors’ consists of the orders Accipitriformes, Falconiformes, Cathartiformes, Strigiformes, and Cariamiformes (Iriarte et al., 2019; Jarvis et al., 2014; McClure et al., 2019), including major species groups like hawks, eagles, vultures, falcons, and

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owls. This group constitutes roughly 5 % (559 species) of bird species, but has an outsized impact on ecosystems (Sergio et al., 2005; Sergio et al., 2006) and human health (Markandya et al., 2008). More than half of raptor species have declining global populations and at least 18 % are under threat of extinction (McClure et al., 2018). Indeed, raptors are more threatened and include a greater proportion of declining species than most other groups of birds (McClure and Rolek, 2020). Wind power infrastructure is a threat to populations of some raptor species (Botha et al., 2017; Carrete et al., 2009; Katzner et al., 2016b); therefore, raptors are often a primary focus of regulations and policy, and of surveys to evaluate impacts of wind facilities and mitigation approaches (Canadian Wildlife Service, 2007; Jenkins et al., 2015; U.S. Fish and Wildlife Service, 2012).

There are several approaches to ameliorate collision mortality for raptors and other wildlife (e.g., de Lucas et al., 2012b; Marques et al., 2014; Sandhu et al., 2022). Such methods follow a well-established hierarchy where avoidance of dangerous sites is the highest priority, followed by minimization of impacts, and finally, compensation for mortality through reduction of deaths from other threats or provision of habitat (Arnett and May, 2016; Kiesecker et al., 2010; Marques et al., 2014). Avoidance of dangerous sites requires pre-construction wildlife surveys or habitat suitability maps to identify those sites and assess environmental impacts (Katzner et al., 2016a; Santos et al., 2018; U.S. Fish and Wildlife Service, 2012). Minimization of impacts is less commonly practiced, in part because of inconsistent evidence of efficacy for these methods, with some approaches such as curtailment (de Lucas et al., 2012a; McClure et al., 2021; Smallwood and Bell, 2020) being more thoroughly tested than others such as acoustic or visual deterrents (Smith et al., 2011). Finally, compensation for mortality has been well-discussed in the literature, but few studies have quantified results stemming from implementation of these techniques (e.g., Arnett and May, 2016).

Because of the ecological significance of raptors and their vulnerability to both individual and population-level effects from wind energy, there is an important need to evaluate the degree of knowledge of the effects of wind energy on these taxa. Here, we review the literature regarding effects of wind power infrastructure on raptors, covering all three stages of the mitigation hierarchy noted above. Our survey advances earlier work (i.e., Conkling et al., 2020) by focusing exclusively on one group of birds of substantial conservation significance, and by expanding the geographic scope from North America to a global perspective. Here we ask: 1) How frequently are both pre- and post-construction surveys for raptors implemented, and how have survey methodologies evolved over time? 2) How frequently are studies for raptors explicitly designed to allow before-after or control-impact analyses? 3) What types of raptor-specific survey data are collected during pre- and post-construction phases, how are surveys standardized across phases and among facilities, and how often do they incorporate detection probabilities in monitoring efforts? and 4) How commonly are impact mitigation approaches implemented for raptor species? This study is therefore designed to gauge the overall rigor of past studies that examined the impacts of wind power infrastructure on raptors and also to quantify the amount of mitigation being conducted to assuage or compensate for raptor mortality.

## 2. Materials and methods

### 2.1. Literature review

To compile literature for this review, we began by surveying the database synthesized in Conkling et al. (2020). However, that study considered both wind and solar energy facilities, was not focused solely on raptors, and only examined work from the USA and Canada that was published in English. We focused the current survey specifically on raptors and wind energy, but we expanded the scope to include anywhere in the world, including both English- and Spanish-language publications.

Briefly, Conkling et al. (2020) searched Web of Science and Google Scholar using the keywords “wind turbine”, “wind”, “solar”, “mortality” “fatality”, “wildlife use”, and “carcass search” along with the names of renewable energy facilities. Those authors searched for reports published from the 1980’s through December 2017 from national databases, as well as California-specific databases because the research in Conkling et al. (2020) was funded partly by the California Energy Commission; databases included (American Wind Wildlife Institute, 2017; California Energy Commission, 2017; National Renewable Energy Laboratory, 2017; Pacific Northwest National Laboratory, 2017). Conkling et al. (2020) also solicited reports from agencies at the State, Federal, and California county level, and accessed data from previous reviews of the effects of wind turbines on birds (Loss et al., 2013) and bats (Thompson et al., 2017). Conkling et al. (2020) also incorporated personal libraries from U.S. Fish and Wildlife Service for California, Nevada, and several Canadian provinces (Alberta, New Brunswick, and Ontario), conducted Google searches to locate specific reports not in above-mentioned databases, and reviewed published bibliographies and reference lists (Argonne National Laboratory and National Renewable Energy Laboratory, 2015; Biosystems Analysis and IBIS Environmental Services, 1996).

We subsetted that existing earlier survey dataset to only consider wind power facilities. However, we also replicated the original keyword searches outlined above to locate additional English-language reports for the same time frame (e.g. 1980–2017) for facilities outside the USA and Canada. In addition, we added Spanish-language reports to Conkling et al.’s (2020) database by performing Google searches using the keywords: “parque eólico reportes aves rapaces pdf”, “parque eólico reporte (country name)”, “estudio de impacto ambiental rapaces pdf”, “impacto parque eólico rapaces pdf”, “informe seguimiento ambiental parque eólico + ‘name of wind facility’”, “estudio impacto ambiental parque eólico + ‘name of wind facility’”. We also searched several publicly accessible government websites (e.g., Norwegian Institute for Nature Research, 2021; Servicio Nacional de Certificación Ambiental para las Inversiones Sostenibles, 2021; Sistema Nacional de Información de Fiscalización Ambiental, 2021) and obtained names of individual facilities to include in searches, identifying those names from lists on government websites and from references in compiled documents. Finally, we solicited reports from colleagues outside of North America and we examined literature cited by some region-specific reviews of wind power reports (e.g., Agudelo et al., 2021). To limit our analyses to raptors, we filtered out reports that did not include this group in monitoring efforts.

### 2.2. Statistical analysis

We analyzed data at two distinct levels (“report” and “facility”) to assess patterns of variation in the construction periods and mitigation practices studied, and the specific study design elements and data collection approaches used. Report-level analyses incorporated data available in individual reports, which are usually specific to a single wind facility or a specific phase of construction or wildlife survey type at a wind facility (e.g., Bloom Biological, 2014a, 2014b; Weller and Domschke, 2015), but may also include data aggregated across multiple time periods (e.g., the entire duration of a multi-year monitoring period; Insignia Environmental, 2012). In contrast, facility-level analyses pooled all available report-level data obtained from multiple construction phases or wildlife survey types for a given facility. Inferences arising from these two analysis levels are different because individual reports often provide key details on specific aspects of data collection, while facility-level analyses allow cumulative assessment of all monitoring practices and construction phases for a particular facility. In all analyses outlined below, it is important to note that these reports reflect the information available in our existing dataset, and thus reflect the minimum level of survey implementation and mitigation types at a given facility. For countries other than the U.S., we were unable to locate publicly available databases of wind facilities similar to the U.S. Wind Turbine Database (Hoen et al., 2021) to generate country-specific annual estimates of renewables buildout. Therefore, we were unable to quantify the proportion of reports and facilities for each country relative to each country's developed MW capacity.

### 2.2.1. *Objective 1—pre vs post-construction surveys*

To determine how frequently both pre- and post-construction surveys for raptors were implemented at the facility-level and whether that frequency changed over time, we first summarized data in individual reports by facility, year of initial facility operation, and construction period (pre-, post-, and both periods). We then grouped data into 5-year bins for initial operation years (e.g., 2006–2010, 2011–2015) to reduce the size of our contingency table and increase numbers of observations within bins. We performed Fisher's exact tests ($\alpha = 0.05$) and pairwise comparisons with Bonferroni-corrected adjusted $p$-values ($\alpha = 0.05$) using packages *vcd* (Meyer et al., 2016) and *RVAideMemoire* (Hervé, 2019) in R (R Core Team, 2019) to determine if the frequency of facilities with raptor survey data from one or both survey periods varied with initial year of operation. We also used Pearson's correlation analyses to examine the relationship between the number of reports on raptors and the initial year of operation.

### 2.2.2. *Objective 2—experimental design*

To examine how frequently surveys for raptors were explicitly designed to allow before-after or control-impact analyses (also referred to as including an "experimental design" component), we identified facilities that performed both pre- and post-construction monitoring for raptors, as well as those that incorporated control or reference sites with no turbines that were located outside the facility footprint. We used the same 5-year data bins as above and again used Fisher's exact tests and pairwise comparisons to determine if the frequency with which facilities incorporated experimental design varied by initial year of operation.

### 2.2.3. *Objective 3—survey types*

To determine what types of surveys for raptors were implemented and whether and how survey types were standardized across time periods and among facilities, we first generated summary statistics that described use of survey types in each construction period (pre- and post-) and at each facility. We classified surveys designed to examine animal use or presence at a facility (hereafter, "wildlife surveys") into four categories: fatality surveys, quantification of local populations ("count"), breeding site surveys (e.g., nest searches), and taxon or status-specific surveys (e.g., raptor migration surveys). We also calculated the number of facilities for which approaches were used to account for imperfect detection (i.e., through quantification of detection probabilities) of live individuals in wildlife count surveys (e.g. distance sampling, mark-recapture methods) and of dead individuals in fatality surveys (e.g. carcass persistence and searcher efficiency trials).

We compiled contingency tables for count, breeding site, and taxon surveys, by facility, construction period, and initial year of operation (in 5-year bins, as above). We then used Fisher's exact tests for each survey type separately to examine whether the frequency with which facilities collecting raptor survey data during pre-, post-, or both construction periods varied by the binned initial year of operation. Because fatality monitoring was conducted at nearly all facilities from which reports were generated, we did not create these tables or run these tests to evaluate variation in the frequency with which fatality monitoring occurred.

### 2.2.4. *Objective 4—mitigation*

Finally, to determine how much mitigation has been implemented for raptors, we calculated the frequency with which mitigation was reported as being implemented and we recorded the type of mitigation used. Facilities typically only report mitigation practices when they occur or when required by reporting mandates (i.e, "presence-only" data). As mentioned previously, we report raw totals to represent the minimum level of implementation and mitigation types at a given facility. Furthermore, given the small number of facilities where mitigation was reported, inferential statistics would have been inappropriate for this dataset. As a result, the summary statistics we provide are the most appropriate method to quantify the trends we noted.

## 3. Results

We compiled 672 reports and citations that provided data from 321 wind facilities in 61 states and provinces and 12 countries (Fig. 1). Of these, 138 contained no relevant data (i.e., did not report avian fatalities or monitor live raptors), duplicated information in another report (e.g., a monthly report included data also contained in an annual report), or were from facilities that were incomplete, never constructed following pre-construction monitoring, or for which the initial year of operation was not reported. These 138 reports were excluded from subsequent analyses (Fig. 2), leaving for analysis 534 reports from 227 facilities in 45 states and provinces in 12 countries (Supporting Information S1–S4).

### 3.1. *Objective 1—pre vs post-construction surveys*

To understand how frequently both pre- and post-construction surveys for raptors were implemented and how survey methodologies have evolved over time, we evaluated both individual reports and data pooled at the level of individual facilities. The majority of individual reports that considered raptors included data only from the post-construction period (86 %; $n = 461$), whereas 12 % contained data only from the pre-construction period. The remaining ~1 % of reports had data covering both periods. In many cases, multiple reports were available for a given facility ($\bar{x}$: 2.34 reports per facility; range: 1–17). When we considered the multiple reports for each facility, 27 % ($n = 62$) of facilities had available data on raptors from both construction phases (Fig. 3).

The number of reports on raptors per facility was positively, but weakly, correlated with initial year of operation ($R^2 = 0.44$). As a consequence, more reports were available from newer facilities (Fig. 4). Despite this, the frequency for which data were available from both construction periods did not vary with initial year of operation (Fig. 4; Fisher's exact: $P = 0.10$).

### 3.2. *Objective 2—experimental design*

Surveys from only 66 facilities (29 %) were explicitly designed to allow before-after or control-impact analyses for raptors. However, of these facilities with such an experimental design element, there were only 16 for which a full before-after-control-impact analysis was implemented; reports from the United States and Spain accounted for the majority of these totals (Table A1). For all others, either a before-after or control-impact study, but not both, was implemented. The proportion of facilities with an experimental design element did not change over time (Fisher's exact: $P = 0.07$).

### 3.3. *Objective 3—survey types*

To characterize types of surveys conducted for raptors and the degree of standardization of survey types during pre- and post-construction periods and among facilities, we used a reduced data set of 465 reports (197 facilities). This data set excluded 69 citation-only records with no information about survey types (Fig. 2, Table 1). Systematic ($n = 369$ reports) and incidental fatality surveys ($n = 1$ report) were conducted almost exclusively (99 %) during post-construction periods. Conversely, surveys for living wildlife usually were conducted during either pre- or post-construction periods, although 27 % ($n = 53$) of facilities had data from both construction phases. Fourteen types of

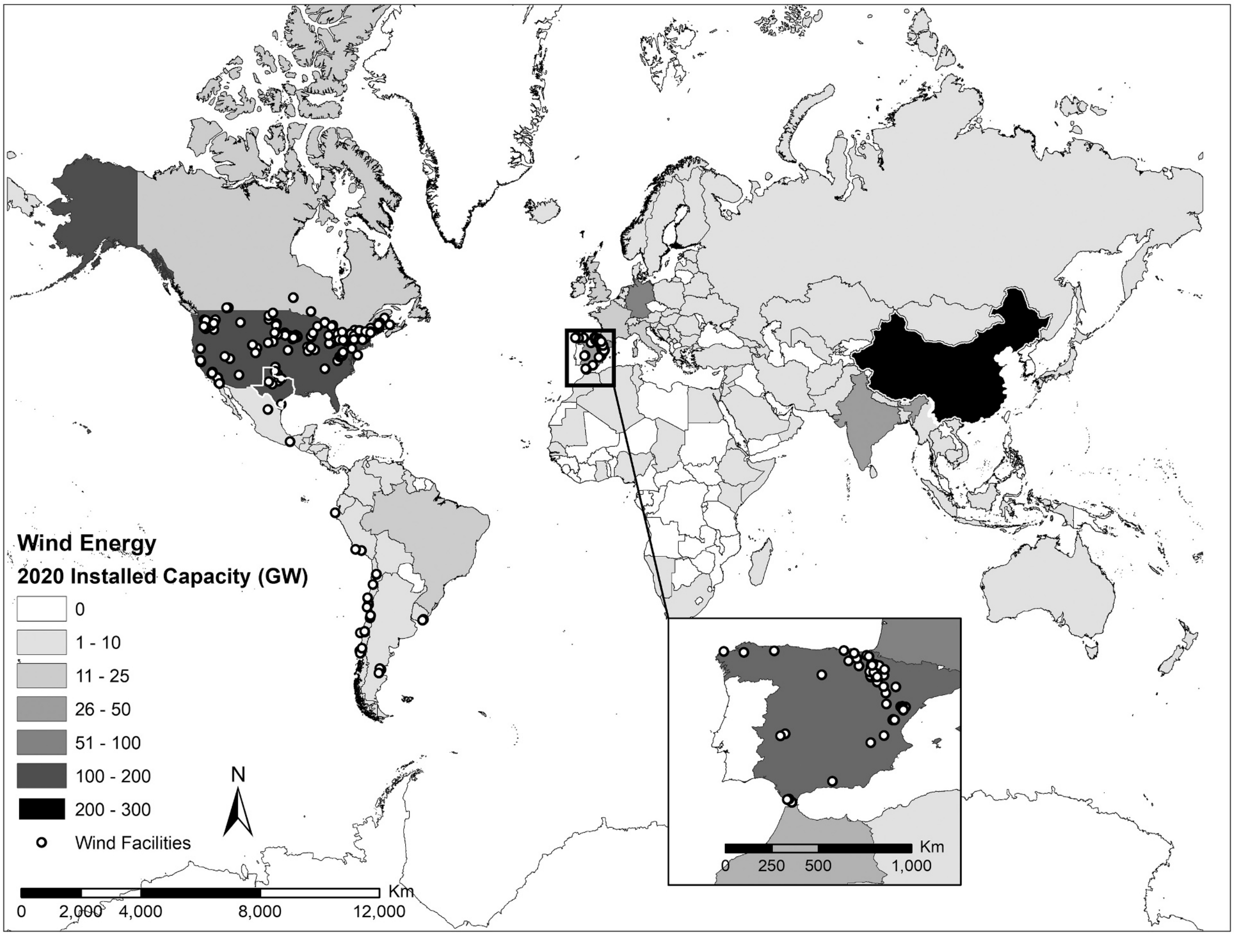

**Fig. 1.** Location of wind energy facilities evaluated in this study that described pre- and post-construction monitoring of raptor species at wind energy facilities in 12 countries during the period 1981–2020. Also shown is the global total installed wind energy capacity (gigawatt) by country as of 2020 (IRENA, 2021). Texas, the U.S. state with the most installed wind capacity (>32GW), is outlined in white.

surveys were used to quantify habitat use by raptors and other avian species at 126 facilities (Fig. 5, Table A1). However, the same survey type was rarely used in both pre- and post-construction monitoring at the same facility ("both" = 13 % in Fig. 5). Neither taxon or species-specific surveys, population counts, nor breeding site surveys became more or less frequent over time (Fisher's exact: $P = 0.40$ (raptor or species-specific), 0.44 (population counts), 0.24 (breeding site)).

Finally, there were 177 wind facilities (95 % of those we considered) for which searcher efficiency and carcass persistence data were incorporated into fatality surveys for raptors to account for imperfect detection of carcasses by observers. However, there were no facilities (0 %) that accounted for detection probability when conducting point counts or other counts of live raptors.

### 3.4. *Objective 4—mitigation*

Mitigation was rarely reported for raptors at wind energy facilities, with only 52 (23 %) facilities reporting implementation of such mitigation measures (Fig. 6, Table A2). The most frequently implemented measure was adjustment of cut-in speeds or curtailment ($n = 33$). Other mitigation changes used were changes in facility lighting ($n = 8$), and adjustment of micrositing ($n = 4$).

## 4. Discussion

Our results reveal a general lack of standardization and rigor in studies of wind power impacts on raptors. Conkling et al. (2020) found similar results across general studies of birds and bats at wind and solar energy facilities. Our results expanded on that study by incorporating data from 12 additional countries and verifying that those general results also apply specifically to raptors, a group of bird species that are of substantial ecological and conservation significance due to their role as top predators and their uncommonness and declining populations.

Our first objective was to determine how frequently both pre- and post-construction surveys were implemented, and whether that frequency changed over time. Ideally, each facility would conduct both pre- and post-construction surveys to assess differences in wildlife fatalities or use, but we found that post-construction monitoring is far more common than pre-construction monitoring, and that neither post-construction nor pre-construction monitoring have become more or less prevalent over time. Post-construction monitoring may be more prevalent than pre-construction monitoring because of regulatory requirements that mandate or encourage post-construction fatality surveys (e.g., U.S. Fish and Wildlife Service, 2012). In contrast, the pre-construction mortality rate at a given site is often assumed to be low, and thus monitoring of a background mortality rate is rarely required or conducted (TEK personal observations; Erickson et al., 2014). The types of pre-construction surveys typically conducted were either field- or office-based. Field surveys were most commonly point counts or targeted monitoring of species of conservation interest such as nest surveys for eagles or other special-status species. Office-based surveys involved literature review and operated on the assumption that risk would be similar, in species and numbers affected, to that at nearby facilities where field surveys had been conducted. It is important to note that our

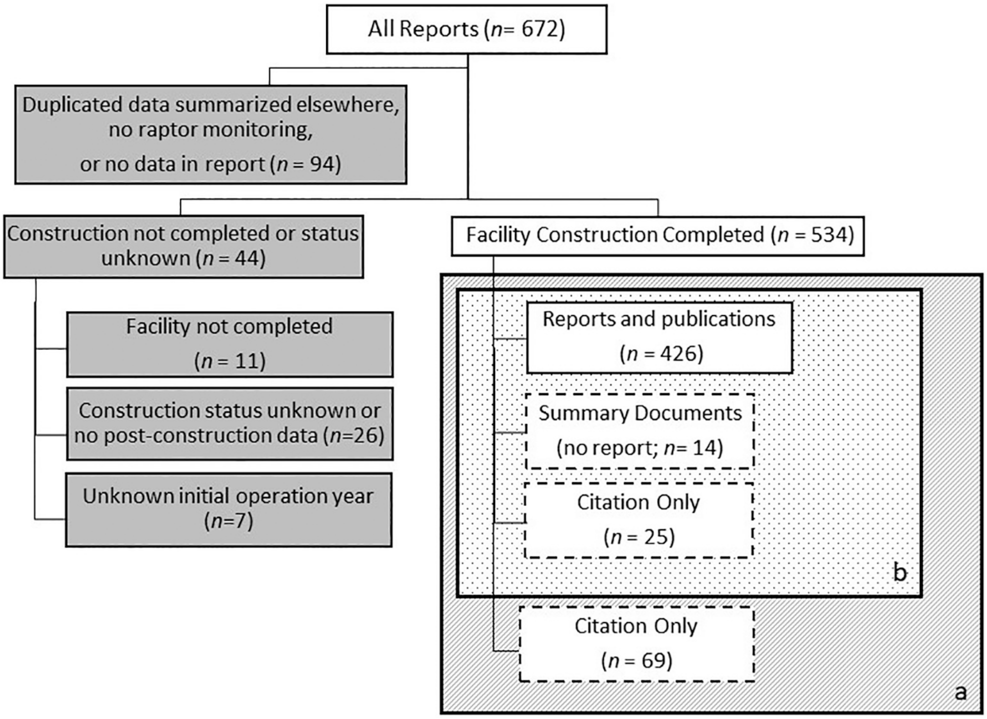

**Fig. 2.** Number of reports evaluated in this study that described pre- and post-construction monitoring of raptor species at wind energy facilities in 12 countries during the period 1981–2020. Categories of reports in dark grey boxes (left) were not included in analyses. Categories of reports in white boxes (right) were included in analyses. Also depicted are the categories of reports used in analysis for objectives one and two (a) and objective 3 (b).

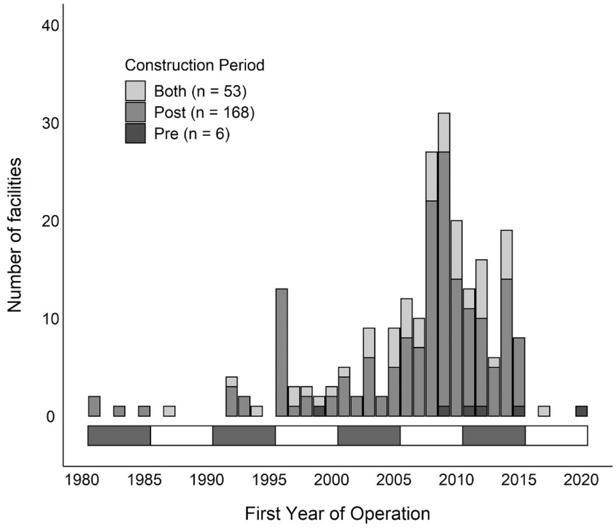

**Fig. 3.** Number of wind energy facilities with reports analyzed in this study of effects of wind energy on raptors at wind energy facilities in 12 countries during the period 1981–2020 (sample size ["*n* ="] provided in figure legend). Data are organized by period (pre- or post-construction periods, or both periods) and by first year of operation. Data for individual facilities included information from 1 to 17 reports in the analyzed dataset (*n* = 534).

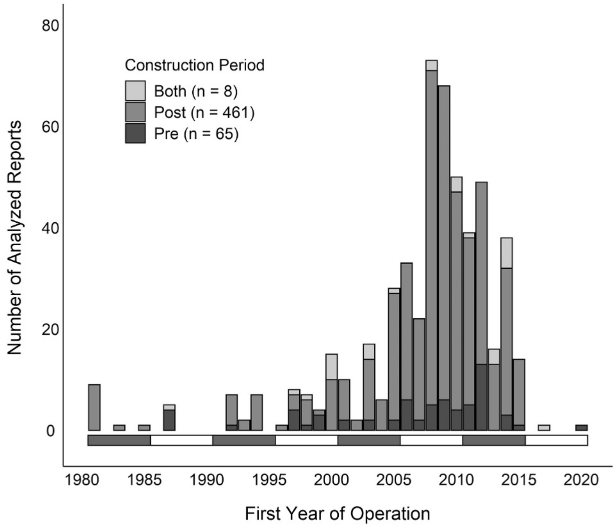

**Fig. 4.** Number of individual reports analyzed in this study of effects of wind energy on raptors at wind energy facilities in 12 countries during the period 1981–2020 (sample size ["*n* ="] provided in figure legend). Data are organized by period (pre- or post-construction periods, or both periods) and by first year of operation. Individual reports included data for 1–22 unique wind facilities.

analyses only examined whether there was a difference in the prevalence of surveys completed within the reports we had available, not whether there were more or less surveys over time. Additionally, given the substantial increase in renewables buildout in recent years, it is unclear whether the frequency of monitoring in either the pre- or post-construction periods has kept pace with the total number of facilities being developed, as we did not have the data to assess this trend.

Our second objective was to examine how often studies of raptors were explicitly designed to allow before-after or control-impact analyses. BACI designs are often used in ecological studies to quantify changes in reference sites or reference time periods that reflect effects on species unrelated to the stressor of interest (e.g., Stewart-Oaten, 1986). Accounting for these other effects allows control of confounding variables and isolation of the effects of the stressor of interest. As such, rigorous controlled studies would bolster inference from research regarding conflicts between raptors and wind power. Unfortunately, strong inference is rarely possible when addressing this problem, as less

**Table 1**

Number of reports used for analyses of the frequency of monitoring for raptor fatalities and wildlife use at wind energy facilities in 7 countries from 1980 to 2020 with data available for different construction periods (i.e., pre-construction, post-construction, or both). Data are arranged by state or province name and whether the facility used the same survey types across both construction periods.

| Country | State or province | # facilities | Construction period | | |
|---|---|---|---|---|---|
| | | | Pre | Post | Both |
| Canada | Ontario | 2 | 2 | 9 | 1 |
| Chile | Antofagasta | 2 | 0 | 4 | 4 |
| | Atacama | 1 | 0 | 1 | 1 |
| | Coquimbo | 2 | 2 | 5 | 3 |
| Mexico | Oaxaca | 1 | 0 | 1 | 1 |
| Peru | Piura | 1 | 0 | 1 | 1 |
| Spain | Andalucia | 1 | 0 | 0 | 1 |
| | Galicia | 1 | 0 | 0 | 1 |
| | Navarra | 5 | 0 | 8 | 7 |
| | Pais Vasco | 3 | 0 | 23 | 8 |
| United States | Arizona | 1 | 2 | 2 | 0 |
| | California | 11 | 18 | 52 | 2 |
| | Maine | 2 | 4 | 3 | 0 |
| | Minnesota | 2 | 2 | 20 | 0 |
| | Montana | 1 | 1 | 2 | 0 |
| | New Hampshire | 1 | 0 | 2 | 1 |
| | Nevada | 1 | 2 | 3 | 0 |
| | New York | 2 | 2 | 7 | 0 |
| | Oregon | 4 | 6 | 16 | 0 |
| | Pennsylvania | 1 | 1 | 4 | 0 |
| | South Dakota | 2 | 2 | 3 | 0 |
| | Vermont | 1 | 4 | 2 | 0 |
| | Washington | 4 | 6 | 6 | 0 |
| | West Virginia | 3 | 6 | 15 | 0 |
| | Wisconsin | 2 | 2 | 3 | 1 |
| | Wyoming | 1 | 1 | 1 | 0 |
| Uruguay | Maldonado | 1 | 0 | 1 | 1 |

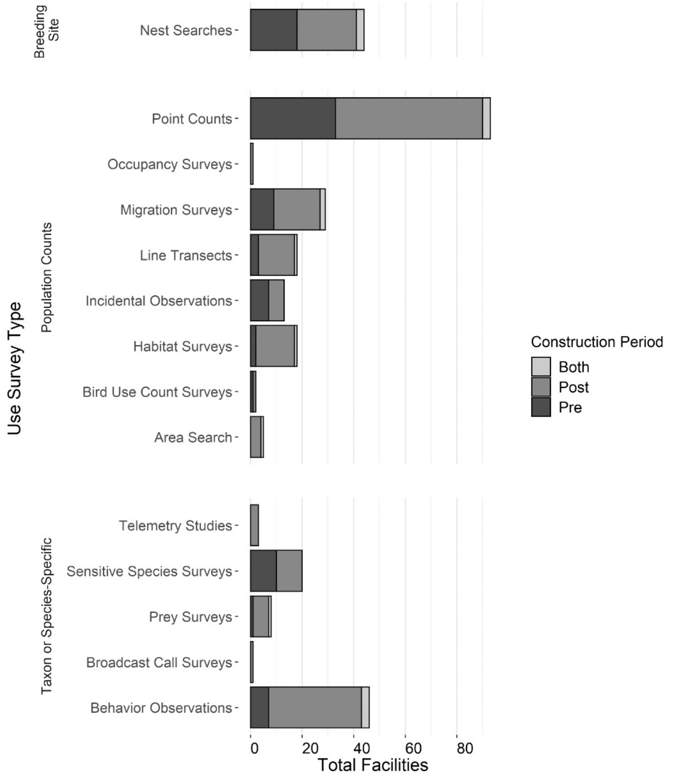

**Fig. 5.** Types and numbers of wildlife use survey methodologies to assess raptor populations applied at renewable energy facilities in 12 countries during the period 1981–2020 with available monitoring reports containing wildlife use data ($n = 126$ facilities). Data are arranged by construction phase (pre-construction, post-construction, or both) and broad categories of survey types (breeding site, population counts, and raptor, or species-specific surveys).

than one-third of wind facilities we considered implemented studies with before-after comparisons or spatial controls. Further, of this subset with a rigorous study design, less than one-quarter incorporated a full before-after-control-impact design (e.g., Curry and Kerlinger, L.L.C., 1998; Shaffer and Buhl, 2016). Instead, most either did a before-after or a control-impact experiment, not both. Thus, general inference into the effects of wind power on raptors is relatively weak, relying mostly on correlational evidence with no reference to background or control conditions. This analysis suggests that calls for more rigor in studies of wildlife within wind power facilities (Huso et al., 2016; Katzner et al., 2016a; Kunz et al., 2007a; Kunz et al., 2007b) have, at least in the case of raptors, generally been ignored.

As our third objective, we examined the types of survey data collected and the degree of standardization of survey data types collected during pre- and post-construction periods and among facilities. We found that the same survey types were rarely implemented both pre- and post- construction at most wind facilities (but see e.g., M. K. Ince and Associates Ltd, 2012). A likely driver of these differences in methods between construction periods is the emphasis on monitoring focal species that vary by country. For example, the majority of monitoring reports in the U.S. are primarily aimed at assessing impacts of renewable facilities on bald (*Haliaeetus leucocephalus*) and golden eagles (*Aquila chrysaetos*) following published guidelines that recommend differing survey use and mortality survey methodologies for pre- and post-construction (e.g., U.S. Fish and Wildlife Service, 2012). Ideally, studies that are effectively designed to understand impacts to wildlife from wind energy would implement the same survey methodologies both pre- and post-construction. If survey types are not the same, then comparison is difficult unless using complex analytical models specifically designed to account for uncertainties in these different data types (see New et al., 2015). For example, pre-construction point counts quantify all observed species at a given site, whereas post-construction carcass searches only document individuals or species that were killed at the site. It is counterintuitive to estimate effects to wildlife by comparing data from these two count types. Thus, the lack of standardization we detected severely hampers inference into the effects of wind power infrastructure on raptor populations.

Spatial and temporal differences in pre- and post-construction monitoring also could reduce the effectiveness of monitoring efforts and the utility of the data for assessing risk to raptors. For example, abundance surveys and point counts occurred most frequently during breeding and wintering periods. Furthermore, we observed a lack of standardization in the time of the day when surveys were conducted. Likewise, fatality monitoring was often concentrated within 100 m of a turbine base to estimate fatalities around an individual turbine. In contrast, the search radii for point counts often extended to 800 m from the observation point to broadly estimate bird use across the entire facility. All these issues may contribute to the documented poor correspondence between pre-construction fatality estimates and post-construction fatality counts due to spatial variation in fatalities across the facility (Ferrer et al., 2012).

Our study also revealed that pre-construction surveys are rarely structured to account for probability of detection. Failure to account for imperfect detection almost certainly biases abundance estimates from pre-construction surveys (Kellner and Swihart, 2014), most likely causing underestimation of true numbers (Kéry and Schmidt, 2008). Undercounting raptors during pre-construction surveys also may contribute to failure to predict the impacts that wind facilities will have on raptors. For example, estimates of percent declines in abundance due to fatalities will be less when based on smaller initial estimates of abundance.

Conversely, calculation of detection probability during post-

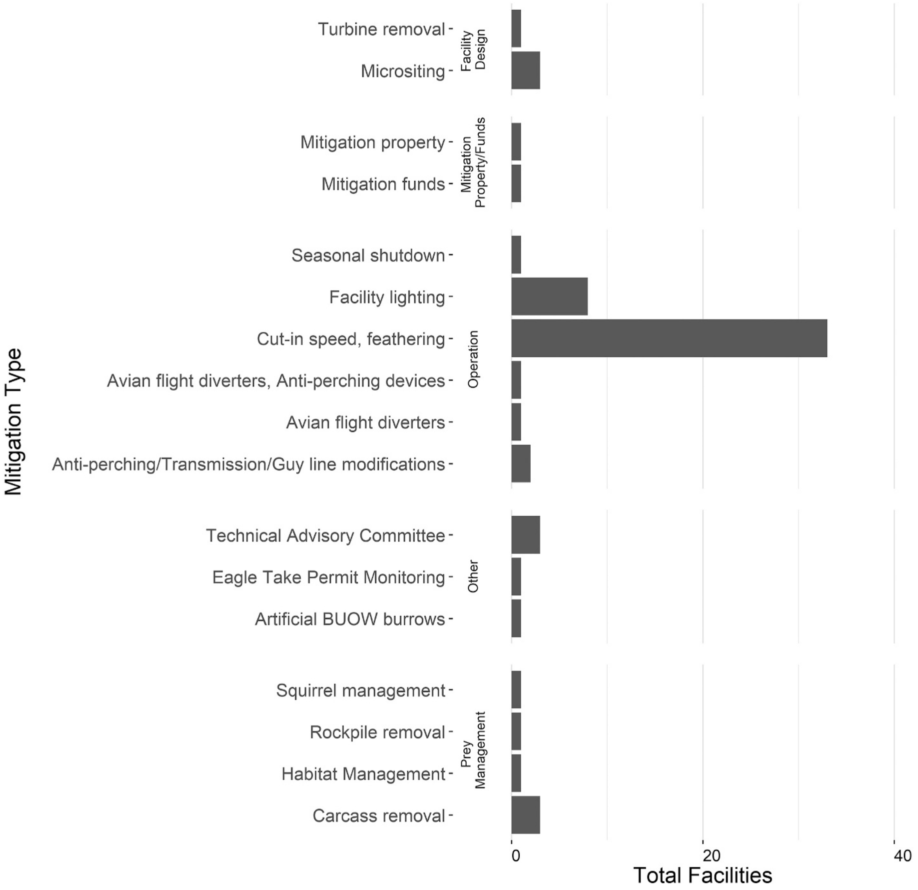

**Fig. 6.** Number of wind power facilities at which mitigation practices were implemented by type of mitigation in this study of effects of wind energy on raptors at wind energy facilities in 4 countries during the period 1981–2020. Totals are only presented for facilities with available monitoring reports containing wildlife mitigation data. Data are arranged by broad categories of mitigation type (facility design, mitigation property/funds, operation, prey management, or other mitigation type).

construction carcass surveys was common (93 %). Such accounting for imperfect detection results in less-biased estimates of mortality during the operation of a wind facility (Huso et al., 2016). The number of raptor fatalities occurring at wind facilities is therefore likely being reasonably well estimated. However, some caution is warranted when interpreting results, because the majority of these studies rely on carcasses of surrogate species (e.g. Galliformes) for searcher efficiency and persistence trials, which may bias estimation of fatalities of raptors (Urquhart et al., 2015). However, without matching pre-construction surveys or proper controls to quantify background mortality, even accurate estimates of mortality have little relevant context and are thus dramatically less useful than they would be if estimated within a more rigorous experimental framework (Conkling et al., 2020).

Finally, we quantified the number of wind power facilities that undertook mitigation for raptor mortality. Despite some well-known examples (May et al., 2020; Watson et al., 2018), relatively few facilities have reported implementation of such actions. This is unexpected given the conservation status of many raptor populations (Buechley et al., 2019; McClure and Rolek, 2020; McClure et al., 2018) and the threat posed by wind power infrastructure (Botha et al., 2017; Carrete et al., 2009). That said, in recent years, one mitigation technology – use of computer vision and machine learning to detect raptors and shut down turbines – has been implemented at a number of facilities (e.g., McClure et al., 2021). However, the value of this approach appears inconsistent (as discussed in PNWWRM XIII (2021)) and additional research is needed to determine if these systems can function similarly across a broad range of species or site-specific environmental variations.

Our sample of reports from wind power facilities is an extremely valuable, but imperfect (Conkling et al., 2020) and incomplete assessment of raptor mortality and mitigation studies at wind facilities around the world. As such, our results should be interpreted with caution. However, they can still provide some insights into global patterns of raptor monitoring and mitigation practices. Bias in this dataset may exist for at least six reasons related to issues such as accessibility and availability of reports, to whether or not surveys are conducted at facilities, and to our strategy to search for reports. First, the spatial sample of reports is likely biased toward countries, states, provinces, or individual jurisdictions that require open reporting of surveys at renewable energy facilities. This is especially true since documents from the initial survey (Conkling et al., 2020) only represented the U.S. and Canada, countries for which we were most familiar with report repositories and databases. Second, sometimes data from pre- and post-construction phases are not made available because of legal concerns (e.g., Dinnell and Russ, 2006; Subramanian, 2012). Third, time lags in publication resulting from ongoing data collection or document review processes might result in newer reports being less frequently available. Fourth, our search could only capture reports available online and some reports might only exist in hard copy. Fifth, our search efforts were limited by the fact that we surveyed for literature in two primary languages. Finally, facilities on privately owned land are not subject to the same monitoring requirements as those on publicly owned land. All of these factors, and perhaps others, certainly influenced which reports were available for our study. These challenges are not unique to our study. For example, when assessing wind energy effects on harriers (*Circus* spp.), Fernández-Bellon (2020) noted similar limitations in document accessibility and data sharing, lack of standardization in monitoring efforts, and geographical and language biases. Additionally, we did not incorporate the facility size or spatial location of individual turbines in our analyses, but the number of turbines or spatial arrangement in the landscape can influence collision risk at a given facility (e.g., Ferrer et al., 2012). Incorporating this information in monitoring reports could improve future efforts to estimate collision risk to raptors at a given facility.

If the availability of reports influenced the representativeness of our bibliography, then that would also influence the inferences we can draw from this analysis. As an extreme example, the U.S. state of Texas contains the most installed wind capacity of any U.S. state (Fig. 1). However, land in this state is 97 % privately owned and surveys and reporting on such lands occur less frequently than on publicly owned lands. As a consequence, we were only able to obtain reports from six of 161 (4 %) operational wind facilities in the state (American Wind Energy Association, 2021). Similarly, China has >272GW of installed wind energy as of 2020, accounting for 42 % of the global capacity (IRENA, 2021), but we were unable to obtain reports from any Chinese facility (Fig. 1). Thus, if surveys differ in design and execution at wind facilities in Texas, China, or any other jurisdiction with limited data, then this would impact the inference we draw from our analysis. We were also unable to determine country-specific annual estimates of wind energy buildout. This would have allowed us to quantify the proportion of reports and facilities for each country relative each country's developed MW capacity. Such data could be highly relevant, because if the rate of increase of wind energy is greater than the rate of change in survey efforts, it could mean that numerical increases we observed over time are actually proportional decreases in standardization and effort. Research efforts incorporating the best management practices discussed in Conkling et al. (2020) and elsewhere (i.e., rigorous study design, consistent monitoring practices, and increased data accessibility and availability) would improve the accuracy of future meta-analyses examining cumulative effects of renewable energy on wildlife populations.

## 5. Conclusions

Conkling et al. (2020) highlighted the value to conservation of research at renewable energy facilities that is question-driven, has temporally and spatially standardized field protocols, and is broadly disseminated to researchers, conservation practitioners, policy makers, and the public. This study reinforces those findings specifically for raptors, a group of bird species that are especially important because of their enhanced conservation status. Understanding effects of wind energy on raptors, including limitations of the collective literature on this topic, may be especially significant in light of the ongoing global expansion of wind energy in rural areas that may encroach on important raptor breeding or wintering habitat and increase exposure to collision risk. Increased application of impact mitigation approaches, especially when it is not feasible to avoid placing wind facilities in high-risk areas, may minimize impacts to raptor populations and allow both wildlife managers and the energy industry to balance renewable energy generation with minimizing impacts to raptor populations.

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## CRediT authorship contribution statement

T.J.C.: conceptualization, data curation, formal analysis, investigation, methodology, resources, writing - original draft, writing - review and editing; C.J.W.M.: conceptualization, funding acquisition, writing - original draft, writing - review and editing; S.C.: data curation, formal analysis, investigation, methodology, resources, writing - review and editing; S.R.L.: investigation, data curation, methodology, resources, writing - review and editing; T.E.K.: conceptualization, data curation, funding acquisition, investigation, methodology, resources, writing - original draft, writing - review and editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christopher McClure reports financial support was provided by Texas Public Policy Foundation. Tara Conkling reports a relationship with Alameda County, CA Wind Repowering/Avian Protection Technical Advisory Committee that includes: consulting or advisory.

## Data availability

The data are provided in electronic supplementary material.

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