Adaptive management to improve eagle conservation at terrestrial wind facilities

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Abstract
The development and installation of renewable energy comes with environmental cost, including the death of wildlife. These costs occur locally, and seem small compared to the global loss of biodiversity. However, failure to acknowledge uncertainties around these costs affects local conservation, and may lead to the loss of populations or species. Working with these uncertainties can result in adaptive management plans designed to benefit renewable energy development and conservation. An example is the U.S. government’s policy for managing bald (Haliaeetus leucocephalus) and golden (Aquila chrysaetos) eagle deaths at terrestrial wind facilities. Using records from 422 U.S. wind facilities we improved the precision of estimates of exposure (8.79 eagle minutes hr⁻¹ km⁻³, SD: 13.64) and collision probability (0.0058 birds per minute of exposure, SD: 0.0038) currently used in U.S. policy. The new estimates for bald (exposure: 3.19 eagle minutes hr⁻¹ km⁻³, SD: 2.583; collision probability: 0.007025 eagles per minute of exposure, SD: 0.004379) and golden (exposure: 1.21 eagle minutes hr⁻¹ km⁻³, SD: 0.352; collision probability: 0.005648 birds per minute of exposure, SD: 0.004413) eagles had a smaller mean and standard deviation. Thus, their implementation within the government’s adaptive management framework could help refine the balance between energy consumption and conservation.

KEYWORDS
adaptive management, bald eagle, Bayesian analysis, golden eagle, renewable energy, risk, wind-wildlife interactions

1 | INTRODUCTION

Energy consumption has increased due to the proliferation of technology, smaller household size and urban sprawl (Liu, Daily, Ehrlich, & Luck, 2013). Nonrenewable energy sources can meet demand, but their finite nature and concern over a changing climate has led to increasing use of renewable energy generated from hydroelectric, solar, and wind, amongst others (e.g., Twidell & Weir, 2015). These sources of energy diminish harmful byproducts, such as greenhouse gas emissions, and are described as “green energy.” However, renewable energy...
has environmental costs, as shown by declining fish populations due to hydroelectric dams (e.g., Haxton & Cano, 2016), lower bird species richness and density at solar facilities (e.g., Visser, Perold, Ralston-Paton, Cardenal, & Ryan, 2019), and bird and bat fatalities at wind facilities (e.g., Barclay, Baerwald, & Gruver, 2007; Carrete, Sanchez-Zapata, Benitez, Lobon, & Donazar, 2009; Kunz et al., 2007). To truly make renewable energy “green,” it is necessary to find a balance between energy generation, climate change mitigation, and species conservation.

Wind power’s history in the United States (U.S.) begins with the first electricity generating wind turbine in 1888, although significant growth in wind energy generation and capacity did not begin until the mid-1990s (Kaldellis & Apostolou, 2018). In addition to producing renewable energy, wind facilities can have direct positive effects on the environment through habitat modification, such as creating artificial reefs at off-shore installations (e.g., Methratta & Dardick, 2019). However, wind facilities can negatively affect bird and bat populations indirectly by creating barriers or changing habitat, and directly through collision mortality (e.g., Barclay et al., 2007; Carrete et al., 2009; Kunz et al., 2007). These risks can vary by species, location, and season, amongst other factors (e.g., Barclay et al., 2007; Barios & Rodriguez, 2004), making it difficult to develop a single management protocol to reduce risk to all wildlife. Even within a single facility, what is helpful for the conservation of one species may be detrimental to another (e.g., Barclay et al., 2007). Experiments at wind facilities are challenging to implement (Baerwald et al., 2009) because the physical structures’ relative permanency makes it difficult to randomize treatments, resulting in studies that can be confounded in space and time. As a consequence, many studies have focused on how species’ behavior and physiology might make them susceptible to the risks posed by wind turbines (e.g., Barios & Rodriguez, 2004; Hull, Stark, Peruzzo, & Simms, 2013).

Collision with operating turbines have been documented for many species, from passerines and bats (e.g., Kunz et al., 2007) to eagles (e.g., Hull et al., 2013; Pagel et al., 2013) and vultures (e.g., Carrete et al., 2009). There are different collision risk factors, some of which are species specific (e.g., Hull et al., 2013). For example, some bat species are at lower risk of collision at higher wind speeds because their probability of flight is lowered (Baerwald & Barclay, 2011). This has led to increasing the wind speed threshold at which turbines begin operation to reduce the number of bat fatalities (Arnett, Huso, Schirmacher, & Hayes, 2011). Thus, successful identification of species-specific risk factors can be effective in reducing, although not eliminating, wildlife fatalities at wind facilities. Given the diversity of wildlife found at wind facilities, there is a wide range of species-specific needs and risks that need to be taken into account if fatalities for all species are to be reduced. However, different species may have conflicting needs and risks, leading many management and conservation plans to focus on reducing wind facilities’ effects on at-risk, endangered, or other legally protected species (e.g., Hull et al., 2013; New et al., 2015).

Within the United States, bald (Haliaeetus leucocephalus) and golden (Aquila chrysaetos) eagles are protected under the Bald and Golden Eagle Protection Act (BGEPA, 16 U.S.C. §§ 668–668d), which was enacted in 1940. Under BGEPA, it is illegal to kill an eagle, even if the fatality results from an accident while performing an otherwise legal activity. Given the observed eagle fatalities at wind facilities within the U.S. (e.g., Pagel et al., 2013), this means wind facilities operating under normal conditions may be in violation of U.S. law. Halting all wind development and dismantling all existing facilities is not a viable option for balancing the positive effects of wind power development on climate change and energy supply against its negative effects on eagles. As an alternative, the U.S. Fish and Wildlife Service (FWS) developed a permitting process that allows some fatalities to occur, provided that actions are taken to mitigate the risk and its effects (USFWS, 2013). The predicted number of eagle fatalities to occur at a wind facility is determined by a collision risk model (CRM) based upon eagles’ potential exposure to operating turbines and the probability that a fatal collision will occur (i.e., collision probability) (New et al., 2015; USFWS, 2013). This prediction is compared with take-limits determined by the species’ estimated capacity to withstand additional mortality. If the predicted take is within the limits, or can be offset with compensatory mitigation, a permit is issued (USFWS, 2016a).

When the CRM was developed, FWS had data on golden eagles from fewer than a dozen wind facilities, and no data on bald eagles (USFWS, 2013). As a result, the estimates of exposure and collision risk for golden eagles were considered reasonable placeholders for bald eagle management until species-specific data became available. However, there was concern from stakeholders that, due to fewer observed fatalities, bald eagles were at less risk of collision compared to golden eagles. Further, the same management is unlikely to be appropriate for both species, given that the bald eagle population has been growing since the 1980s, (e.g., Cruz et al., 2019; USFWS, 2016a), while more recent estimates have indicated that the golden eagle population has remained stable over the last decade (e.g., Neilson et al., 2014; USFWS, 2016a).
Rather than allowing this uncertainty to stymie eagle conservation, FWS placed their permitting process within an adaptive management framework to help balance energy development and eagle conservation. This involved permitting facilities at the fatality prediction’s 80th quantile, which reduced the probability a permit would be exceeded and followed the precautionary principle by overestimating a facility’s potential effect on eagle populations (USFWS, 2016b). Wind facilities were required to collect data prior to construction and after they became operational to help inform facility-specific estimates of eagle risk, as well as to improve knowledge at the national level, thus allowing for the reduction of uncertainty at multiple scales. The intent of the FWS was to update their guidance every 5 years, since even such a limited data collection period can help inform adaptive management (USFWS, 2013).

Records from 422 wind facilities across the U.S. were reviewed for data to update and improve the species-specific exposure and collision risk of golden and bald eagles. The aim was to explore the effectiveness of FWS’ policy and permitting process for eagle management, particularly with regards to how new information can be used to update and refine exposure and fatality estimates, ideally improving accuracy and precision. To demonstrate the value of these updates, we evaluated the new bald and golden eagle specific distributions for exposure and collision, and then calculated their resulting fatality estimates for a case study from Converse County, WY, which we compared to the fatality estimates obtained when using the original priors from the Bayesian collision risk model (New et al., 2015).

2 METHODS

2.1 Data

Records from wind facilities were reviewed to determine if they included data on the minutes of eagle exposure and numbers of fatalities for input into the collision risk model. The records included letters, maps, the names of wind facilities in summary documents or emails, as well as full reports of the site. Some facilities only monitored for bats, whereas other collected full or partial documentation of eagle fatalities and site use. We did not knowingly exclude any wind facilities in FWS’ databases, resulting in 422 wind facilities whose records, reports, and data were provided to FWS by over 20 different environmental consultants, state and federal agencies, NGOs, and other organizations.

We defined the suitability criteria for exposure (Table 1) and collision (Table 2) were defined to determine whether a wind facility’s data could be included in the analysis. Suitability was based on the requirements of New et al. (2015)’s CRM (Equations (1) and (2)). Availability to FWS was specified because in some cases reference to data collection was made in the records available to the FWS (e.g., in email communication), but the data were not included in the existing documentation (e.g., due to data sharing concerns). For collision probability, wind facilities that were not built, or were under construction, were immediately excluded.

| TABLE 1 | Criteria used in this study to determine whether the information available from a wind facility was suitable for inclusion in the analysis of bald and golden eagle exposure |
|---|---|
| **Exposure criteria** |
| The wind facility was terrestrial |
| Raw data, or documented data summaries, were available to FWS |
| Data were collected prior to the wind facility’s construction |
| Eagle minutes, or eagle observations, were recorded and available to FWS |
| Bald and golden eagle minutes or observations were uniquely specified |
| The maximum height and distance to which eagles were recorded was documented |
| The total amount of time spent sampling was documented, or could be calculated |

| TABLE 2 | Criteria that, in addition to those defined in Table 1, were used in this study to determine whether the information available from a wind facility was suitable for inclusion in the analysis of bald and golden eagle collision probability |
|---|---|
| **Collision criteria** |
| Data on eagle fatalities were collected postconstruction |
| Postconstruction monitoring took the form of standardized surveys |
| The details of the surveys, including the total duration of the monitoring, number of turbines searched, size of the search plots, and transect width were documented |
| Estimates of both searcher efficiency and carcass persistence for the wind facility were documented, or could be calculated from raw data |
| The number of operating turbines at the facility, as well as their height and radius, was documented |
| The fatalities were specifically identified as golden or bald eagles |
| All the required information and documentation were available to FWS |
because no collisions could have occurred at those locations. Wind facilities that collected information that did not meet the criteria for the exposure data were also excluded, since the CRM assumes (New et al., 2015; USFWS, 2013) there is a relationship between preconstruction exposure and postconstruction fatalities. This assumption was necessary because, while many facilities collected data on eagle site use prior to construction, the industry objected to a requirement that they also collect postconstruction exposure data, thus FWS capitated to a relationship defined in this way.

For eagle exposure, the data we used in the analysis took the form of point count surveys at individual wind facilities. During the surveys, observers recorded the minutes eagles spent in flight and/or the number of eagles recorded. The specifics of the surveys differed across the wind facilities on a number of accounts, including the number of survey points and duration. The number of survey points varied from one to 57, based on the size of the wind facility, and all facilities surveyed each point on multiple occasions at different times of the year. The duration of the point counts varied across the facilities, from 20 min to a maximum of 2 hr. This lack of standardization across surveys does not present an issue for the analysis of exposure, since the CRM standardizes the eagle use by the amount of survey effort. We directly account for the variation between postconstruction surveys for eagle carcasses with regards to search interval, number of searches, spatial coverage, and the length of time covered by the surveys (see Table S1) in the resulting estimates of eagle fatalities (Dalthorp et al., 2017).

2.2 | Analysis

We carried out our analyses to calculate species-specific distributions for exposure and collision risk using FWS’ CRM in a Bayesian framework. In order to calculate new prior distributions for the CRM it was necessary to have data available on bald and golden eagle exposure and where available, fatalities, from multiple wind facilities. We calculated project-specific estimates of bald and golden eagle exposure, fatalities, and collision risk as per New et al. (2015), and we combined the posterior distributions for each facility using mixture models to obtain species-specific parameter estimates at the national level.

2.2.1 | Collision risk model

The CRM (New et al., 2015) predicts eagle fatalities ($F$, eagles year$^{-1}$) based on the species’ probability of collision ($C$, eagles eagle-min$^{-1}$), exposure ($\lambda$, eagle-min hr$^{-1}$ km$^{-3}$), and an expansion factor representing a wind facility's hazardous space–time ($\varepsilon$, hr km$^3$ year$^{-1}$):

$$F = \varepsilon\lambda C,$$  

where $\lambda$ is a function of the observed eagles minutes ($k$) and total survey effort in space and time, and $\varepsilon$ is a function of the total daylight hours per year ($r$, hr), the number of turbines ($n_{\text{turb}}$), the height of the turbines hazardous space ($h$) and the area swept by the turbines’ rotor blades, which is determined by $r$, the rotor’s radius:

$$\varepsilon = \tau n_{\text{turb}} h \pi r^2.$$  

The prior distributions on the exposure ($\Gamma[0.415, 0.0472]$) and probability of collision ($\beta[2.31, 396.69]$) (New et al., 2015) were intended to capture the range of values typical for wind development sites. Assuming conjugate distributions (beta-binomial and gamma-Poisson) for the parameters and data (Gelman, Carlin, Stern, & Rubin, 2004) enabled closed-form calculation for the posterior distributions for $\lambda$, $C$ and $F$. For detail, see USFWS (2013) Appendix D, New et al. (2015) and Appendix S1.

2.2.2 | Exposure estimates

Calculation of eagle exposure required information on the observed time the birds spent in flight, as well as survey effort in space and time. Many wind facilities collected information before FWS’ survey protocols (USFWS, 2013) were available, resulting in records reporting the number of eagles observed as opposed to flight time. To avoid biasing the data by the systematic exclusion of these facilities, we constructed a model to predict eagle minutes at a wind facility based upon the number of eagle observations. We fit the model separately to bald and golden eagle data from a subset of wind facilities that recorded information on both eagle minutes and the number observed. This information was available from 13 and 18 sites for golden and bald eagles, respectively.

We explored Poisson regression and a Poisson-normal hierarchical model to estimate the relationship between recorded eagle minutes and the count of eagle observations. We chose the latter for its lower deviance, better fit to the data, and ability to predict the data’s large variance. The model took the form of a log–log generalized linear regression to downweight the effect of large surveys:
\[ k_f \sim \text{Poisson}(\gamma_f - 1) \]
\[ \log(\gamma_f) \sim N(\hat{c} \cdot \log(n_f^{\text{abs}} + 1), \sigma_c^2), \]  (3)

where, subscript \( f \) indicates the \( f^{th} \) wind facility, \( k_f \) was the number of eagle minutes, \( n_f^{\text{abs}} \) was the number of eagle observations recorded, \( \gamma_f \) was the Poisson rate of exposure and \( c \) was the conversion of eagle observations to eagle minutes with a log-normal variation of \( \sigma_c^2 \). We used \( \log(x + 1) \) to include surveys that recorded zero observations. Both \( c \) and \( \sigma_c^2 \) have noninformative uniform priors. We truncated the log-normal distribution (only values >1.0 retained), so the Poisson rates would be above zero. The species-specific models were used to estimate golden and bald eagle minutes at 31 and 28 wind facilities, respectively, that recorded observations of eagles but not eagle minutes. The predictions of \( k_f \) and their uncertainty, were used to estimate the site- and species-specific estimates of eagle exposure.

Equation (3) was fit using JAGS (Plummer, 2003) within the statistical programming language R (R Core Team, 2019) via the rjags (Plummer, 2016) and runjags (Denwood, 2016) packages. For both species, we ran four chains of 10,000 iterations, with 40,000 discarded as burn-in and the Brooks-Gelman-Rubin statistic (R; Brooks & Gelman, 1998) used to monitor convergence.

### 2.2.3 Fatality estimates

We used U.S. Geological Survey’s Evidence of Absence (EoA) model and software (v2.0; Dalthorp et al., 2017, Appendix S2) to estimate eagle fatalities at a facility. EoA was used instead of the more recently developed Generalized Estimator (GenEst, Dalthorp et al., 2018), since GenEst is inappropriate in situations where no carcasses were found (see Dalthorp et al., 2018 for details). Estimations were performed for each data subset (facility, species, and, if relevant, different phases of data collection), totaling 72 analyses (Table 3). EoA uses Bayes’ formula to calculate the posterior distribution of fatalities, given the observed number of carcasses (restricted to those remains found during official searches, see Appendix S3), probability distribution of detection probabilities, and the prior distribution of fatalities. EoA estimates the detection rate using the search schedule (see Appendix S3 for information on each facility’s search schedule), distribution of carcass arrivals through time, persistence of carcasses through time, and searcher efficiency at each search (Dalthorp et al., 2017, Appendix S2).

EoA considers searcher efficiency and carcass persistence probabilistically and estimates both using data from each facility. For the searcher efficiency distribution, EoA requires data on the number of carcasses placed on the landscape and subsequently found by searchers: these data were available for 11 facilities. For the seven where only efficiency rate was available we assumed a mid-range number of carcasses (50) was placed (see Appendix S3).

Facilities typically reported carcass persistence as a mean persistence time with little supporting information (e.g., no error bounds on estimate) or with insufficient data to re-estimate persistence functions (see Appendix S3). We therefore used an exponential function to model carcass persistence, assuming the mean persistence time was functionally fixed by setting the confidence bounds to a nominal value of ±0.1 days (see Appendix S3). This permitted process uncertainty in carcass persistence, while minimizing parameter uncertainty from a poorly informed estimator. For facilities with more detailed data, we determined the maximum likelihood estimate of the persistence time under an exponential distribution (see Appendix S3).

The posterior distributions of fatalities resulting from the above calculations are representative only of those that occurred in the searched area at each wind facility. To make them representative of the entire facility, we used information on the fraction of turbines searched at each facility for each study duration (see Appendix S3) in a deterministic expansion. Thus, we used EoA to estimate the posterior probability distribution of the total number of fatalities at each facility during the study duration, and standardized the distribution to the time frame of 1 year through a deterministic conversion, producing a probability distribution of fatalities per year.

### 2.2.4 Species-specific estimates

We used the statistical programming language R (R Core Team, 2019) for our assessment of species-specific exposure and collision probability. In addition to the data on eagle minutes and fatalities already described, we also required information on survey effort and the hazardous space–time (\( \epsilon \), Equation (2)). Both values were constants calculated from data specified as part of the data suitability criteria (Tables 1 and 2).

A Gibbs sampler (Casella & George, 1992) was used to find the project-specific posterior distributions for exposure and collision risk. When estimating collision probability for some facilities, we subset the analyses by survey period when the study design for monitoring for remains of eagles changed over time, or when wind facilities were built in phases, so that the fraction of turbines searched varied between study durations. When the
| Facility | Species | Time period | Expected value | Median | HPPV | L 95% | U 95% |
|----------|---------|-------------|----------------|--------|------|------|------|
| AC5185N  | Golden  | 1           | 3.5            | 3.3    | 1.1  | 1.1  | 9.8  |
| AC5185N  | Bald    | 1           | 0.7            | 0      | 0    | 0    | 4.3  |
| BB6190I  | Golden  | 1           | 0.3            | 0      | 0    | 0    | 3.0  |
| BB6190I  | Bald    | 1           | 0.3            | 0      | 0    | 0    | 3.0  |
| BD6351O  | Golden  | 1           | 0.4            | 0      | 0    | 0    | 2.5  |
| BD6351O  | Golden  | 2           | 1.1            | 0.5    | 0    | 0    | 6.0  |
| BD6351O  | Golden  | 3           | 1.4            | 0.5    | 0    | 0    | 7.5  |
| BD6351O  | Bald    | 1           | 0.4            | 0      | 0    | 0    | 2.5  |
| BD6351O  | Bald    | 2           | 1.1            | 0.5    | 0    | 0    | 6.0  |
| BD6351O  | Bald    | 3           | 1.4            | 0.5    | 0    | 0    | 7.5  |
| BF10651I | Golden  | 1           | 2.4            | 1.0    | 0    | 0    | 13.0 |
| BF10651I | Bald    | 1           | 2.4            | 1.0    | 0    | 0    | 13.0 |
| CA7606W  | Golden  | 1           | 0.2            | 0      | 0    | 0    | 2.2  |
| CA7606W  | Golden  | 2           | 13.1           | 12.2   | 8.1  | 2.7  | 32.4 |
| CA7606W  | Golden  | 3           | 5.6            | 5.4    | 4.7  | 2.5  | 10.5 |
| CA7606W  | Bald    | 1           | 0.2            | 0      | 0    | 0    | 2.2  |
| CA7606W  | Bald    | 2           | 1.9            | 0      | 0    | 0    | 10.8 |
| CA7606W  | Bald    | 3           | 0.3            | 0      | 0    | 0    | 1.8  |
| EB4693O  | Golden  | 1           | 2.2            | 1.1    | 0    | 0    | 13.0 |
| EB4693O  | Bald    | 1           | 2.2            | 1.1    | 0    | 0    | 13.0 |
| HG2102U  | Golden  | 1           | 0.5            | 0      | 0    | 0    | 3.0  |
| HG2102U  | Bald    | 1           | 0.5            | 0      | 0    | 0    | 3.0  |
| PO7053C  | Golden  | 1           | 0.5            | 0      | 0    | 0    | 3.1  |
| PO7053C  | Bald    | 1           | 0.5            | 0      | 0    | 0    | 3.1  |
| PO7053C  | Bald    | 2           | 0.03           | 0      | 0    | 0    | 0.7  |
| PR3496O  | Golden  | 1           | 0.2            | 0      | 0    | 0    | 2.0  |
| PR3496O  | Bald    | 1           | 0.2            | 0      | 0    | 0    | 2.0  |
| QQ5262C  | Golden  | 1           | 12.7           | 12.2   | 10.8 | 5.4  | 23.3 |
| RO4757A  | Golden  | 1           | 4.6            | 4.0    | 2.8  | 1.0  | 11.6 |
| RO4757A  | Bald    | 1           | 2.8            | 2.3    | 1.0  | 0.3  | 8.3  |
| RQ2001I  | Golden  | 1           | 22.8           | 20.9   | 16.7 | 6.3  | 50.1 |
| RQ2001I  | Golden  | 1           | 20.0           | 17.7   | 12.5 | 4.2  | 50.1 |
| RQ5014V  | Golden  | 1           | 2.8            | 1.0    | 0    | 0    | 15.6 |
| RQ5014V  | Bald    | 1           | 2.8            | 1.0    | 0    | 0    | 15.6 |
| RR3306O  | Golden  | 1           | 0.3            | 0      | 0    | 0    | 2.7  |
| RR3306O  | Bald    | 1           | 0.3            | 0      | 0    | 0    | 2.7  |
| RS1236U  | Golden  | 1           | 6.5            | 6.1    | 5.1  | 2.0  | 14.2 |
| RS1236U  | Bald    | 1           | 0.7            | 0      | 0    | 0    | 4.1  |
| VX2855B  | Golden  | 1           | 0.03           | 0      | 0    | 0    | 0.3  |
| VX2855B  | Golden  | 2           | 0.1            | 0      | 0    | 0    | 0.7  |
| VX2855B  | Bald    | 1           | 0.03           | 0      | 0    | 0    | 0.3  |
| VX2855B  | Bald    | 2           | 0.1            | 0      | 0    | 0    | 0.7  |
subsets were necessary, we calculated the project-specific distributions of collision probability for each species from mixture distributions based on the within project posteriors from each study duration. We then used all the site-specific information to build species-specific mixture distributions for exposure and collision risk. The mean and variance of the mixture distributions were used to define the parameters for the gamma and beta distributions that, respectively, describe the variation in exposure and collision risk for bald and golden eagles nationally.

### 2.2.5 Case study

To explore the implications of using species-specific information, we compared the fatality predictions from the three sets of prior distributions: in the absence of pre- and post-construction monitoring, when only preconstruction data were available, and when both eagle use and eagle fatality data had been collected. The data to inform the model came from an operational wind facility in Converse County, Wyoming, with 110 turbines, an expansion factor of 588.62 hr km\(^{-3}\), 103 eagle min observed during 47.05 hr km\(^{-3}\) of effort, and an estimated 3.98 eagle fatalities year\(^{-1}\) (New et al., 2015).

### 3 RESULTS

#### 3.1 Data

The earliest wind facility considered in this analysis was operational in 1983, while the most recent are facilities that, as of 31 December 2016, were in the planning stages. Data were available from 38 states (Alabama, Alaska, Arizona, Arkansas, California, Florida, Georgia, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Michigan, Minnesota, Mississippi, Montana, Nevada, New Hampshire, New Mexico, New York, North Carolina, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Vermont, Washington, West Virginia, Wisconsin, Wyoming) and one territory (Puerto Rico).

Using the suitability criteria for exposure data (Table 1), 71 wind facility sites were identified as having data appropriate for informing eagle exposure. Combined with the 9 sites used in New et al. (2015), information from a total of 80 wind facilities was available to inform exposure, 38 of which explicitly monitored for both golden and bald eagles. The remaining sites only made reference to one eagle species, making it impossible to infer whether the unmentioned species was absent from the wind facility, or seen but not recorded. Based on the species of eagle recorded, of the remaining wind facilities, 22 were considered to have data only relevant to golden eagles, and 20 to have data only relevant to bald eagles. This gave a total of 60 and 58 wind facilities to inform golden and bald eagle exposure, respectively.

Of the 71 wind facilities, 18 met the suitability criteria for collision data (Table 2) making them appropriate for inclusion in the collision probability analysis. Combined with the 4 sites used in New et al. (2015), a total of 22 wind facilities were available to inform collision risk. Of the 22 wind facilities, 14 had relevant data on both golden and bald eagles, while the remaining 8 had data relevant only to golden eagles. Therefore, a total of 22 and 14 wind facilities were used to inform golden and bald eagle collision probability, respectively.

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### 3.2 Exposure estimates

For golden eagles, the estimates of the mean conversion factor of eagle observations to minutes, \( \hat{c} \), (1.27, SD: 0.067) and its variation, \( \hat{\sigma}_{c} \), (0.62, SD: 0.16), translate to an average of 2.57 (SD: 1.60) golden eagle minutes per
eagle observation. For bald eagles, the estimates of $\hat{c}$ (1.16, SD: 0.057) and $\hat{\sigma}_c$ (0.78, SD: 0.16), translate to an average of 2.21 (SD: 1.49) bald eagle minutes per eagle observation.

### 3.3 Fatality estimates

There were 37 detected eagle remains, only one of which was a bald eagle (see Appendix S3). The estimated annual

![FIGURE 1](image-url)

**FIGURE 1** The distribution of exposure ($\lambda$) for golden eagles (a), bald eagles (b), and a comparison of the species-specific collision probability priors to the one presented in New et al. (2015) (c). The species-specific distributions were based upon a mixture distributions built from the posterior distributions of exposure from the sites identified has having new information on golden and bald eagles. The vertical lines represent the means of the gamma distributions. The insert provides a more detailed view of the distributions for those sites with golden eagle exposures $\leq$ 1 eagle min hr$^{-1}$ km$^{-3}$ (a) and those sites with bald eagle exposures $\leq$ 2 eagle min hr$^{-1}$ km$^{-3}$ (b).
rate of fatalities ranged from 0.03 to 22.8, with a mean of 2.3 (SD: 4.1) (Table 3). The estimated fatality rates tended to be higher for golden eagles (2.8 eagles yr\(^{-1}\), SD: 4.68) than bald eagles (0.9 eagles yr\(^{-1}\), SD: 0.95).

### 3.4 Species-specific estimates

The species-specific estimates for eagle exposure had a mean of 1.21 eagle minutes hr\(^{-1}\) km\(^{-3}\) (SD: 0.352) for golden eagles and 3.19 eagle minutes hr\(^{-1}\) km\(^{-3}\) (SD: 2.583) for bald eagles (Figure 1a,b). The estimate of average exposure for both species has decreased compared to the previous prior (8.79 eagle minutes hr\(^{-1}\) km\(^{-3}\), SD: 13.64; New et al., 2015), although the shift is less pronounced for bald eagles (Figure 1c).

The species-specific estimates for collision probability had a mean of 0.005648 birds per minute of exposure (SD: 0.004413) for golden eagles and 0.007025 eagles per minute of exposure (SD: 0.004379) for bald eagles (Figure 2a,b). Comparing these updated distributions to those from New et al. (2015) indicates that the modes

![Golden Eagle Collision Probability Prior](a)

![Bald Eagle Collision Probability Prior](b)

![Collision Probability Priors](c)

**FIGURE 2** The distribution of collision probability (C) for golden eagles (a), bald eagles (b) and, a comparison of the species-specific collision probability priors to the one presented in New et al. (2015) (c). The species-specific distributions were based upon a mixture distributions built from the posterior distributions of collision probability from the sites identified has having new information on golden and bald eagles. The vertical lines represent the means of the beta distributions, as well as the medians in (a) and (b).
have shifted to the left (Figure 2c), and the most likely value for each species’ collision probability has decreased compared to the previous prior (0.0058 birds per minute of exposure, SD: 0.0038; New et al., 2015). However, because of greater uncertainty in the estimate of collision probability for bald eagles, the mean is higher than reported in New et al. (2015).

3.5 | Case study

The implications of the species-specific distributions can be demonstrated by comparing the fatality predictions from the three sets of prior distributions. Using the expansion factor from the facility in Converse County, WY, but not the available pre- or post-construction data, the 80th quantile for the original priors is 42.8 eagle fatalities year\(^{-1}\) (mean: 30.12 fatalities year\(^{-1}\), SD: 58.9). When only pre-construction data are available the 80th quantile for the original priors is 11.02 eagle fatalities year\(^{-1}\) (mean: 7.48 fatalities year\(^{-1}\), SD: 4.97), and when post-construction fatality data are also available, the 80th quantile is 6.32 fatalities year\(^{-1}\) (mean: 4.80 fatalities year\(^{-1}\), SD: 1.98).

For the species-specific priors, when using the expansion factor but not the available pre- or post-construction data, the resulting fatality predictions are substantially lower compared to the original priors, at 4.66 golden

![Figure 3](https://example.com/figure3.png)

**FIGURE 3** Histograms of the posterior distribution of fatalities (F) for the original CRM priors from New et al. (2015) (a, b, c) and the bald (d, e, f) and golden (g, h, i) eagle specific priors, in the absence of any pre- or post-construction data (a, d, g), when only pre-construction data are available (b, e, h) and when pre- and post-construction data are available (c, f, i). The vertical lines represent the mean and 80th quantile in each figure.
eagles year⁻¹ (mean: 4.03 fatalities year⁻¹, SD: 10.20) and 4.2 bald eagle fatalities year⁻¹ (mean: 13.3 fatalities year⁻¹, SD: 61.3) at the 80th quantile (Figure 3a,d,g). Using only preconstruction data, the species-specific priors result in slightly higher values than the original priors, better representing the potential variation in fatalities across a wider spatial range, and resulting in fatality predictions of 11.44 golden eagles year⁻¹ (mean: 7.26 fatalities year⁻¹, SD: 6.48) and 13.82 bald eagle year⁻¹ (mean: 9.03 fatalities year⁻¹, SD: 7.17) (Figure 3b,e,h). When postconstruction fatality data are also included, the three sets of priors gave almost identical results, with the 80th quantile for the species-specific priors resulting in a fatality prediction of 6.00 golden eagles year⁻¹ (mean: 4.47 fatalities year⁻¹, SD: 2.01) and 6.32 bald eagle fatalities year⁻¹ (mean: 4.75 fatalities year⁻¹, SD: 2.06) (Figure 3c,f,i). Given that the species-specific priors distributions are more representative of the existing knowledge of the eagles’ risk, they are the best supported approach to predicting fatalities.

4 | DISCUSSION

There is a global benefit to reducing fossil fuel use (e.g., Rao et al., 2016; van Vuuren et al., 2017), but the potential environmental cost of renewable energy (e.g., Carrete et al., 2009; Haxton & Cano, 2016; Visser et al., 2019) cannot be ignored. This creates an apparent tradeoff, whereby in preserving the global environment, we may cause the loss of some of the ecosystems, habitats and species we are trying to protect. It can be argued that these local losses are reasonable, given the costs associated with climate change’s current trajectory (e.g., Allison, Root, & Frumhoff, 2014; Thomas et al., 2004; Warren et al., 2013). However, the impacts of these losses are wider reaching than previously recognized, particularly for eagles (Katzner et al., 2017), and the cumulative damage at the local level may have severe implications without consideration of the wider landscape in which it is occurring. Individual stakeholders may rarely have sufficient information to make decisions at anything but the local scale. Instead, policy that takes into account a broader scale and existing uncertainties can be important in guiding individual stakeholder decisions.

In the U.S., energy policy has been evolving since the first utility and power laws were passed in 1935 (74-333 15 U.S.C.A. § 79 et seq.; 16 U.S.C. 791-828c), and now includes renewable energy (e.g., Chernyakhovskiy, Tian, McLaren, Miller, & Geller, 2016). Many rules and regulations focus on wind power (e.g., NRC, 2007), including promotion of its development (e.g., Sherlock, 2018). However, given the bird and bat fatalities known to occur at wind facilities (e.g., Barclay et al., 2007; Carrete et al., 2009; Kunz et al., 2007), there are also policies to ensure that the cumulative loss across multiple installations does not threaten species’ persistence. FWS’s programmatic environmental impact statement for the eagle rule revision (USFWS, 2016a) is one such policy seeking to balance wind energy development, U.S. law, uncertainty, and species conservation.

When first implemented, FWS’ eagle conservation plan used the available data from a small number of wind facilities to inform the predicted risk to bald and golden eagles (USFWS, 2013). Although the plan was intended to be used in an adaptive management framework, thus improving as additional data were collected, this initial small sample size raised questions among stakeholders about the policy’s effectiveness in balancing wind power’s development with bald and golden eagle conservation. To address this concern, and demonstrate the effectiveness of the adaptive management framework, we collated information from terrestrial wind facilities in the U.S., generating substantially more data than has been available for similar assessments of species risk (e.g., Hull et al., 2013; New et al., 2015). For both species, the larger sample size reduced the uncertainty in eagle exposure (Figure 1c). There was a slight increase in the variability around both estimates of collision probability (Figure 2c), accurately reflecting the greater spatial and temporal scale of the information now available to inform collision probability, because the parameter’s initial distribution was based on data from a single geographic region.

The distributions of bald and golden eagle exposure and collision risk (Figures 1c and 2c) overlap with one another. The bald eagle estimates were more variable, and the species had higher mean exposure and collision risk in comparison to golden eagles. While there were fewer bald eagle data available, which can contribute to the increased variability, bald eagle exposure was less variable than the initial prior for λ, thus providing an improvement. Furthermore, there were negligible differences between the posterior distributions for collision probability, despite the greater data available for golden eagles (Figure 2c).

Changing the priors has implications for bald and golden eagle management and conservation in the U.S. Using the 80th quantile for the permitting process’ initial estimate of fatalities was intended to insert conservatism in the face of uncertainty, protecting the species while motivating wind facilities to monitor and collect data to help improve the estimate of their effect on the eagle populations. The expectation was that as more data became available the uncertainty in the eagle fatality estimates would decrease (USFWS, 2013). When data are
absent, this is exactly what happens (Figure 3a,d,g); the 80th quantile, due to the lower means and variation, produces substantially lower fatality estimates for the species-specific priors compared to the original distributions. The importance of data collection in reducing uncertainty can be seen in how pre-construction exposure data lowers the fatalities estimates, and the use of postconstruction data results in no remaining sensitivity to the choice of prior distributions.

Given the similarities in collision probability and rate of exposure for the two species, the data do not currently support the contention that bald eagles are less likely to collide with wind turbines than golden eagles (USFWS, 2016a). Consequently, the stakeholder debate regarding the eagles’ relative risk may be a result of fewer documented bald eagle fatalities at wind facilities compared to golden eagles. This may be a result of fewer wind facilities being built within the riparian habitat preferred by bald eagles (Schmucker et al., 2020), or even juvenile bald eagles being mistaken for golden eagles. However, fewer observations does not mean fatalities are not occurring, only that they are not being seen (Table 3). The absence of direct observations creates a bias due to the availability heuristic, in which people make decisions and draw conclusions based on the information they mentally access the most quickly (Tversky & Kahneman, 1973). For eagle fatalities at wind facilities, the majority of stakeholders are likely to have access to information on the recorded number of eagle remains found during carcass searches. These data inform the estimated number of fatalities to have actually occurred, but these estimates may not have been communicated with all stakeholders. This may lead to the belief that bald eagles have a lower probability of collision than golden eagles.

These results will not end the debate as to the actual risk faced by golden and bald eagles, or the best approach for balancing energy development and eagle conservation. Future analyses could benefit from additional data made publicly available from wind facilities, for example, by reducing the self-selection bias in the literature. Yet, even acting within the current limitations, as more data are collected the assessment of risk can be refined to take into account additional factors, such as habitat type and season. Regardless, our results can help us better understand the potential environmental costs of wind power. The improved species-specific fatality predictions enable a better assessment of an individual facility's risk to each species, and the effects it will have on species conservation. This highlights how adaptive management can lead to improved estimates, potentially reducing the need for mitigation, while still protecting species of concern. This, in turn, may allow more informed decisions about the environmental cost of renewable energy.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

Leslie New, Mark C. Otto, Emily Bjerre, Michael C. Runge, and Brian Millsap conceived and designed the analysis. Leslie New, Juniper L. Simonis, and Mark C. Otto analyzed the data. Leslie New, Juniper L. Simonis, Mark C. Otto, Emily Bjerre, Michael C. Runge, and Brian Millsap contributed materials, data and analysis tools. Leslie New, Juniper L. Simonis, Mark C. Otto, Emily Bjerre, Michael C. Runge, and Brian Millsap wrote the article.

DATA AVAILABILITY STATEMENT

Data used in this analysis were provided to the U.S. Fish and Wildlife Service as confidential business information (19 CFR § 201.6), so only those data provided in Appendices S3 and S4 can be made publicly available.

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**SUPPORTING INFORMATION**
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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