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RESEARCH ARTICLE

Assessing carcass relocation for offsetting golden eagle mortality at wind energy facilities

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Abstract

As wind energy expands to achieve the United States' net zero emission goals, compensatory mitigation will be required to offset negative effects on birds and bats. The golden eagle (*Aquila chrysaetos*) is particularly susceptible to collision with wind turbines, but only 1 option for offsetting mortalities has been approved by the United States Fish and Wildlife Service despite many sources of anthropogenic-caused mortality. We update a previously developed vehicle-collision model with data collected during 3 winters from 2016 to 2019 and integrate a resource equivalency analysis so that relocation of road-killed game animals can be used as mitigation to offset incidental mortality. We parameterized golden eagle behaviors using motion-sensitive cameras placed at roadside carcasses. We quantified the effects of different carcass-relocation schemes based on vehicle and carcass characteristics observed for Wyoming, USA. Our model results indicate that while eagles saved per relocated carcass depends on relocation interval and vehicle traffic volume, carcass relocation is a viable mitigation strategy; up to 7 eagles could be saved each year in some counties. While some uncertainty remains about the precise credit received from each carcass relocated, delaying the inclusion of additional mitigation methods prevents opportunities for conservation action. An adaptive management program could be a way forward where management and monitoring are combined to further improve estimates of mitigation credit.

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KEYWORDS

Aquila chrysaetos, Bald and Golden Eagle Protection Act, compensatory mitigation, scavenger conservation, simulation model, take offsets, vehicle collision

Wind power is a growing source of energy in the United States and with the recent passage of the Inflation Reduction Act, will continue to expand. A recent report on the potential for the United States to meet a net zero carbon emissions goal suggests that the country will need to increase energy production from wind turbines by 2.5 to 3.0 times the current installed capacity (Larson et al. 2021). Unfortunately, wind turbines can also have negative effects on wildlife such as birds and bats (Allison et al. 2019) including mortality, referred to as incidental take. Eagles are particularly susceptible to incidental take (Pagel 2013), and the United States Fish and Wildlife Service (USFWS) has concluded that the golden eagle (*Aquila chrysaetos*) population in the United States is limited by anthropogenic mortality (USFWS 2016); any increase in mortality could lead to a population decline inconsistent with the preservation standard set by the USFWS in the proposed revised eagle rule (USFWS 2022*a*, *b*). Thus, any permits to take golden eagles at wind energy facilities must accomplish no net loss through implementation of actions that avoid, minimize, and offset the predicted take.

Despite the sources of anthropogenic-caused mortality for eagles, retrofitting electric power poles to prevent electrocution of eagles is the only current option approved in the proposed eagle rule revision for wind projects seeking permits (USFWS 2013). Having just 1 option can limit the ability of wind energy companies to implement the mitigation options required for compliance with the rule. Other sources of mortality and reduced reproduction include lead poisoning from scavenged gut piles, loss of habitat and prey sources, and collisions with vehicles while scavenging on roadkill (Allison et al. 2017), but these mitigation options are rarely used; their application lacks guidance from the USFWS.

Although requirements for approval of mitigation options have not been stated formally, the approach used to translate mitigation actions into offset credits, the estimated number of golden eagles saved each year, would benefit from following 3 interrelated criteria. First, the mitigation actions must be scientifically rigorous and transparent (e.g., the logic has been subject to review and collectively agreed upon; Allison et al. 2017). Second, the efficacy of a mitigation approach needs to be verified (i.e., the predictions are defensible, models have been tested against observation data, and the level of uncertainty is sufficient for use with mitigation; Cochrane et al. 2020). Finally, the effect of mitigation should be measurable in units identical to the predicted take allowing for easier comparisons to show that the mitigation is equivalent to or greater than the take to be offset (i.e., must be able to translate the number and frequency of carcasses relocated into golden eagles saved). The USFWS provides an example in the eagle conservation plan guidance of how to use resource equivalency analysis (REA) to calculate lost eagle-years due to electrocution mortality (USFWS 2013) and achieve the goal of offset equivalence to take.

Lonsdorf et al. (2018) developed frameworks for predicting mortality due to collisions from vehicles while an eagle is scavenging on roadkill. The structure of the vehicle collision model was vetted by experts and is logical and straightforward as it lays out the steps that could lead to a vehicle collision: given data from departments of transportation on the occurrence of roadkill, the model describes the number of eagles detecting roadkill, their feeding time on the carcass, the number of vehicles near the carcass, and then predicts the probability of an eagle being hit. While there is confidence in the structure of the model, few data were available to parameterize it, so experts were surveyed to elicit functional forms and parameter values. The resulting estimates for mortality rate had considerable uncertainty and were not integrated with an REA. The authors concluded that prioritizing research to update the relationship between eagles and carcasses would increase the reliability of predictive modeling efforts and specific mitigation values.

Two recent studies have since been published with results that could be leveraged to refine the vehicle collision model to increase its acceptance and use as an offset option for eagle take. First, Slater et al. (2022) recently completed an assessment of golden eagle behavior at carcasses along roads. Using motion-sensitive cameras, they recorded eagle use at >150 carcasses along roads in Oregon, Wyoming, and Utah. These data could be used to estimate the functional forms and parameter values for carcass use in the vehicle collision model. Second, Millsap et al. (2022) evaluated survival rates and the cause of death for golden eagles, collating data from over 175 eagles fitted with transmitters and were able to identify the cause of death for 126 of them. Among the several causes of death from anthropogenic sources, Millsap et al. (2022) suggested that collisions lead to a roughly 2% annual mortality rate, and that around half of collisions were with vehicles, mostly during the winter scavenging season. Millsap et al. (2022) provides a valuable constraint to the outcomes that can be used to identify plausible parameter values. Together, these 2 studies could help improve confidence in the parameter estimates and functional forms, providing necessary verification of the model's predictions.

Using insights and data from these 2 recent studies to improve confidence in the output of the Lonsdorf et al. (2018) vehicle collision model, our goal was to improve the ability to use carcass relocation as a mitigation option. Hereafter, carcass relocation refers to moving a carcass ≥12 m away from the roadside, following Slater et al. (2022). While factors could constrain the ability to move the carcass safely, such as property boundaries, topography, or fencing, Slater et al. (2022) reported that 2 people could easily and quickly move a carcass with rope and a sled under any conditions. We integrated the updated model with the REA to translate the model output into mitigation credit. We developed a workflow based on nationally available traffic data and applied the workflow to a case study in Wyoming to illustrate the model's potential application. We evaluated the potential effectiveness of roadkill relocation to offset incidental take by addressing if the effectiveness of the option varied with the strategy taken (location and amount of effort) and if the effectiveness was enough for roadside carcass relocation to be a viable option for mitigating incidental take.

STUDY AREA

While the main purpose of this paper is to describe improvements to the golden eagle–vehicle collision model, we applied the model to Wyoming. Wyoming has an area of just over 253,000 km^2 and is a well-known breeding area for golden eagles. Wyoming's topography is diverse and characterized by a mix of rugged mountain ranges, broad valleys, and plains. Within this diverse topography, the sagebrush steppe ecosystem is widespread across Wyoming, particularly in the southwestern and central parts of the state. This ecosystem is dominated by sagebrush (*Artemisia* spp.) and other shrubs, grasses, and forbs.

METHODS

We developed a model (Figure 1) of golden eagle mortality due to vehicle collisions. This model is conceptually like the model of Lonsdorf et al. (2018) but is parameterized using a combination of empirically derived and inferred parameters, rather than by expert judgment. We derived the empirical parameters from a large dataset of eagle–carcass roadside interactions obtained by HawkWatch International (HWI) and chose the inferred parameters to ensure that estimated golden eagle mortality agrees with recent observations (Millsap et al. 2022).

Like the Lonsdorf et al. (2018) model, there are 3 external factors that set the stage for the model: the number of golden eagles at risk, which is a function of the density of eagles; the number and size of deer (*Odocoileus* spp.) carcasses expected; and the road structure on which the carcasses are found represented by traffic volume (t). The new model structure diverges from the previous model by simulating the fate of a carcass and eagle behavior each day for a season. Modeling carcasses each day allows us to be explicit about carcass relocation strategies and keep track of the number of carcasses collected and the mitigation created by removing each carcass. The simulation models each carcass twice: with and without a given carcass relocation strategy.

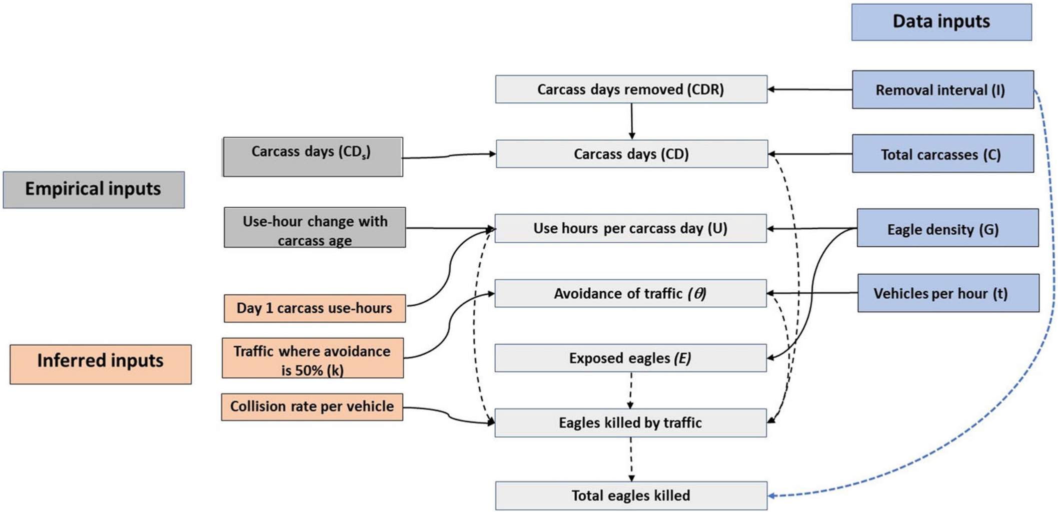

FIGURE 1 Model diagram illustrating the cause-to-effect relationships (directional arrows) between input and output parameters in the golden eagle vehicle collision model for the assessment of data from 2016 to 2019 in Wyoming, USA. Blue boxes represent input data, dark grey boxes are parameter estimates derived from empirical studies presented in this paper, salmon-colored boxes are parameter estimates inferred from results from other studies and light grey boxes are model calculations. Solid lines show how parameter values are integrated into equations and dashed lines indicate where the results of one equation are integrated into another. The number of eagles killed is summed over all road segments in a simulation. Adapted from Lonsdorf et al. (2018).

Model description

Our updated approach calculates the number of eagles killed (M) by determining risk created by a single carcass and then summing over the risk of each of n total carcasses. This is expressed by the following equation:

$$M = \sum_{i=1}^{N} (1 - (1 - \mu)^{v_i H_i}), \tag{1}$$

where μ is the vehicle–eagle collision probability, v_i is the traffic volume in average vehicles per hour (vph) where carcass (i) occurs, and H_i is the number of eagle use-hours per carcass. This equation is conceptually identical to the power function in Equation 1 of Lonsdorf et al. (2018), with the exponent representing the number of vehicles passing scavenging eagles and the base representing the survival probability. The nature of the individual terms is different. The number of eagle use-hours per carcass (H_i) is calculated as a sum over the days that the carcass is available because the use-hours per day (h_d) is a decreasing function of time:

$$H_i = (1 - \theta_t)\varepsilon \sum_{d=1}^{D_i} h_d \tag{2}$$

Here, D_i is the number of days carcass i is available, h_d is the expected number of hours eagles will scavenge each day carcass i is available in the presence of the reference density of eagles, θ_t is the avoidance probability due to traffic volume t; and ε is a unitless factor modifying the day 1 carcass-use hours. The value of ε is constrained by the requirement that modeled overall golden eagle mortality due to vehicle strikes agrees with values in the literature (Millsap et al. 2022). The model assumes that road avoidance is a direct and saturating function of average vehicle volume/hour and avoidance affects all eagle age classes equally.

Eagles can be disturbed by vehicle traffic such that as the volume of cars per hour increases, an increasing portion of the eagles perceive the road as no longer suitable for scavenging. In Lonsdorf et al. (2018), experts believed that increasing traffic would reduce the number of eagles scavenging and the time spent on the carcass by those eagles that still scavenged. The avoidance probability (θ_t) for each road with traffic volume t is:

$$\theta_t = \frac{t^2}{t^2 + k^2}, \tag{3}$$

where t is the traffic volume (vehicles/hour) and k is the traffic avoidance parameter, the traffic volume with 50% traffic avoidance. Experts suggested previously that k was between 10 and 35 vehicles/hour (Lonsdorf et al. 2018). Provided that the collision probability μ is very small, the factor ε can also serve to modify the reference eagle density or μ (see equations in Supporting Information). Avoidance is 0% with 0 cars/hour and at some traffic volume avoidance approaches 100%.

Parameter estimates using observed data

We focused our model improvements on updating the representation of golden eagle behavior at carcasses. The HWI data consisted of 1,933 photo interpretations of eagle behavior at roadside deer carcasses, captured with motion-sensitive cameras. Slater et al. (2022) provides additional details. The interpretations were from a larger set of motion-sensitive camera observations, and we omitted 12 interpretations because of evident transcription errors. The data included a unique identifier for each camera and provided the length of time the camera observed the carcass. For purposes of modeling the camera data, we assumed that this corresponded with the actual length of time the carcass was available for golden eagle scavenging.

We recognize that the carcass may have been scavenged or decayed prior to placing the camera (although cameras were placed preferentially near recent roadkills), and we discuss the potential effects on the model below. Further, a reviewer analyzed each camera for each frame, and noted when they observed a golden eagle arriving at the carcass and leaving, which allowed computation of the time spent scavenging at the carcass. Using the HWI data, our goals were to improve the parameter (D_i) representing the expected number of carcass-days available if there is no relocation and to parameterize the number of hours scavenging per carcass day.

When an ungulate is killed by a vehicle collision, the carcass becomes available for scavenging by eagles, but over time, the carcass quality declines as carcass-days increase and eventually the carcass is no longer available or has degraded to the point of having no value to eagles. To estimate the probability that the carcass persists, we fit a distribution to the HWI data for each carcass on the number of observed days they persisted. From the resulting frequency distribution of carcass days from 75 carcasses (Figure 2A), we fit a Cauchy distribution such that the probability that carcass i persists for d days is: $D_i = \frac{2N}{\pi\gamma\left(1+\left(\frac{d-x_0}{\gamma}\right)^2\right)}$, where d can take on positive integer values, γ is a scaling factor, and N is a normalization factor that assures that the discrete sum over probabilities is 1. We chose a Cauchy distribution with offset parameter $x_0 = 0$ because it has the following properties appropriate to the problem at hand: a fat tail and thus can represent the data points >30 days; monotonic decrease from the y-intercept; a single-parameter distribution, thus decreasing the likelihood of overfitting; and lower fitting errors than other distributions meeting the above 3 criteria.

We fit carcass persistence by determining the parameter γ, which led to the lowest error in an ordinary least squares (OLS) sense, where the OLS calculation was extended out to 100 days as the upper limit for the calculation. We tested several other functional forms for the model (including a Gaussian distribution, a 1/t type of distribution, and an exponential distribution) and confirmed that they led to a higher error or had undesirable properties for carcasses aged beyond a few days (Tables S1–S3, Figures S1–S3, available in Supporting Information).

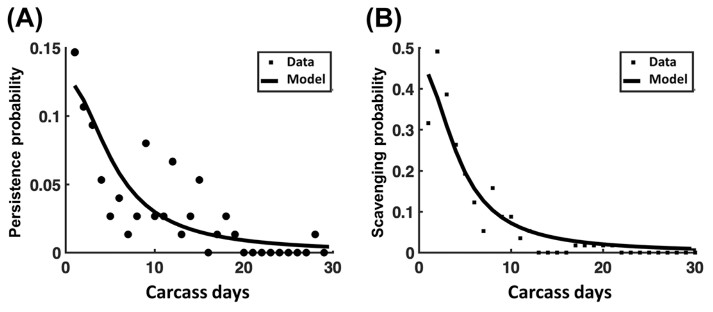

FIGURE 2 The effect of deer carcass age (days) on persistence, scavenging, and use by golden eagles from 2016 to 2019 in Wyoming, USA. A) Deer carcass persistence data based on HawkWatch International (HWI) data and B) daily probability of scavenging calculated as the number of carcasses with observed scavenging that many days after motion-sensitive camera is set divided by the number of cameras. The model is a Cauchy distribution with $\gamma = 5.56$. C) Hours/carcass day if there was scavenging. The model is a Cauchy distribution with parameter $\gamma = 4.32$.

Our assessment of the HWI data suggested that use-hours can be modeled by a 2-step process that retains use-hours' dependence on carcass age. The first step is to determine the probability that the carcass is scavenged at all; the second is to determine the amount of time spent per day of scavenging when observed. The use-hours per carcass day is the product of these processes, and for simulation purposes we assumed scavenging every day with the number of use-hours discounted by the probability of scavenging.

To estimate the probability that a deer carcass is scavenged, we fit a Cauchy distribution to the HWI data in a manner analogous to fitting carcass-days (and choosing a Cauchy distribution for similar reasons; Table S4, available in Supporting Information). For each deer carcass, we assessed the number of days (from initiation of photography) where ≥1 complete scavenging interval was observed.

To model the expected use hours per scavenged carcass, we fit a Cauchy distribution to the average observed use hours per scavenged carcass as a function of the day (Figure 2C). The parameters of that distribution ($\gamma = 9.267$) are determined from the HWI data and do not change in modeling vehicle strike. Because there is large variability in use-hours, our use-hour model samples a value from a half-normal (positive values only) distribution with mean value equal to the average use-hours per day.

When applying the use-hours per day function in the model, we assumed the decrease in use-hours per day follows the fitted model, but we multiplied the entire function by a constant corresponding to a correction for day-1 use hours. In other words, we fit use-hours per day (Figure 3) multiplied by a constant, ε, when applying to the model. There are several reasons why such a correction may be necessary; primarily, the observed use-hours data is of eagles in the presence of traffic, but the model in Equation 1 handles decreases in scavenging due to traffic through the avoidance function θ. Other possible reasons include discrepancies in the density of eagles or the effects of carcass aging prior to the start of observations.

Simulation model

We implemented a numerical simulation using the MATLAB coding language (Mathworks, Natick, MA, USA). Following Lonsdorf et al. (2018), the simulation leverages vehicle traffic and carcass data from the Wyoming Department of Transportation (Wyoming Department of Transportation 2013) and as a first step within each county places a county-specific number of carcasses on roadways with vehicles per hour data characteristics. If the number of carcasses is fractional, there is stochastic rounding to a bounding integer (e.g., an average of 54.3

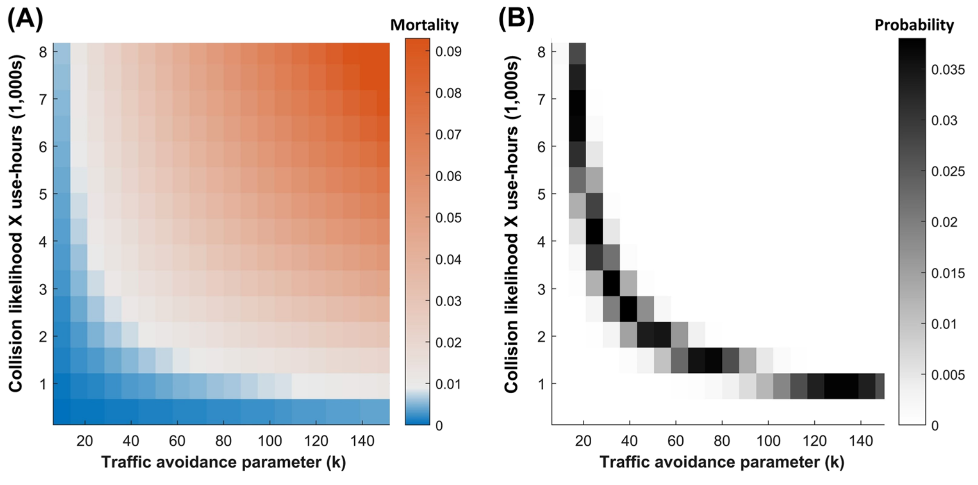

FIGURE 3 The relationship between model parameter combination and survival and resulting probability of being selected in a mitigation simulation based on golden eagle data collected from 2016 to 2019 in Wyoming, USA. The traffic avoidance parameter *k* (Equation 3) varies from 10 to 150. The product of collision likelihood and use-hour scalar varied from 0.0008 to 0.004. A) Surface plot of simulated eagle mortality with no carcass relocation for a variety of parameters. B) Probability of selecting the parameter combination given Millsap et al. (2022) results.

carcasses has a 70% chance of being simulated as 54 carcasses and a 30% chance of being simulated as 55 carcasses). The distributions of carcass persistence days and use-hours are each sampled, and the mortality is calculated from Equations 1 and 2, first with zero relocations, then with carcass relocations at tested intervals: 1, 3, 7, 14, and 30 days. Relocation intervals begin randomly relative to carcass days. If the relocation day occurs on the final day of carcass availability, this is counted as a carcass relocation and the number of use-hours on that final day is reduced by 50%. This procedure is repeated for 500 iterations per interval to allow calculations of 20th, 50th, and 80th percentile values.

We then used the updated simulation model to evaluate relocating carcasses from roads in Wyoming on golden eagle vehicle collisions, using the same data from Lonsdorf et al. (2018), which analyzed data from a 10-year study of roadkill on Wyoming highways. We assessed the effect of relocation rate from 1 to 30-day intervals applied to all roads within each of Wyoming's counties.

Inferred parameters

There are 3 parameters in the model of Equation 1 (collision probability μ, traffic avoidance half-saturation constant k, and use-hour scaling constant ε; Figure 1). Provided that eagle–vehicle collisions are rare ($\mu < 1$), the parameters μ and ε are effectively linked (see reduction from 3- to 2-parameter model in Supporting Information) and can be treated as a single parameter, $\varepsilon\mu$. We attempted to determine k empirically, but there were not enough data to estimate a distribution or relationship between traffic volume and flushing rates.

There are *a priori*, a range of possible values of μ and ε for which the formalism of the present model can be used. Before simulating the effects of carcass relocation, we explored a range of values of the traffic avoidance parameter k, the collision probability μ, and the use-hour scaling constant $\mathcal{E}$. We varied k from 10 to 150, expanding the range from the previous expert elicitation (Lonsdorf et al. 2018), and we similarly used a ranged of values from the product of $\varepsilon \times \mu$ to simulate the resulting eagle mortality as a function of these drawn parameters. Each combination predicted number of golden eagles killed by vehicle collisions in Wyoming. Within all parameter combinations generated by experts, golden eagle mortality ranged from 0.02% to 9.47%. To estimate the effects of mitigation, Lonsdorf et al. (2018) previously sampled all combinations of parameter values uniformly such that each parameter value was equally likely, independent of other parameter values.

These values can now be further constrained with updated knowledge of expected adult eagle mortality due to collisions and the proportion of collisions that were with vehicles. Millsap et al. (2022) provides estimates and sources of annual mortality for golden eagles. Out of 27,281 eagles observed at the start of a year, they estimated 560 died from collisions leading to a mortality rate from collisions of 2.05% (95% credible interval from 1.38% to 2.76%). Millsap et al. (2022) also reported on more precise causes of death from 175 eagles that were fitted with transmitters, including 16 that died from collisions. Of those, 10 were of known causes, and of those, 5 were from vehicle collisions, with the others with wind turbines, trains, or power lines. Although the transmitter data provides a small sample size, the combination of these findings indicated that about half of all mortality from collisions could be due to vehicles. Millsap et al. (2022) does state that they could not statistically differentiate collision sources, indicating that vehicle collision could be somewhat higher or lower, depending on the proportion of all collisions that were with vehicles. For the purposes of setting constraining parameter space, our estimate uses all available information.

Using a normal distribution, we probabilistically sampled the parameter space to simulate the effects of relocating carcasses on mortality so that the estimated mortality from vehicle collisions in Wyoming would be consistent with estimates from Millsap et al. (2022). Specifically, the probability of drawing a parameter combination, c, that yielded an estimated statewide mortality rate of m, was $p(c|m) = \left(\frac{1}{\sigma\sqrt{2\pi}}\right)e^{-\frac{(m-\delta)^2}{(2\sigma^2)}}$, where δ and σ represent the target mean mortality rate and standard deviation. We used Millsap et al. (2022) to represent mean and standard deviation, setting δ as 0.0103 and σ to 0.00175, which leads to the target expected mortality rate of 1.03% with 95% credible interval of ±0.35%.

Integrating model with resource equivalency analysis

In the eagle conservation plan guidance (USFWS 2013), the USFWS provides a resource equivalency analysis (REA) example to calculate compensatory mitigation designed to offset golden eagle take at wind energy facilities (https://www.fws.gov/media/golden-eagle-mortality-resource-equivalency-analysis, accessed 13 Dec 2022). Using knowledge of golden eagle life history, the REA helps to determine mitigation effort required to save a given number of golden eagle adults as a function of expected incidental take. For example, Lehman et al. (2010) estimated that electrocution from power poles led to mortality of ≥0.0036 eagles/pole/year. The REA determines the expected net present value of each lost adult eagle, which is a function of its lifetime reproductive value. Specifically, the REA uses the expected age structure and life history to translate the change in yearly mortality into direct and indirect effects of either the loss of a bird or saving a bird, accounting for age-specific reproduction and mortality. Then, using information on the effect of mitigation, it uses the same logic to determine the effort required to offset the expected take. Thus, given the number of eagles saved per retrofitted power pole, the REA can help determine how many total poles need to be retrofitted given the expected take. We applied this framework for carcass relocation to estimate the golden eagles saved for each carcass relocated.

To connect to the REA, we summed the carcasses relocated for each simulation, determined the change in eagle mortality, and divided the total eagles saved by the carcasses relocated to estimate eagles saved per carcass. We then use the REA to determine the expected total benefits of removing a single carcass, compared to the expected REA-estimated total effect of incidental take. The ratio of loss to the benefits per carcass relocated, multiplied by 1.2 to meet offset to take ratio requirements stated in the Eagle Act (USFWS 2016), provides the number of carcasses needed to be relocated each year. If the carcasses relocated each year is greater than those expected from observed data, the duration (number of years) of mitigation effort should increase until the impact of mitigation reaches the target.

RESULTS

Carcass persistence and use

We identified 75 carcasses, of which 57 had a complete observation of golden eagle scavenging. We fit a histogram of days of carcass availability (Figure 2A) to a Cauchy distribution, resulting in a probability of carcass persistence. Golden eagles spent an average 2.4 days scavenging per carcass (134 scavenge-day observations). We fit the histogram of these 134 points (normalized by 57 carcasses) to a Cauchy distribution (Figure 2B). During the first day, nearly 60% of carcasses were scavenged, but that probability declined as the carcass aged. In contrast to the original representation of scavenging, carcass use-hours depended on the amount of time the carcass was available such that as the carcass days increased, the maximum use-hours per carcass day tended to decline (Figure 2C). For example, if a carcass was available for 1 or 2 days, as several were, HWI's data indicated that some carcasses had few use-hours, but some had higher use. The upper bound of use-hours declined as carcass days increased. Analysis of HWI's data indicated that 2 processes can be modeled to represent carcass use as a function of carcass age. First, we can represent the likelihood, which decreases with carcass age, that the carcass is scavenged at all. Second, the length of time an eagle spends on the carcass if there is scavenging also declines with carcass age.

Updated parameter estimates

Originally, the Lonsdorf et al. (2018) model assumed that as the average number of eagles per available carcass increases, the average amount of scavenging time by individual eagles declines somewhat because of competition. The net result is that use-hours per carcass-day gradually increases with increasing eagle density. The observed data showed more carcass days relative to expert elicitation but fewer scavenging hours per day.

Experts believed that as eagle density increased, the use-hours per eagle would decrease. Lonsdorf et al. (2018) represented this assumption with a power function: $U = c \times G^z$, where U is use-hours, c is a scalar, G is the average density of eagles (number/km^2) in the county, and the power-function scalar (z) is set to 0.5 to approximate the decreasing use with increasing density. This function implicitly assumed that the use hours per carcass-day was independent of carcass-days (i.e., the age of the carcass). Following Lonsdorf et al. (2018), we used a uniform golden eagle density across all of Wyoming of 0.03/km^2 (Nielson et al. 2014, 2016) and experts suggested that the parameter c was between 3 and 15, leading to an estimated range of carcass use-hours per day of 0.5 to 2.6.

The resulting mortality for this range of inferred parameters (assuming no relocations; Figure 3), along with a contour indicating the family of parameter values of k and $\varepsilon\mu$ led to 1.03% (±0.35% credible interval) mortality due to vehicle collisions. The shape of this equal-mortality contour reflects that expected mortality can be obtained in the model with high traffic avoidance and high collision likelihood (small k and large $\varepsilon\mu$) or low traffic avoidance and low collision likelihood (large k and small $\varepsilon\mu$.)

Effect of location and relocation interval

The potential mitigation credit gained from carcass relocations is strongly influenced by the location of mitigation and the relocation interval (Figure 4). Carcasses are not evenly distributed across Wyoming counties and the traffic volume upon which carcasses are found varies among and within counties too. Thus, the expected maximum number of carcasses that could be relocated per year in each Wyoming county varies widely and depends on the relocation interval; carcasses relocated with daily relocation range from >250 in Lincoln County to <10 in Crook County with the median relocated in Wyoming of around 60 carcasses in Platte County (Figure 4A). Increasing

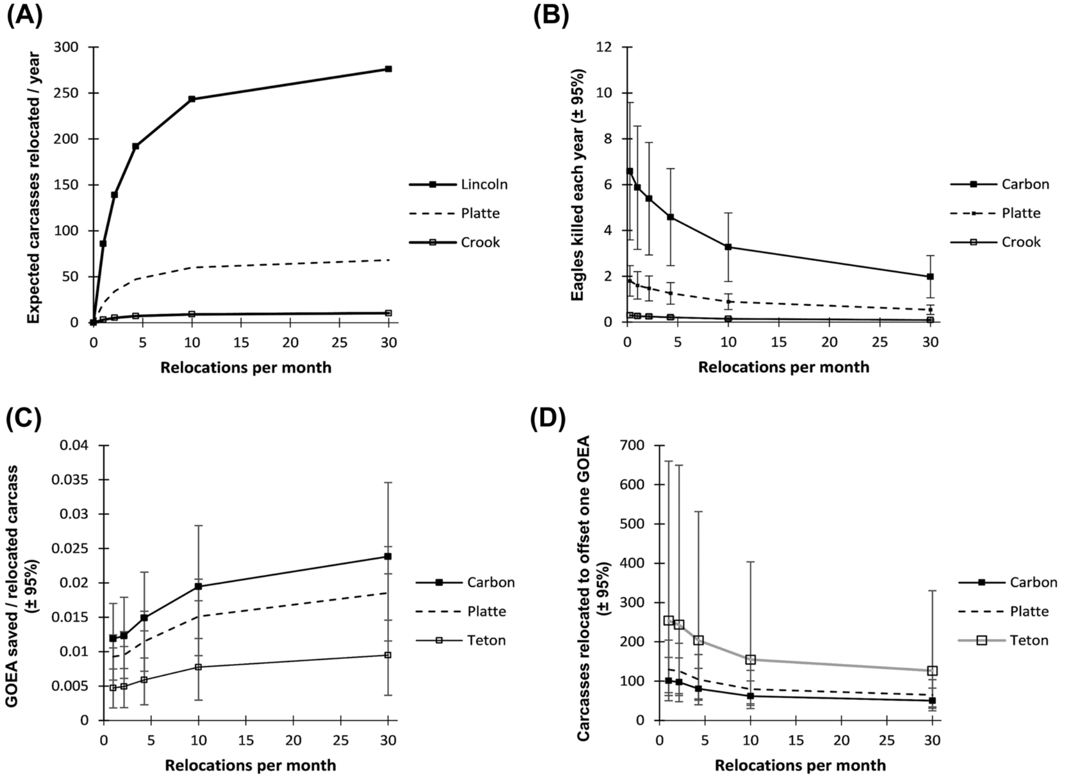

FIGURE 4 The effect of carcass location and relocation interval on a range of mitigation impacts for golden eagles (GOEA) based on data collected from 2016 to 2019 in Wyoming, USA. In each panel, the county with maximum mitigation impact is shown with a solid line and filled, square marker, the county with minimum impact is shown with a solid line and open, square marker and the median county is shown with dashed line and no marker. Error bars represent 95% credible intervals. A) The number of carcasses relocated each year, B) the expected eagles killed each year from vehicle collisions, C) the credit expected per carcass relocated, and D) the number of carcasses needed to be relocated to offset one eagle taken each year.

relocation leads to reduced eagle death but mortalities vary across counties with expected annual mortality dropping from 10 to <4 eagles in Lincoln County with daily relocations but with little effect on mortality in Crook County (Figure 4B). Across all Wyoming counties, credit per carcass relocated can vary nearly 6-fold with a maximum median number of golden eagles saved per carcass relocated of around 0.024 (95% credible interval = 0.015–0.035) for Carbon County and a minimum of 0.019 (0.003–0.021) in Teton County with daily relocation (Figure 4C).

As the interval between carcass relocations increases, the number of carcasses relocated decreases, the number of eagles saved decreases, and the credit per carcass relocated decreases. Because we assumed that the attractiveness of carcasses declines with increasing age of the carcass, the model predicts that eagles spend most of their total scavenging time in the first few days carcasses are available. As credit per carcass relocated declines with fewer relocations, it follows that the integration with the REA would indicate that more carcasses will have to be relocated to achieve a targeted credit with a maximum of approximately 125 carcasses needed in Teton County with daily relocation versus 50 in Carbon County (Figure 4D). Credit is highest in counties with carcasses found on roads with intermediate to low traffic volume (Figure 5).

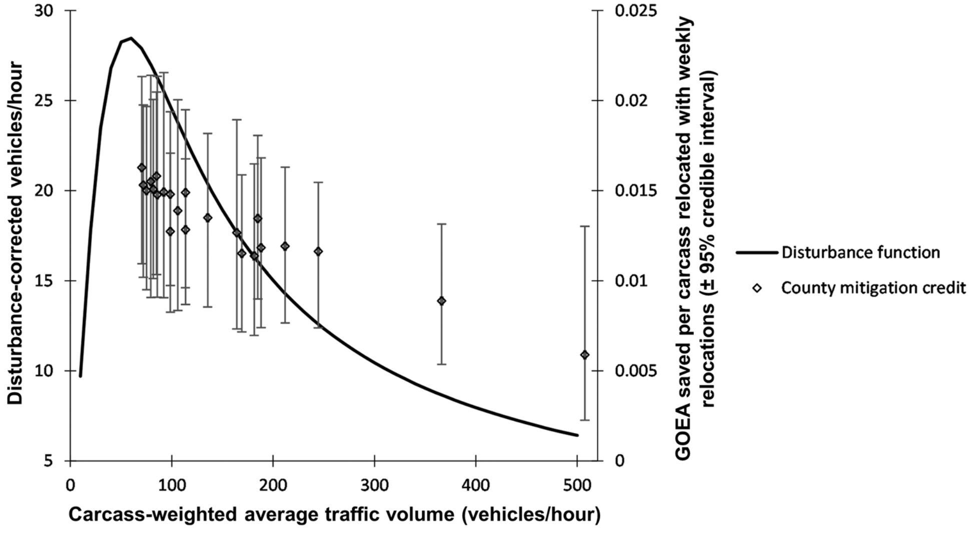

FIGURE 5 Relationship between carcass-weighted county average traffic volume and mitigation credit for golden eagles (GOEA) based on data collected from 2016 to 2019 in Wyoming, USA. Error bars represent 95% confidence intervals. As traffic volume increases, the number of cars passing by a carcass along the road potentially increases but will also disturb any eagles feeding on the carcass. The maximum risk of eagle–vehicle collisions, and opportunities for mitigation credit per carcass relocated, should occur at an intermediate traffic volume.

Viability for offsetting take

Given that the distribution of deer carcasses and mortality from eagle–vehicle collisions across counties is not uniform, not all counties have equal potential for mitigating incidental take when these results are integrated into the REA (Figures 5 and 6). Counties that have high credit per carcass relocated and many carcasses available to be relocated have the greatest capacity to provide mitigation credit. Based on the median estimate of credit per carcass and daily effort to relocate carcasses, there are several counties where this effort would not be expected to offset the take of a single eagle (Figure 6D; white). Other counties, however, could provide annual credits to offset nearly 7 eagles killed each year (Figure 6D; black).

DISCUSSION

With updated parameter estimates, carcass relocation can be a viable option for mitigation efforts designed to offset incidental take of golden eagles from wind turbines. With empirical observations of mortality from vehicle collisions and behavioral studies of eagle foraging on carcasses, the updated model's predictions are defensible and the integration of the model results into a USFWS-developed resource equivalency analysis provides clear guidance on effort needed to offset mitigation.

The results also suggest that the per-unit effectiveness of carcass relocation at reducing eagle mortality and the expected number of carcasses available make carcass relocation a viable mitigation option. Given the expected golden eagle mortality rate from vehicle collisions of around 1.03%, our results suggest that each carcass relocated could save ≥0.024 eagles and, with a 1.2-to-1 offset-to-take ratio requirement, would require moving 50 carcasses in a year. Past roadkill surveys indicate that there should be sufficient carcasses to relocate each year to achieve this level of mitigation. The credit per carcass relocated is nearly equivalent to the effectiveness of a single power pole retrofit even though a power pole accumulates credit over many years, whereas the relocation of a single carcass

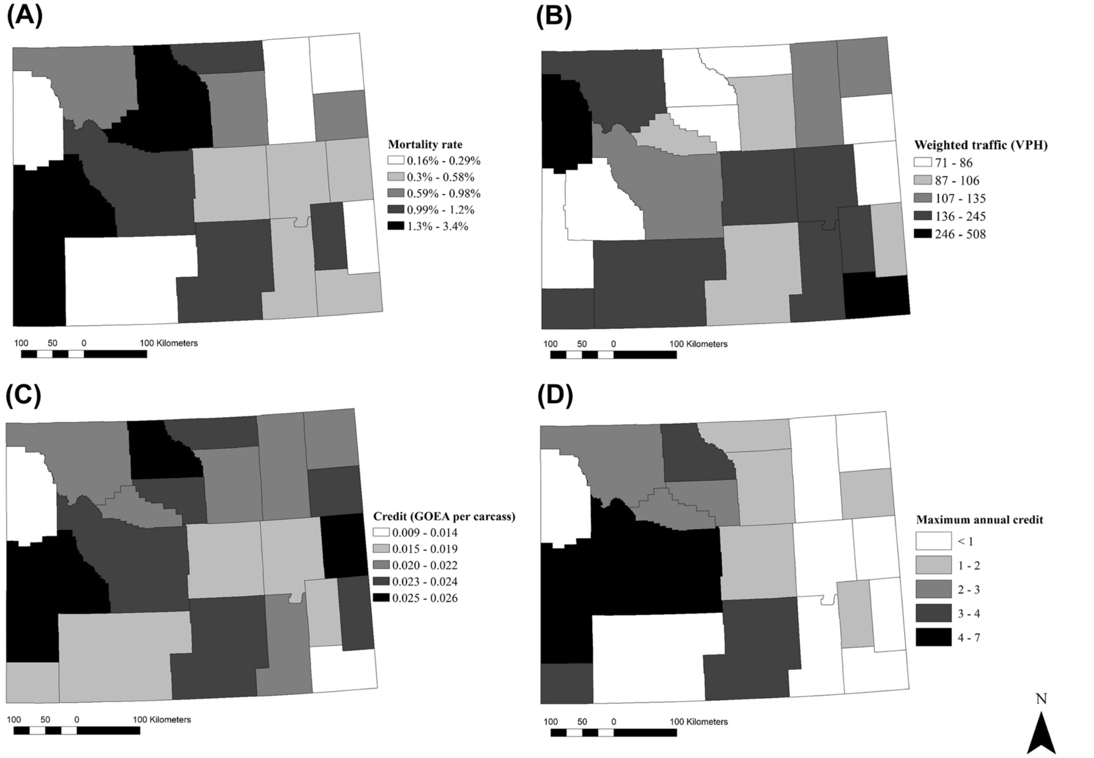

FIGURE 6 Baseline mortality from golden eagle–vehicle collisions and potential mitigation credit from carcass relocations from 2016 to 2019 in Wyoming, USA, counties. A) While mortality from vehicle collisions for all of Wyoming is expected to be around 1%, our results indicate that mortality varies across the state with some counties having 3% and some as low as 0.1%. B) The traffic volume where deer carcasses occur also varies across the state, C) the potential golden eagle (GOEA) mitigation credit per carcass relocated varies among counties, and D) the total potential credit gained from removing carcasses varies as a function of the credit per carcass relocated and the number of carcasses available in the county, with a high of nearly 7 eagles saved per year if all deer carcasses were relocated in the county.

offsets take for only that year. Overall, our results suggest roadkill relocation can be adopted as another option for mitigation.

Unlike power pole retrofitting, which provides a long-term reduction in risk, carcass relocation reduces mortality risk associated with each relocation and the risk is likely to return without sustained interventions. In other words, if a take permit lasts for five years and the relocation efforts are designed to offset annual take, the mitigation would need to occur each year. Moreover, integrating behavioral studies with the REA indicate that the effectiveness of carcass relocation depends on the expected age of the carcass when relocated and its location. Because carcasses become less attractive and less used over time, the expected credit per carcass relocated declines as days between relocations increase (Figure 2). Also, increasing traffic can reduce time spent feeding at a carcass, indicating roads of intermediate traffic volume are likely to have higher credit than those with heavy or little traffic, where there is less risk of collision with vehicles. This contrasts with power poles where eagle density is really the only factor that would affect credit because all poles have assumed constant risk.

There are several reasons to suggest that there should be ample opportunity to use carcass relocation as a mitigation. First, traffic data for most major roads are widely available so integrating these data into an analysis like this one should be straightforward. Second, there is increasing understanding of factors that would predict areas where wildlife–vehicle collisions are most likely to occur. Several recent studies indicate that traffic volume and ungulate density are both strong predictors of ungulate collision risk (Clevenger et al. 2015, Nelli et al. 2018, Mayer et al. 2021), in addition to land cover and seasonality. Deer–vehicle collisions are estimated to cause over $3 billion in damage within the United States (Gilbert et al. 2017) and the ability to predict collision risk should continue to improve. When these locations are identified, our results suggest that there should be sufficient opportunity to use this technique.

While there should be ample opportunities to accumulate mitigation credit, we anticipate that developing and certifying specific mitigation strategies will be potentially challenging. Because carcasses age, there is potential to overestimate the credit if all carcasses relocated are credited similarly regardless of the carcass condition or age. Our results summarize county-wide estimates for credit, but ultimately relocation effort is likely to involve driving specific roads regardless of political boundaries (i.e., roadkill hotspots). Our results indicate that the strongest predictor of credit is the type of road, so it is possible to use the approach we laid out to provide more refined credit estimates based on road traffic volume. Because the effort and results of the work will need to be monitored and certified, identifying hotspots of opportunity could be helpful in reducing the scale of effort required to monitor and certify mitigation. For example, a recent assessment by the Wyoming Department of Transportation identified 22 1.6-km road segments where >10 wildlife vehicle collisions occurred each year (Riginos et al. 2016) with >65 ungulate carcasses occurring from the top 4 1.6-km segments. Depending on the traffic volume of these hotspots, our analysis suggests that up to 2 eagles could be saved per year from ungulate carcass relocations during migration season when most collisions occur, thereby making both the mitigation effort and ability to monitor it easier.

Our analysis indicates that some uncertainty remains about the carcass credit because of the stochastic nature of the deer–vehicle collision process and parametric uncertainty. We used estimates from Millsap et al. (2022) for eagle mortality from vehicle collisions and the variation in mortality estimate to parameterize our model. The credit per carcass relocated and the effort needed to offset take is highly sensitive to this estimate. For example, if the expected mortality from vehicle collisions is 2%, approximately double the current estimate, the credit per carcass relocated would also double. We are reassured that a recent 2-year study by HWI in western Wyoming is in general agreement with the Millsap et al. (2022) eagle mortality estimate (S. J. Slater; HWI, unpublished data). Another potential source of uncertainty is the dependence of results on the vehicle-avoidance parameter k, which translates traffic volume into time spent scavenging on a roadside carcass. Application of these results in areas with traffic density characteristics unlike those of our study area would benefit from further study of the relationship between traffic volume and scavenging behavior (Equation 3).

Finally, our work suggests that meeting the required standards for mitigation may be preventing opportunities for conservation actions. While there is still some uncertainty, one must recognize that the uncertainty distribution of credit is one-sided (i.e., we know that carcass relocation could be beneficial, but incentives are delayed because of the standards required to determine more precisely how much benefit). Going forward we recommend an adaptive management approach (Moore et al. 2011, Williams 2011) where *a priori* predictions of carcasses relocated and golden eagle mortality (Bay et al. 2016) are compared with observations as mitigation proceeds. This would allow for conservation action and research to be done simultaneously, and credit could be updated as the efforts proceed. Doing so would allow progress toward net zero carbon emissions to move forward more quickly while we learn about how best to conserve biodiversity.

MANAGEMENT IMPLICATIONS

Carcass relocation should be added as an acceptable mitigation option. The data required to determine credit (traffic volume, expected hotspots of roadkill, and eagle density estimates) are available beyond the example we used in Wyoming. If incentivized, carcass relocation banks could be created by organizations that could standardize relocation intervals and develop a carcass-quality certification process to make these easier for energy companies.

This kind of program could be used to develop a portfolio of mitigation options to achieve enough mitigation credits if relocation alone is insufficient, although an analysis of mortality at many wind farms estimated that 0.3–3.0 eagles are killed per year per wind farm, within the range of potential credits available. If such a program were created, before-after-control-impact-style research could be done to monitor the effect of reducing carcasses, and when paired with the modeling work, could be used as adaptive management to address the remaining uncertainty in the parameters.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

No live animals were harmed or handled as part of this research, and all assessments were made of previously collected and published data. Those data were originally from observations of live eagles that were collected passively by cameras or from moving vehicles on established roadways.

DATA AVAILABILITY STATEMENT

Data available on request from the authors. The data that support the findings of this study are available from the corresponding author upon reasonable request. Model code used in the analysis will be made available via Github.

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SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

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