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Research Article

Modeling Golden Eagle-Vehicle Collisions to Design Mitigation Strategies

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ABSTRACT The incidental take of golden eagles (*Aquila chrysaetos*) as a result of wind energy development requires some form of compensatory mitigation. Although several options have been proposed, only one has been formerly accepted and implemented, and the lack of options can limit the permit process for wind facilities. We developed a model to estimate numbers of golden eagles that die when struck by vehicles when eagles scavenge road kill to evaluate removal of road-killed carcasses as an additional mitigation option. Our model estimates vehicle collision rates as a function of eagle densities, road traffic volume, and animal carcass abundance at the scale of a Wyoming, USA, county during fall-winter, and quantifies the effects of different mitigation strategies, including estimates of uncertainty. We evaluated the plausibility of our model estimates by predicting mortality rates for each county in Wyoming and comparing overall state mortality to current estimates of mortality using derived estimates from expert judgment. We also developed a context-dependent analysis of potential mitigation credits controlling for carcass number, traffic volume, and background carcass removals. We found that mitigation credit should be highest in areas with greatest number of carcasses. Collision mitigation is a potentially useful addition to the mitigation toolbox for wind energy development or other activities that need to offset predicted golden eagle mortality and satisfy incidental take permit requirements.

KEY WORDS *Aquila chrysaetos*, Bald and Golden Eagle Protection Act, compensatory mitigation, offset, scavenger conservation, simulation model.

Wind energy development is a rapidly expanding source of renewable energy, but the production of electricity with wind generators may result in incidental take of golden eagles (*Aquila chrysaetos*) in the western United States (Pagel et al. 2013), triggering regulatory constraints under the Bald and Golden Eagle Protection Act (i.e., Eagle Act; U.S. Fish and Wildlife Service [USFWS] 2013). The current status of the golden eagle in the western United States is uncertain, but estimates suggest the species is either stable or undergoing a slight decline (USFWS 2016*a*). On this basis, the USFWS will only issue permits for wind facilities or other actions that result in either an increase in golden eagles or a net take of zero (USFWS 2016*b*). The established rules within the Eagle Act require that any take must be demonstrably and quantifiably offset by either reducing deaths from other causes or increasing recruitment at least equal to the projected incidental take to achieve no net loss within the affected breeding population (USFWS 2016*b*). Further, methods for compensating incidental take of eagles must be quantifiable, scientifically credible, and verifiable. To date the only method that has been used as compensation for eagle mortality is retrofitting of power poles to prevent electrocution of eagles by covering exposed power lines (USFWS 2013, 2014, 2015). The urgent need for additional offsetting tools, such as reducing eagle mortality due to vehicle collisions (Allison 2012), led to our study.

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Vehicle collisions are a recurrent source of golden eagle deaths (Phillips 1986, Franson et al. 1995, Craig and Craig 1998, Harmata 2002, Hunt 2002) that cause an estimated 1% annual mortality in the western United States (Hunt 2002; USFWS 2013, 2016*a*,*b*). Much of this mortality and the opportunities for mitigation occur in fall and winter (Kalmbach et al. 1964, Kochert et al. 2002, Watson 2010) when more typical eagle prey are hibernating or less available (MacLaren et al. 1988, Harlow and Menkens 2011), which may increase scavenging by eagles (Phillips 1986, Applegate et al. 1987, Wilmers et al. 2003, Blázquez et al. 2009). At the same time, road kill of ungulates typically peaks in winter, and cooler temperatures facilitate longer persistence of carcasses (Jennelle et al. 2009, Santos et al. 2011). Together, these factors make it more likely that golden eagle collisions with vehicles occur in the fall and winter, and also afford the opportunity to concentrate the use of carcass removal as a compensatory mitigation option during this period.

To date, biologists have not yet studied the full suite of causal links between environmental factors, eagle behavior, and vehicle collision-caused mortality, making its application to mitigation challenging because of inherent uncertainty. For carcass removal to be accepted as a mitigation method, however, it must meet the clear standards for compensatory mitigation set forth in the USFWS's Eagle Conservation Plan Guidance (Eagle Guidance; USFWS 2013). First, eagle mortality caused by wind turbines and mitigation credits generated through carcass removal to offset this mortality must be quantified to individual eagles, or to eagle bird-years as appropriate to account for net differences in eagle maturity and reproduction within a breeding population. Second, eagle mortality and mitigation credits are each assessed as expected outcomes averaged over the permit period, which currently is set to a maximum of 30 years with a review every 5 years. Third, permits may require a precautionary increment added to mitigation as a hedge against uncertainty in eagle mortality predictions. The Eagle Guidance illustrates application of a risk-averse model for predicting number of eagle fatalities at wind facilities (incidental take), requiring compensation for the upper 80% confidence limit (or equivalent) of predicted incidental take (USFWS 2013: Appendix D). The Eagle Guidance does not provide a parallel quantitative standard for treating uncertainty in mitigation credits (i.e., in predicting the number of eagles saved from mitigation activities). However, the guidance does recommend developing explicit scenarios for future conditions (models) with and without proposed mitigation, and accounting as appropriate for dynamic trends, time lags, discounting, and spatial variation.

We developed an approach aimed at meeting the Eagle Guidance by using the framework of Cochrane et al. (2015) to evaluate untested vehicle collision mitigation methods with expert elicitation and modeling, quantifying the parameters with a mixture of relevant data and, where data were lacking, expert judgments. To deal with epistemic uncertainty, we worked with a panel of eagle biology experts to build a quantitative model representing their beliefs about the causal relationships linking eagle scavenging to vehicle strikes. We examined the plausibility of our model by using it to predict mortality in Wyoming from carcass removal data provided by the Wyoming Department of Transportation (WYDOT). In addition, we integrated efficiency analysis with an approach to develop a framework for collision mitigation that is scientifically defensible and seeks to identify the most efficient contexts for mitigation despite the underlying uncertainty. We used the model to compare how mitigation credit per additional removal effort may vary as a function of traffic volume, golden eagle density, and background carcass removal scenarios.

METHODS

We worked with a team of 8 golden eagle experts to develop and parameterize a simulation model (Fig. 1) that estimates how many golden eagles are killed by vehicle collisions while they scavenge on animal carcasses. When an ungulate is hit and killed by a car, an eagle may find and scavenge the carcass and then itself may be hit by another passing car. If there is a constant probability of an eagle being hit with each passing car, it follows that the more cars passing by the eagle while it scavenges, the greater the chance of a collision. The larger the carcass, the longer it takes to be fully scavenged, and the more cars that pass by the eagle while it is scavenging, the higher the probability the eagle is hit and killed. At the same time, however, disturbance from traffic can drive the golden eagle off the carcass and thereby reduce collision risk, and some high volume of traffic may deter eagles from ever landing on the carcass, reducing collision risk to zero.

Temporal and Spatial Scale of the Model

Although our model should be generalizable, we specifically evaluated mitigation opportunities during the fall-winter season (Oct–Mar) when collision mortality is assumed to be greatest and where there is a large winter population of eagles (USFWS 2016*a*). In Wyoming's cold climate, golden eagles may be food limited in winter because live prey such as ground squirrels (*Spermophilus* spp., *Urocitellus* spp.) are relatively scarce and carrion is too sporadic in distribution and frequency to saturate demand for food (Applegate et al. 1987, MacLaren et al. 1988, Wilmers et al. 2003, Harlow and Menkens 2011). For spatial scale, we evaluated a typical Wyoming county scale ($\sim$10,000 km^2) to estimate the expected (average) number of eagles killed for each level of traffic volume and assumed that eagles could range throughout a county of that size during the winter (Braham et al. 2015). We assumed in our model that mitigation would be most effective with carcass sizes that are large enough to persist on roadways and are too heavy for eagles to remove for consumption elsewhere. Our analysis considered 2 size classes of carcasses: small ungulate carcasses such as deer (*Odocoileus* spp.) and pronghorn (*Antilocapra americana*) and large ungulates such as elk (*Cervus canadensis*) and moose (*Alces alces*).

We applied the logic and the temporal and spatial scales described above to develop a quantitative estimate of mortality from vehicle collisions. Collision risk is a function of the number and size of carcasses, the number of days each carcass was available for scavenging adjusted for carcass removals by road crews, the density of eagles in the area, the volume of traffic, and the per-vehicle collision risk to a scavenging eagle (Fig. 1). The model quantified these cause-effect relationships in the steps described below.

We predicted mortality for each of 2 eagle age classes as a function of carcass size, road traffic volume, and the frequency of carcass removal. The model used age-specific parameters for use hours and collision probability because the 8 experts agreed that juvenile eagles ($<$1 yr) spend proportionally more time scavenging and experience higher collision risk on average than older, more experienced adult foragers ($\geq$1 yr).

Model Description

Eagles are adept at finding carcasses in open terrain, including widely dispersed carcasses (Wilmers et al. 2003, Blázquez et al. 2009, Sánchez-Zapata et al. 2010). If a

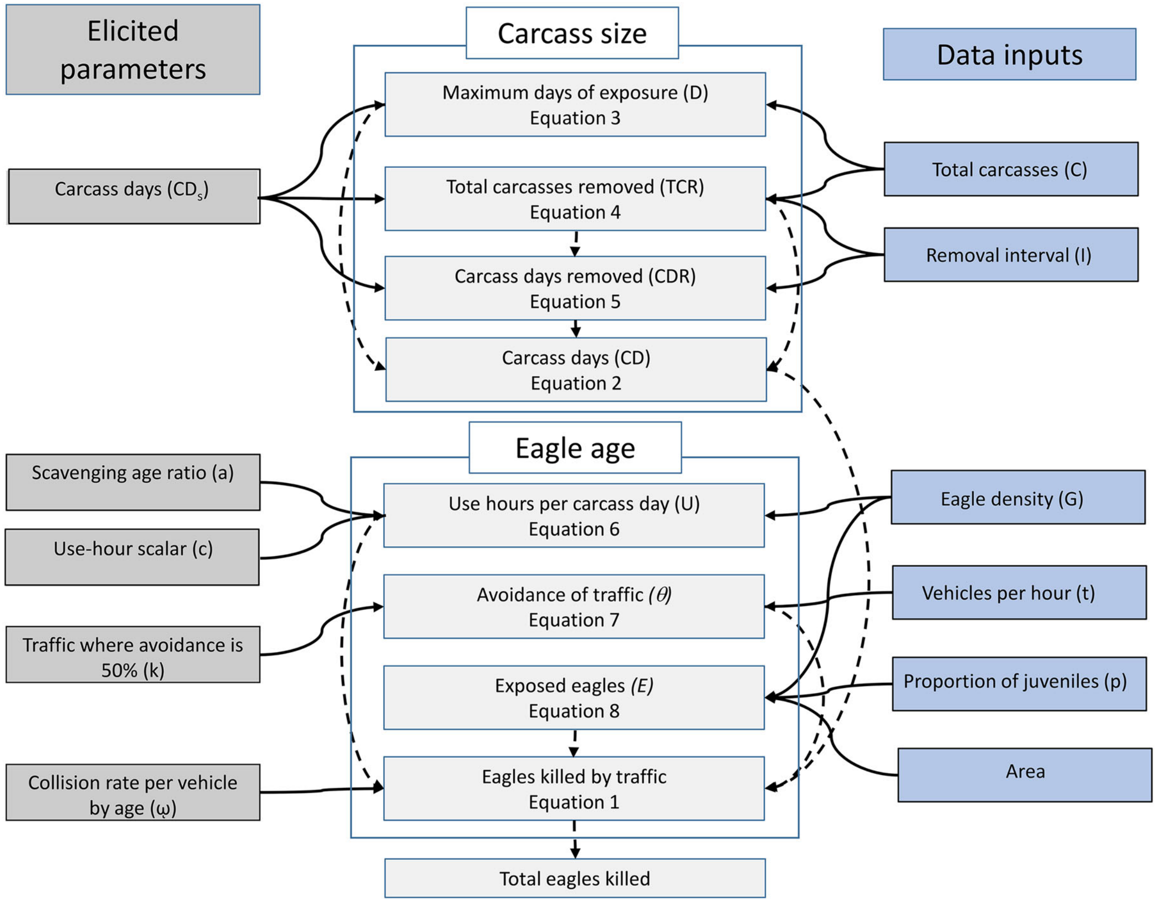

Figure 1. Model diagram illustrating the cause-to-effect relationships (directional arrows) between input and output parameters in the golden eagle vehicle collision model for Wyoming, USA. Blue boxes represent input data, dark grey boxes are estimates developed from expert beliefs, and light grey boxes 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.

carcass is present, we assume that the time it takes ≥1 eagle to find it and the subsequent time those eagles spend around the carcass is based only on the carcass persistence (days available in an edible form for scavenging; Santos et al. 2011), the average density of eagles in the region, and the degree to which traffic avoidance is precluding eagles from landing or scavenging on a road. We also assumed that collision is a vehicle-eagle interaction resulting in eagle fatality and that collision risk posed by a single vehicle passing an eagle is the same regardless of how many vehicles are passing per hour. Thus, we assume the collision probability per vehicle is a constant, estimated as an average across all types of vehicles, and the number of collisions increases directly with increasing vehicle volume per hour for a given number of carcasses and total use-hours at a specified eagle density.

The overarching functional relationship to estimate the number of eagles killed on any road with traffic volume (t) and carcass removal interval (r), $\hat{Y}_{r,t}$, is:

$$\hat{Y}_{r,t} = \sum_a \left(1 - (1 - \omega_a)^{\left(t \times CD_{r,t} \times U_a \times (1-\theta_t)/E_t\right)}\right) \times E_t, \qquad (1)$$

where ω_a is the per-vehicle collision probability for age group a; t is the traffic volume in average vehicles per hour (vph); $CD_{r,t}$ is the number of available carcass-days after removals on each road considering interval r (days) and traffic volume t; U_a is the expected number of hours scavenging per carcass-day per eagle for age group a; θ_t is the avoidance probability due to traffic volume t; and E_t is the number of eagles exposed to roads of traffic volume t. In summary, the base of the power function is per-vehicle survival probability for a single eagle and the exponent is a product that yields the expected number of vehicles passing each scavenging eagle.

Carcass-days.—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. The carcass may also be moved by road maintenance crews, thereby reducing potential exposure of eagles to vehicles. There are 2 potential effects of removal on carcass days; removals can reduce the expected number of carcasses, and the number of days carcasses are available. The adjusted exposed carcass-days available by traffic volume and adjusted for carcass removal, $CD_{r,t}$, is equal to the maximum carcass-days available ($D_{s,t}$) minus the number of carcass days removed, which itself is the product of carcasses removed ($TCR_{s,t}$) and the reduction in carcass-days of exposure per carcass (CDR_t) summed over all carcass sizes (s).

$$CD_{r,t} = \sum_s D_{s,t} - \left(TCR_{s,t} \times CDR_t\right) \quad (2)$$

Maximum days.—For each road with traffic volume t and each size class s, the maximum carcass-days is the number of carcasses by size ($C_{s,t}$) multiplied by the expected carcass duration of that size class (CD_s).

$$D_{s,t} = C_{s,t} \times CD_s \quad (3)$$

Carcasses removed.—Some carcasses may be removed via routine road maintenance activities. We estimated the number of remaining carcasses on the road on a typical day by comparing the average persistence of the carcasses to how often they were picked up (removal interval; I). If the removal interval exceeded the average persistence of the carcasses (carcass-days), we removed a proportion of carcasses equal to the ratio of carcass persistence relative to the interval's duration. If the removal interval is less than the persistence, then at some point, every carcass will be removed.

$$I > CD_s: \quad TCR_{s,r,t} = C_{s,t} \times CD_{s,t}/I \quad (4)$$

$$I \leq CD_s: \quad TCR_{s,r,t} = C_{s,t}$$

Reduced days of exposure per carcass.—As with carcasses removed, the reduction in carcass-days depended on whether the removal interval was shorter or longer than the typical persistence of the carcasses. When the removal interval was the same or longer than the average carcass-days per carcass by size, the average days remaining for the carcasses on the road was, on average, one half of the typical carcass-days minus 1. For example, if carcasses lasted 4 days, for each carcass killed per day we expected on average over time that 4 carcasses would be on the ground aged 1, 2, 3, and 4 days, or average 2.5 days old with 1.5 carcass-days remaining. We assumed that removal pickups occur no sooner than one half day on average after the animal was killed and in increments of full days after that. When the removal interval was more frequent than the average carcass-days persistence, then the average age of carcasses picked up depended on the interval or how many carcasses could have accumulated on the road since the previous pickup rather than the average full number of carcass-days for that carcass size:

$$I \geq CD_s: \quad CDR_{s,t} = (CD_s - 0.5) - ((CD_s - 1) \times 0.5) \quad (5)$$

$$I < CD_s: \quad CDR_{s,t} = (CD_s - 0.5) - ((I - 1) \times 0.5)$$

Use-hours per carcass day.—We defined use-hours per available carcass-day as $\geq$1 eagle present around a carcass in 1-hour increments when both the carcass and eagle(s) were within vehicle striking distance on or near a road travel lane. As eagle density increases, the average number of eagles per available carcass increases, and the average amount of scavenging time by individual eagles declines somewhat because of competition (Wilmers et al. 2003). The net result is gradually increasing use-hours per carcass-day with increasing eagle density. Because data were not available on time typically spent feeding per available carcass, we elicited expert knowledge (Supplement A, available online in Supporting Information) to project the rate at which carcasses were visited by golden eagles as a function of golden eagle density and age class. Based on the results of the elicitation, we fit a function to estimate average eagle use-hours per carcass-day based on average eagle density. Experts believed that use-hours per eagle would decrease as eagle density increased and that juvenile eagles spend more time scavenging road kill, so we apportioned use-hours into 2 age classes. Note that the age ratio of use-hours was distinct from the population average age ratio. The average use-hours per carcass day for juveniles and adults, U_{juv} and U_{ad}, was:

$$U_{juv} = c \times G^z \times a_{juv} \quad (6)$$

$$U_{ad} = c \times G^z \times \left(1 - a_{juv}\right),$$

where the use-hours scalar (c) and the age ratio of use-hours (a) are drawn randomly for each simulation from ranges reflecting expert uncertainty (Table 1), G is the average density of eagles (number/km^2) in the county, and the scalar z is set at 0.5 to approximate the decreasing use-days with increasing density.

Table 1. Summary of collision model parameters between vehicles and golden eagles, Wyoming, USA, including the source of the parameter values and the range of values used. The power function for use-hours was set to 0.5. The 3–15 range for the scalar in the use-hours power function equates to use-hours per carcass day from 0.85 to 3.75 when eagle density is 0.03/km^2. If the source of the value was from experts, we obtained this information through expert elicitation (Supplement A), otherwise it was a part of a controlled simulation.

Parameter	Source	Type	Low	High
Carcass-days per large ungulate carcass (CD_{size})	Experts	Stochastic	5	10
Carcass-days per small ungulate carcass (CD_{size})	Experts	Stochastic	3	5
Traffic volume (vph) where avoidance is 50% (k)	Experts	Stochastic	10	35
Scalar for power function of use-hours by eagle density (c)	Experts	Stochastic	3	15
Scavenging age ratio (a_{juv})	Experts	Stochastic	0.22	0.35
Collision probability per vehicle (ω_{adult})	Experts	Stochastic	0.0002	0.0015
Collision probability per vehicle (ω_{juv})	Experts	Stochastic	0.0002	0.0030
Total carcasses (C)	Input	Fixed	0	180
Removal interval (I)	Input	Fixed	1	30
Eagle density (G)	Input	Fixed	0.03	0.03
Traffic in vehicles per hour (t)	Input	Fixed	5	200
Proportion of juveniles (p)	Input	Fixed	0.17	0.17

Avoidance of traffic.—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 (Bautista et al. 2004, May 2015). The 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. We assumed that road avoidance is a direct and saturating function of average vehicle volume per hour and avoidance affects all eagle age classes equally. By definition avoidance was 0% with 0 cars/hour and at some traffic volume avoidance was or approached 100%. We fit a monotonically increasing and saturating function to model this relationship with a half-saturation constant indicating the traffic volume with 50% traffic avoidance (Supplement A). The avoidance probability for each road with traffic volume t (θ_t) was:

$$\theta_t = \frac{t^2}{t^2 + k^2}, \quad (7)$$

where k is a half-saturation constant indicating the traffic volume that leads to 50% avoidance.

Exposed eagles.—We assumed that all golden eagles in the region are potentially exposed to road kill at least some time during winter. Over the long run, eagles are exposed to carcasses by road type in direct proportion to how much of each road type is available, without regard to how individual road segments are configured or individual traits of the eagles including breeding or residency status. To determine exposed eagles per road type for juveniles and adults ($E_{juv,t}$ and $E_{ad,t}$) we simply determined the product of the county's total area (km^2), the eagle density G, the percentage of the population that are juveniles (p_{juv}), and the proportion left after traffic avoidance θ_t:

$$E_{juv,t} = \text{area} \times G \times p_{juv} \times (1 - \theta_t) \quad (8)$$

$$E_{ad,t} = \text{area} \times G \times \left(1 - p_{juv}\right) \times (1 - \theta_t).$$

Background Data and Uncertainty

Carcass days per carcass.—The number of carcass days available per carcass, CD, represents a key source of exposure for eagles, but because data are limited, we elicited estimates from experts (see Supplement A for elicitation methods; Table 1, values elicited from experts). We used the results of the elicitation to set upper and lower bounds for carcass days. We simulated the uncertainty in carcass-days for different sized animals, CD_s, by drawing randomly for each model simulation from this range for large and small ungulates.

Vehicle traffic levels and number of animal carcasses.—We explored how traffic volume, t, and number of carcasses occurring on each road type per season, C_s, affected golden eagle mortality rates and potential mitigation credit. We used available data on traffic volume for Wyoming (WYDOT 2013) to set the range of potential traffic volume and carcass numbers. From 2006 to 2015, the WYDOT collected data on number of large and small ungulates killed on state roads during 6 winter months on each level of traffic volume in each Wyoming county based on carcass removals. These data provided spatially explicit estimates on average annual daily traffic on state, United States, and interstate highways.

Carcass removal intervals.—Because of the variation in background or *status quo* removal intervals, we decided to include removal interval as an additional context to the model. We spoke to state and county highway maintenance staff to determine the interval range in days between visits by road maintenance crews for each traffic level. We learned that removal intervals vary among counties and by road type. In general, however, crews visit higher-volume roads more frequently than low-volume roads. Road maintenance schedules differ between state and county crews, and by road type. The state typically visits and maintains the lowest traffic (<20 vph) roads only once or twice a week, whereas a typical 45-vph state road is visited every other day and for 200-vph roads state crews are out daily. County roads are maintained less frequently. County roads with the lowest traffic (<20 vph) might be visited only once every 2 weeks, and the highest volume county roads (~90 vph) are maintained only every 1–2 days. To cover a range of possible removal intervals, we varied the monthly number of carcass removals from never to daily (i.e., from 0 to 30 days spent removing per month).

Collision probability per vehicle.—We derived a collision probability per vehicle, ω, from experts' beliefs about the number of collisions that occur with every 10,000 vehicles passing a scavenging eagle, including uncertainty (Table 1). For example, a long-term average of 5 collisions/10,000 vehicles is equivalent to a collision probability of 0.005/vehicle. To allow for the experts' belief that eagles <1 year old were more likely to be struck by a vehicle, the model drew values for the collision probability by age, ω_{age}, randomly from a uniform distribution defined by the range representing the experts' uncertainty (Table 1).

Golden eagle density.—We used an average density of 0.03 eagles/km^2 based on recent surveys of Wyoming (Nielson et al. 2014, 2016). We did not vary the golden eagle density in our analyses.

Integrating uncertainty.—We elicited expert opinion for 5 of the model parameters where we lacked empirical data (Cochrane et al. 2015) to describe a plausible range of parameter values or functional responses: probability of collisions during exposure for juveniles and adults (ω_a), the number of days road-kill carcasses were available for scavenging (CD), the number of hours per day eagles were present around those carcasses as scavengers (U_a; specifically the scalar, c, that affects the functional response), the portion of use-hours by juveniles and adults (a_{juv}), and the portion of eagles that were precluded from scavenging because they were disturbed by the volume of vehicle traffic (θ_t). In our simulations, the values for carcass days of large and small ungulates were perfectly correlated to preserve the assumption that carcass days for large ungulates are always greater than small ungulates. Similarly, values for collision probability for adults and juveniles are perfectly correlated preserving the assumption that adult collision probability is less than juveniles. Based on the elicitation results, we estimated upper and lower bounds for the parameter values (Table 1). See Supplement A for details of the expert panel selection, structured elicitation methods and results, and methods of fitting functions to elicited value ranges.

Applying the Model

Predicting mortality with uncertainty.—To integrate uncertainty in our predictions, we used the range of estimates provided by experts for each of the 5 parameters in the model, and assumed a uniform probability distribution between the upper and lower bounds. For a given simulation, we used the model's mortality prediction resulting from randomly drawn numbers from uniform distributions of each parameter (Table 1). We simulated mortality in a prototypical Wyoming county that has an area of 10,000 km^2 (median size of Wyoming counties is $\sim$10,600 km^2) and 300 golden eagles for a single 6-month winter. We simulated mortality arising from each context (each combination of traffic, carcass number, and removal number) under uncertainty 5,000 times and provide the median, and 20th and 80th percentiles of the results, following the Eagle Guidance reporting of incidental take. In each context, we assumed that all roads were identical in terms of traffic, carcass density, and removal interval, which allowed us to create a lookup table for all potential combinations that we could apply to actual county data where traffic and carcasses are heterogeneous. Thus, we assumed that the effect of carcasses found on different road segments that have the same traffic and removal intervals could be combined.

Estimating mortality probability in Wyoming.—We used the average number of large and small carcasses for managed road segments and the traffic volume occurring on each road segment in each Wyoming county (Fig. 2) as input to estimate county mortality rates. We summarized these data by county to determine the average seasonal number of large ungulate and small ungulate carcasses on each road type (traffic volume). The data from WYDOT represent total carcasses removed (*TCR* from Equation 4) along specific road segments, and thus may not represent all potential carcasses occurring on the road. If we knew the removal interval for each road, however, we could estimate the carcasses observed simply by solving for the unknown parameter, $C_{s,t}$, representing total carcasses. Using Equation 4 and rearranging terms, we find that $C_{s,t} = TCR_{s,t} \times I/CD_s$. For example, if the number of small ungulate carcass removed (*TCR*) is 3, the removal interval is weekly (i.e., $I = 7$ days) and the median carcass days (CD_s) for small ungulates is 4, then the estimated number of carcasses prior to removal would be 5.25. Our conversations with maintenance staff suggested the background removal intervals can range from once every 2 weeks to 2 times/week, so we estimated mortality based on 3 assumptions of carcass removal intervals of 14, 7, and 3.5 days. We used the adjusted number of carcasses to estimate the number of eagles killed on each road type given the number of carcasses and each removal interval.

Estimating mitigation credit.—We assume that mitigation of vehicle collisions will occur by increasing the number of carcass removals beyond any existing removal activity. The effect of this added effort is likely to be context-dependent, and we used the model to establish those baseline contexts by simulating how removal interval affects the expected number of eagles dying as a function of traffic volume and carcass number. To develop the contexts, we used 10 years of data on carcass removals from WYDOT (2013) to set the range of small and large ungulate carcasses found on roads of different traffic volume within a Wyoming county. Small carcasses ranged from 0 to >200/county (averaged over a 10-year period) and large carcasses ranged from 0 to 17. To simplify concepts for this proof of concept, we ran the models with only small carcasses, ranging from 0 to 200 in number. Traffic volume ranged from a low of 5 vehicles/hour in rural areas to >1,000 vehicles/hour in urban areas along interstate highways. Preliminary analyses with the model indicated

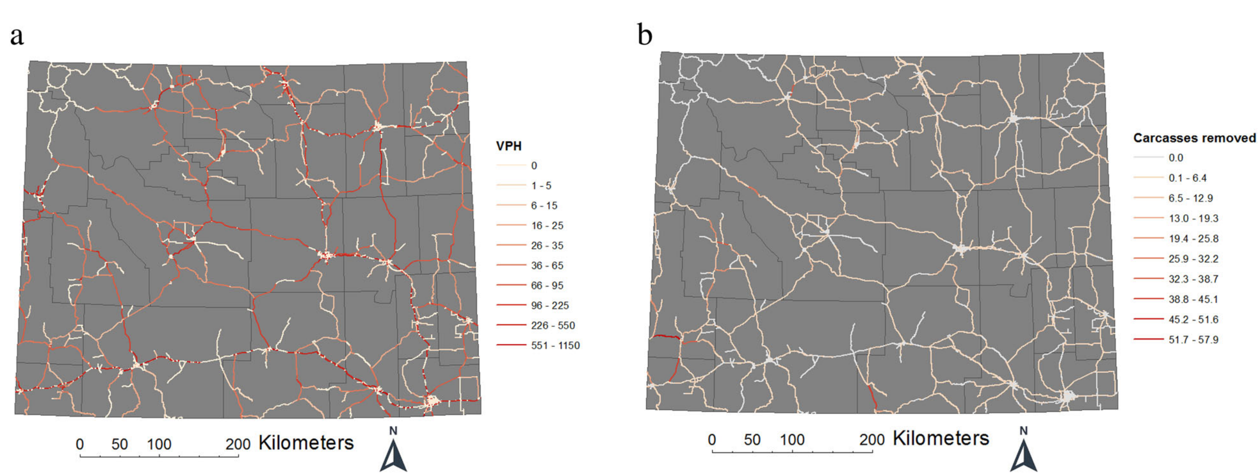

Figure 2. Observed vehicle traffic volume (a) and animal carcasses removed (b) for the entire state of Wyoming, USA. Both data sets are from the Wyoming Department of Transportation (WYDOT). Traffic volume is represented by vehicles per hour (VPH) with the volume colored light to dark representing light to heavy traffic volume. Carcasses removed are based on average annual carcasses removed by WYDOT from 2006 to 2015 during October through March. Lighter colors indicate fewer carcasses removed and darker colors indicate greater number of carcasses removed.

that collisions are predicted to be unlikely with traffic volume >200 cars/hour, so we analyzed mitigation from 5 to 200 vehicles/hour.

We modeled potential mitigation actions as carcass removals, stipulating the number of removal days per month by road type from 0 to 30 removals/month (i.e., from never to daily removals). These allowed us to compare changes in mortality and eagles killed across a range of potential changes in removal. In other words, credit occurs by a change in removal interval. We defined the mitigation credit (i.e., expected eagles saved) as the reduced eagle collision mortality with mitigation compared with the *status quo* routine as a function of traffic volume *t* and changes in removal schedule (r') such that mitigation credit ($M_{r',t}$) is:

$$M_{r',t} = \widehat{Y}_{r,t} - \widehat{Y}_{r',t}, \quad (9)$$

where $\widehat{Y}_{r',t}$ represents the mortality from an increased removal interval r' on a road with traffic volume t.

Sensitivity analysis.—We analyzed the relative influence of uncertainty in the stochastic model parameters on collision mortality (Table 1). The sensitivity of each stochastic model parameter (Table 1) was indicated by its standardized regression coefficient (*t*-value, a unitless quantity; Cross and Beissinger 2001) calculated from the best fit of a multiple linear regression model of the 5,000 iterations with resulting predicted mortality (McCarthy et al. 1995, Lonsdorf et al. 2009). We repeated the sensitivity analysis for each traffic volume (vph) level.

RESULTS

The simulation model predicted that as carcass numbers increase, expected mortality increased (Fig. 3a). However, traffic volume and removal intervals mediated the effect of carcass number on eagle mortality rates (Fig. 3b and 3c, respectively). All else being equal, increasing carcass density caused eagle mortality to increase most at relatively low amounts of traffic (Fig. 3b). At the lowest traffic volume, the rate that mortality increased with increasing carcass number was limited by the number of vehicles passing each carcass. In contrast, at high volumes of traffic, mortality was limited by the disturbance that reduced the time eagles collectively spent foraging on each carcass. Unsurprisingly, we found that as removal intervals increase, predicted eagle mortality decreased. Increasing removal intervals from 0 to 5 removals per month reduced mortality considerably, leading to a 30% reduction in eagle mortality caused by collisions regardless of vph (Fig. 3c), and the model predicts that just under 15% of the background mortality will still remain when carcasses are removed every day.

We estimated overall golden eagle mortality in Wyoming with 3 scenarios of background number of removals equal to 2, 4 and 8 times/month (removal intervals of ~14, 7, and 3.5 days), resulting in median estimates of 203, 86, and 32 deaths/year, which is equivalent to overall mortality rates of 2.7%, 1.1%, and 0.4%, respectively (Table 2). Given that overall estimates of mortality due to collisions are around 1% (USFWS 2016*b*), our predictions seem plausible. However, the model predicted fairly substantial variation in mortality rates among counties due to differences in carcass numbers (Table 2). The model predicted that western and northern counties would have greater mortality than eastern counties (Fig. 4).

For a given number of carcasses and traffic volume, the model predicted that the potential opportunity for mitigation increased with decreasing background removal intervals (Fig. 5). All else being equal, the greater the number of carcasses expected on a segment of road, the higher the

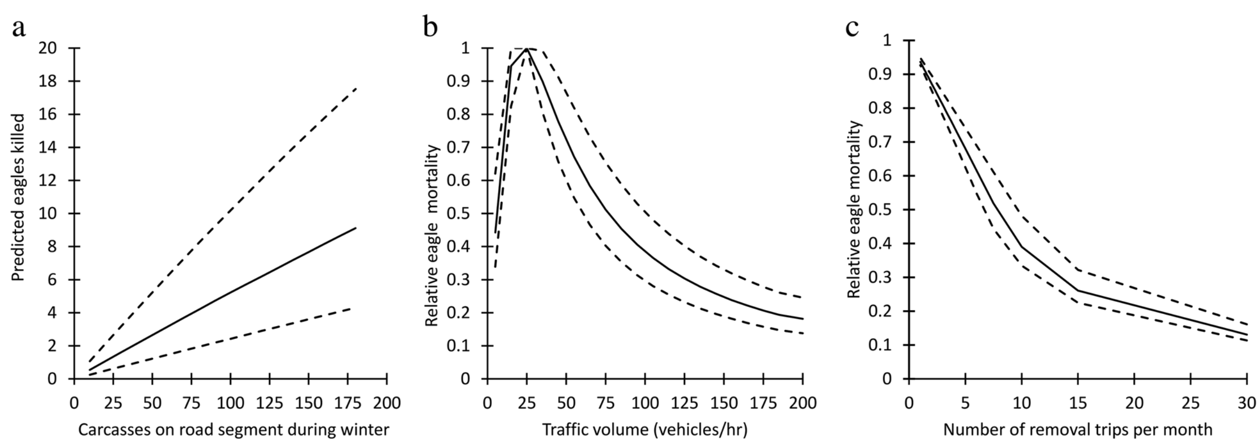

Figure 3. Summary results illustrating relationship between predicted golden eagle mortality and carcass number (a), traffic volume (b), and carcass removals (c) Wyoming, USA. a) Predicted number of eagles dying versus carcasses found on roads assuming an eagle density at 0.03/km^2 in a sample area of 10,000 km^2. We performed these simulations under riskiest conditions for eagle-vehicle collisions: a traffic volume of 25 vehicles/hr with no background carcass collection. Overall, mortality increases with increasing number of carcasses. b) Relative eagle mortality versus traffic volume (vehicles/hr). The potential maximum mortality is predicted by the total number of carcasses on a road but then is rescaled by traffic volume (i.e., mortality relative to the maximum). Relative mortality refers to the proportion of eagles killed compared to the maximum possible. Maximum relative mortality for any carcass amount is predicted on a road with 15–35 vehicles/hour. Traffic greater than or less then this volume would reduce expected eagle mortality. c) Relative mortality versus number of removal trips per month. As the number of removals per month increases, the relative mortality probability decreases. In each panel, the solid line represents the median results from 5,000 simulations and the 2 dashed lines represent the 20th and 80th percentile estimates.

Table 2. Estimated state and county annual golden eagle-vehicle mortality probability (with 20th and 80th percentile estimates) from October to March for Wyoming, USA, for 8, 4, and 2 removal trips per month. These results are based on vehicle traffic and carcass removal data provided by the Wyoming Department of Transportation. Golden eagle density was set at 0.03/km^2.

County or state	Expected eagle population size	Eight removals (3.5-day interval)	Four removals (7-day interval)	Two removals (14-day interval)
Albany	334.8	0.002 (0.001–0.003)	0.005 (0.002–0.009)	0.011 (0.005–0.023)
Big Horn	245.4	0.011 (0.005–0.022)	0.030 (0.014–0.060)	0.070 (0.032–0.140)
Campbell	373.5	0.001 (0.000–0.002)	0.003 (0.001–0.006)	0.007 (0.003–0.014)
Carbon	618.8	0.006 (0.003–0.012)	0.016 (0.007–0.032)	0.038 (0.018–0.075)
Converse	331.4	0.001 (0.001–0.003)	0.003 (0.002–0.007)	0.008 (0.004–0.017)
Crook	222.6	0.001 (0.000–0.001)	0.002 (0.001–0.004)	0.004 (0.002–0.009)
Fremont	719.9	0.004 (0.002–0.009)	0.011 (0.001–0.025)	0.027 (0.012–0.058)
Goshen	173.4	0.001 (0.000–0.002)	0.003 (0.001–0.005)	0.006 (0.003–0.013)
Hot Springs	155.9	0.008 (0.004–0.018)	0.023 (0.010–0.048)	0.052 (0.024–0.106)
Johnson	324.4	0.004 (0.002–0.009)	0.012 (0.006–0.024)	0.029 (0.014–0.056)
Laramie	208.8	0.002 (0.001–0.003)	0.004 (0.002–0.009)	0.010 (0.005–0.021)
Lincoln	318.2	0.013 (0.006–0.029)	0.036 (0.016–0.077)	0.083 (0.038–0.172)
Natrona	417.7	0.002 (0.001–0.004)	0.006 (0.003–0.012)	0.014 (0.007–0.029)
Niobrara	204.2	0.001 (0.001–0.003)	0.003 (0.002–0.008)	0.008 (0.004–0.018)
Park	541.4	0.003 (0.001–0.007)	0.009 (0.004–0.019)	0.020 (0.009–0.044)
Platte	164.0	0.006 (0.003–0.011)	0.015 (0.007–0.030)	0.035 (0.017–0.068)
Sheridan	196.4	0.006 (0.003–0.011)	0.016 (0.007–0.032)	0.037 (0.017–0.074)
Sublette	383.5	0.009 (0.004–0.020)	0.025 (0.011–0.055)	0.059 (0.027–0.127)
Sweetwater	815.2	0.001 (0.000–0.002)	0.002 (0.001–0.004)	0.005 (0.002–0.010)
Teton	327.6	0.001 (0.000–0.002)	0.002 (0.001–0.004)	0.004 (0.002–0.010)
Uinta	162.2	0.013 (0.006–0.028)	0.035 (0.016–0.073)	0.080 (0.038–0.161)
Washakie	174.3	0.008 (0.004–0.017)	0.022 (0.010–0.046)	0.050 (0.023–0.104)
Weston	186.5	0.004 (0.002–0.008)	0.010 (0.005–0.022)	0.025 (0.011–0.052)
Wyoming	7,600	0.004 (0.002–0.009)	0.011 (0.005–0.024)	0.027 (0.012–0.055)

background mortality and thus the greater potential credit (Fig. 3). Potential mitigation credits are dependent on expected carcasses encountered, the traffic volume of the road upon which the carcasses will be encountered, and the current removal intervals from maintenance crews or other activities. Together, these 3 variables establish a cap on potential credit.

The model results indicated that the relationship between carcass number and mortality rates is most sensitive to epistemic uncertainty for the time eagles spend at the carcass and collision probability per passing vehicle (Table 3). The consequence of this shows increasing variation in expected mortality with increasing carcass availability (Fig. 1a). Uncertainty in golden eagle use-hours per available carcass-day had a greater influence on mortality probability than the number of days the carcass was available for scavenging or the age ratio of eagle scavenging use-hours (Table 3). In contrast, the effect of vph and removal intervals on relative mortality are insensitive to uncertainty in scavenging behavior (Fig. 3b and 3c); in other words,

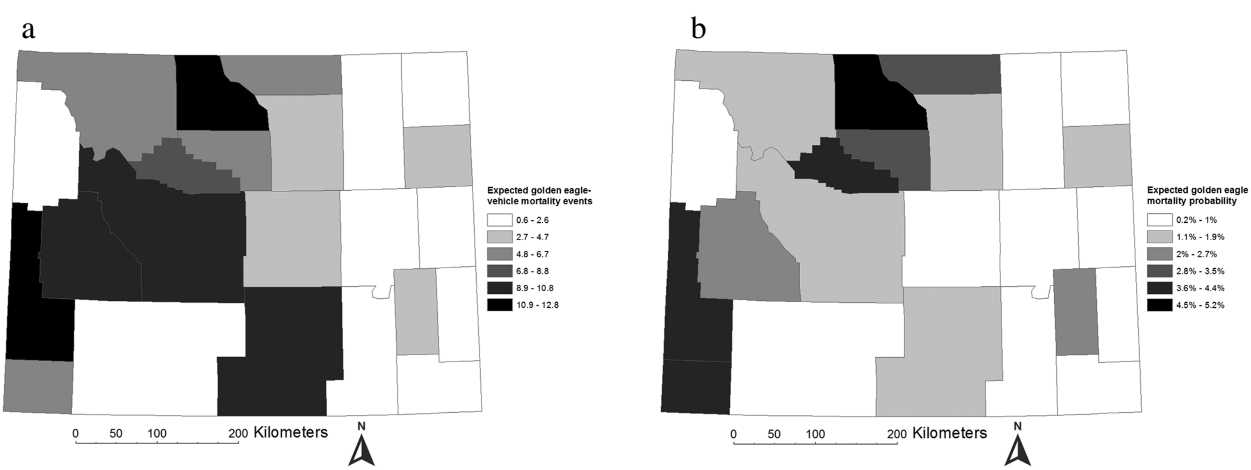

Figure 4. Model-predicted median annual golden eagle deaths (a) and mortality probability (b) for each Wyoming County, USA assuming a background removal interval of 7 days (1 removal/week) based on observed data on carcasses removed and traffic volume provided by Wyoming Department of Transportation. Actual removal intervals vary depending on whether roads are managed by the state or county, but conversations with management suggest removals are typically once or twice a week. Counties with greater predicted deaths or higher mortality rates are shaded darker than counties with lower mortality.

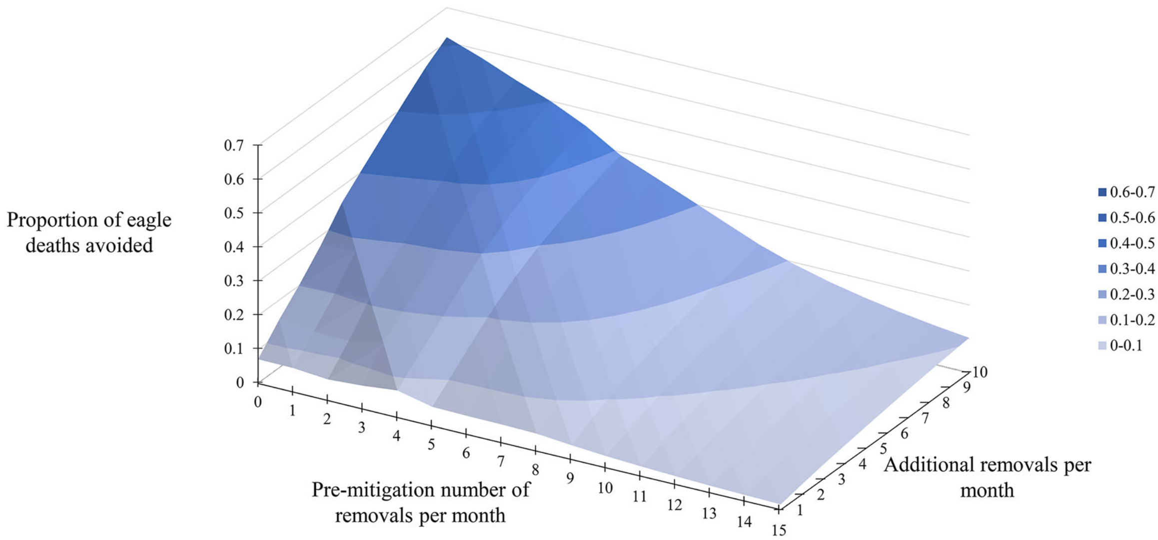

Figure 5. Relative mitigation credit (proportion of golden eagle deaths avoided) given background removal intervals and additional effort in Wyoming, USA. Darker values indicate greater potential credit and lighter values indicate less potential credit. Realized credit can be determined by multiplying relative credit by the expected mortality given traffic volume and expected number of carcasses found along the monitored road.

regardless of other parameter values, mortality is highest from traffic volume of 15–35 vph and the relationship between relative mortality and removal interval is not affected by epistemic uncertainty in the model.

DISCUSSION

We designed the golden eagle-vehicle collision model to be useful for assessing potential mitigation strategies by transparently depicting the effect of epistemic uncertainty on mortality estimates, and using units comparable with the USFWS's (2013) compensatory mitigation standards. The use of probabilistic model outputs facilitates applying a risk management standard that is comparable to estimates of predicted take used by the Eagle Guidance (USFWS 2013). Models, however, are hypotheses or purposeful representations of reality (Starfield 1997) built on many simplifications and assumptions, including expert judgment. A pragmatic model such as ours selectively represents the ecological components and functional responses scientists believe are most influential to the focal outcome and simulates these relationships forward in time with uncertainty. Hence, the model and its predictions can never be strictly verified, but we can assess the model's plausibility (Drescher et al. 2013) and usefulness for problem solving (Starfield 1997).

For a plausibility test, we compared the model's mortality estimates with the information available on golden eagle vehicle collision rates in North America. The cause-specific mortality rates estimated by our model are reasonable and consistent (McBride and Burgman 2012) with available information indicating that vehicle collisions cause approximately 1% annual mortality in golden eagles in the western United States (collisions account for ~5% of the 20% total annual mortality among post-fledging eagles; Hunt 2002, USFWS 2013). Even though confidence intervals for eagle collision deaths were large (most 80% CIs covered an order of magnitude), the expected mortality outcomes were generally robust to uncertainty in key structural elements of the model and to parameter values, varying from 0.1% to 3.0% median

Table 3. Sensitivity values (T-values) for 5 expert-elicited parameters by traffic volume. We ran the sensitivity analysis with 100 small ungulate carcasses, 0.03/km^2 golden eagle density, 10,000 km^2 area, and no removals, Wyoming, USA. We calculated the T-values from multiple regressions of simulation results for traffic volume ranging from 5 to 95 vehicles per hour (vph).

	Expert-elicited parameter				
Traffic volume (t)	Carcass days (CD)	Use-hours power function scalar (c)	Traffic (vph) where avoidance is 50% (k)	Collision probability per vehicle (ω)	Scavenging age ratio (a)
5	47.0	132.0	14.7	158.3	8.7
15	37.7	107.2	64.7	128.8	6.6
25	31.2	88.9	86.7	107.1	5.1
35	27.9	79.7	95.9	96.1	4.2
45	26.1	74.5	100.6	90.0	3.5
55	25.0	71.5	103.6	86.5	3.1
65	24.3	69.6	106.0	84.3	2.7
75	23.8	68.4	108.0	82.9	2.3
85	23.4	67.6	109.9	82.0	2.0
95	23.2	67.0	111.7	81.3	1.7

mortality rates (Table 2). Thus, the prototype model seems plausible. Scientific credibility also depends on transparency, and capacity for testing and updating the model. We document the model's computer code in Supplement B (available online in Supporting Information).

Mitigation Analysis

Our prototype analyses suggest that eagle collision deaths could be most effectively reduced through targeted removal efforts in specific contexts of expected carcasses, traffic volume, and background removal. Although increasing the number of removals will generally lead to more potential credits (Fig. 4), there are clearly contexts where traffic volume and expected number of carcasses combine to suggest greater potential reductions in mortality when compared to background. We estimate that background mortality probability of eagles caused by carcasses on roads with 15–35 vph is nearly double the probability of carcasses at 65 vph and this difference increases with increasing traffic volume. Similarly, if ongoing removal intervals are much greater than once per week, the potential to further reduce mortality through additional removals declines. In short, potential credits are context-dependent.

When these insights are applied to observed traffic data and carcasses, there are clearly hotspots of mitigation opportunity in Wyoming (Fig. 4), such as western Wyoming. Our map of potential credit (Fig. 4) suggests how spatial analysis could improve the tactical efficiency of mitigation by identifying the best travel routes to address (i.e., those with historically high occurrences of carcasses on roads with relatively low traffic volume). Our approach also provides estimates of uncertainty that can be used to develop risk-based determinants of mitigation credit for different removal options.

In response to uncertainty, decision makers may award even fewer mitigation credits than the median projection. For example, a lower confidence interval estimate of eagles saved, such as 20%, would mirror the degree of caution USFWS (2013) uses in estimating eagle take (Cochrane et al. 2015). The model could be used to plan strategic removal programs, but credits would be awarded based on actual carcass removals. Mitigation would provide an opportunity adaptively update the model by comparing the actual number of carcasses removed to number predicted to inform future uses of the model (Williams 2011). Also, if offsets are not contemporaneous with the estimated eagle take, the USFWS (2013) stipulates discounting credits by 3%/year.

Model Updating For Future Application

We designed the model as a prototype framework assuming it would be updated before it is applied for a specific mitigation plan and permit decision. Updating should reduce uncertainty in the model's parameter values and resulting predictions; it may also adjust (improve) the model's underlying assumptions and prediction accuracy. Site-specific parameters, including eagle density, road density, traffic volume, carcass removal schedules, and road kill (carcass) abundance and distributions, may be estimated from existing data, or permit applicants may need to complete local surveys on county roads or any other roads not managed by a state's department of transportation. In particular, road-kill patterns (frequency of road-kill species predicted by vph) are not generalizable across roads and regions (Bissonette and Kassar 2008, Gunson et al. 2011). Gathering carcass data at a potential mitigation site would determine if road kill is more numerous on either lower or higher traffic roads, which would affect eagle mortality rates in our model. The eagle behavioral parameters we developed from expert opinion, including carcass scavenging, traffic avoidance, and collision rates, may also be updated through monitoring and experimental research.

Research targeting the most tenuous and influential assumptions built into the model would enhance confidence in the model's predictive ability. The experts defined a small set of key factors influencing long-run average collision mortality, rather than explicitly decomposing the finer details of complex behavioral responses or annual demographic and environmental stochasticity imbedded in these functions. For example, the use-hours parameter assumes eagle scavenging is a simple direct function of eagle density averaged across the county and behavior of individual eagles including 1) whether they are resident or migrants, 2) whether they select for or against particular road types (other than traffic avoidance), and 3) how they respond to different carcass species (we did account for carcass size), conditions (other than days carcasses are edible), and locations (on or within 10 m of a travel lane). Although we assume these contributory factors are encompassed adequately in an average value for use-hours per carcass, this hypothesis can be tested as the numerical function relating use-hours to eagle density is updated. Similar studies could test assumptions linking scavenging rates to eagle age, and avoidance and collision rates solely to traffic volume. Scavenging studies would also determine the extent to which small animal carcasses contribute to scavenging time and collision risks, offering additional mitigation opportunities.

To reduce the bounds of uncertainty in mortality estimates, research focusing on the parameters that were most influential to eagle mortality in simulated sensitivity analysis would be beneficial. Uncertainty in the parameters we based on expert judgment could be reduced through active adaptive management of mitigation projects, or through research on eagle behavior independent of mitigation design. Research priorities depend on which parameters were most influential in predicting mortality and thus the change in mortality resulting from mitigation and on the practicality (cost) and power (benefit) of the specific research to reduce uncertainty and change mitigation strategies (Runge et al. 2011). From our prototype analysis we concluded that eagle scavenging and traffic avoidance behaviors are tractable, high priority targets for initial study, even though these parameters were somewhat less influential than collision rates in predicting collision mortality. In contrast, it would be challenging to update the collision probability parameter empirically, requiring extensive sampling effort to observe infrequent collisions at random locations without observer effects.

Based on the findings in our prototype analysis, United States Department of Interior biologists are pilot testing video and radar methods to quantify eagle scavenging by eagle age, carcass types and locations (controlled experiments), and traffic volume, speed, and local eagle density (concurrent surveys). These studies will also test the model assumption that the age structure of collision mortality is comparable with age distribution of eagles taken incidentally at wind energy facilities (or any permitted activity); if ages differ, then take and offsets can be converted into bird-years for debits and credits as detailed by USFWS (2013). With all model parameters updated except the collision probability per use-hour, we can run the model, compare the eagle death estimates with expected total collision mortality (based on telemetry), and adjust the collisions/use-hour parameter as needed. Thus, we can use the model to update the experts' estimates for this untestable yet critical parameter linking specific mitigation levels (carcasses removed from specific roads) to quantitative mitigation credits (eagle deaths avoided).

Our prototype analysis illustrates how carefully designed simulation is useful to developing compensatory mitigation plans. Updated, site-based data will be needed for any actual mitigation planning or Eagle Act permit analysis. Despite substantial uncertainty about collision death rates, the model suggests robust strategies for allocating mitigation effort by location and time are possible. Our results indicate that there should be little uncertainty about the relative effect of changes in removal schedules on eagle mortality and the basic understanding that areas with higher concentrations of road kill would predict higher mortality. Thus prioritizing research to update influential parameter values (i.e., the relationship between eagles and carcasses) will increase the reliability of predictive modeling efforts and specific mitigation values. By representing and quantifying the consequences of epistemic uncertainty, the approach allows us to analyze the numerical effects of collisions and mitigation, and inform risk management decisions (Cochrane et al. 2015). Because the extent of effort involved in offsetting strategies is also quantified, simulation modeling fosters analysis of mitigation efficiency and strategic planning.

MANAGEMENT IMPLICATIONS

Carcass removal should be one of the easier mitigation options to use and improve. Much of the data required to predict mortality (average annual vehicle traffic, the number of carcasses found, removal intervals, and estimates of golden eagle density) are available throughout much of the United States. Indeed, given the availability of these data, it should be relatively straightforward to apply the model in other areas of the country where conditions are similar to Wyoming in the winter. Predicted unavoidable take of eagles at proposed wind energy facilities is often <1 bird/year (from Eagle Act permit applications; Allison 2012; USFWS 2014, 2015). Thus, conducting collision mitigation may be economical where power pole retrofitting is not an offsetting option or in addition to this option. Locations with less frequent routine road maintenance, such as county roads, provide the greatest potential for collision mitigation credits. Furthermore, the model also provides predictions as to where collisions are most likely providing opportunities to test and improve the model's predictions using adaptive management.

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