Ecological Applications, 25(6), 2015, pp. 1518–1533

Modeling with uncertain science: estimating mitigation credits from abating lead poisoning in Golden Eagles

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Abstract. Challenges arise when renewable energy development triggers "no net loss" policies for protected species, such as where wind energy facilities affect Golden Eagles in the western United States. When established mitigation approaches are insufficient to fully avoid or offset losses, conservation goals may still be achievable through experimental implementation of unproven mitigation methods provided they are analyzed within a framework that deals transparently and rigorously with uncertainty. We developed an approach to quantify and analyze compensatory mitigation that (1) relies on expert opinion elicited in a thoughtful and structured process to design the analysis (models) and supplement available data, (2) builds computational models as hypotheses about cause–effect relationships, (3) represents scientific uncertainty in stochastic model simulations, (4) provides probabilistic predictions of "relative" mortality with and without mitigation, (5) presents results in clear formats useful to applying risk management preferences (regulatory standards) and selecting strategies and levels of mitigation for immediate action, and (6) defines predictive parameters in units that could be monitored effectively, to support experimental adaptive management and reduction in uncertainty. We illustrate the approach with a case study characterized by high uncertainty about underlying biological processes and high conservation interest: estimating the quantitative effects of voluntary strategies to abate lead poisoning in Golden Eagles in Wyoming due to ingestion of spent game hunting ammunition.

Key words: Aquila chrysaetos; *Bald and Golden Eagle Protection Act; compensatory mitigation; decisions in response to uncertainty; expert opinion; incidental take; lead abatement; lead poisoning; modeling with uncertainty; simulation model.*

Introduction

One challenge in the global push toward renewable energy sources is assuring that new infrastructure development complies with existing species protection laws (Ruhl 2012). To achieve "no net loss" of ecological or biodiversity values, environmental policies and regulations typically impose a hierarchy of avoidance, minimization of onsite effects, and restoration measures before compensation (also known as biodiversity offsetting) is considered to offset residual negative effects (BBOP 2012, Gardner et al. 2013, Bull et al. 2014). In addition, compensatory gains should be measurable, directly comparable with the predicted losses, and clearly attributable to the proposed mitigation action (Bull et al. 2013, BBOP 2012). These laudable standards could limit offset mitigation options to only well-established methods with empirical track records. But the toolbox of established methods can be insufficient to meet offsetting demand. The gap between pressing needs for mitigation and available methods can be bridged with experimental implementation of "unproven" methods, provided care is taken to deal transparently and rigorously with uncertainty throughout permitting analysis and implementation. Such is the case in the western United States where the Bald and Golden Eagle Protection Act of 1940 (Eagle Act), as interpreted by the U.S. Fish and Wildlife Service (Eagle Rule; USFWS 2009*a*), allows for development of innovative mitigation approaches to offset incidental taking of Golden Eagles (*Aquila chrysaetos*) associated with wind energy development.

Permitting of take under the Bald and Golden Eagle Protection Act.—The Eagle Act generally prohibits killing or otherwise "taking" eagles, although take may be permitted when it is incidental to otherwise lawful activity (under certain conditions [USFWS 2009*a*]). To receive a permit for incidental taking, predicted losses must be reduced to the maximum extent practicable and technically achievable via application of advanced conservation practices. Further, the USFWS (2009*a*) has set regional take thresholds to ensure that permitted take does not cause or contribute to the decline of breeding eagle populations. For Golden Eagles, the take thresholds are currently set to zero or "no net loss" at

Manuscript received 25 May 2014; revised 10 December 2014; accepted 16 December 2014. Corresponding Editor: S. S. Heppell.

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the scale of regional breeding populations, because all populations are considered vulnerable to declines; e.g., natural demographic compensation will not suffice to replace incidental take (McGowan et al. 2011). Any unavoidable take must be "demonstrably and quantifiably offset" by either reducing deaths of Golden Eagles from other causes or increasing recruitment of new adult Golden Eagles at least equal to the projected incidental take within the affected breeding population region (USFWS 2009*a*).

Wind energy facilities are at risk of taking Golden Eagles through collision fatalities, injuries, or other prohibited disturbance (Pagel et al. 2013) in violation of the Eagle Act. To facilitate wind energy development while sustaining healthy eagle populations, the USFWS (2013) developed Eagle Conservation Plan Guidance (Eagle Guidance) that outlines the recommended steps a wind energy company should follow to achieve the no net loss standard and receive a take permit. The Eagle Guidance spells out how different compensatory mitigation modeling methods may be used to predict the numerical effects of compensatory mitigation on eagle survival and reproduction, based upon resource equivalency analysis (USFWS 2013: Appendix G). Management actions must be "scientifically credible" and "verifiable" to qualify as compensatory mitigation.

The USFWS (2013) describes one compensatory mitigation approach as satisfying Eagle Act standards: retrofitting of power poles to prevent electrocution of eagles. Additional mitigation choices are needed where power pole retrofitting is not an available option; proposed methods include abatement of eagle–vehicle collisions, increasing abundance of eagle prey to increase eagle productivity, and reducing blood lead levels to increase eagle survival (USFWS 2013). However, before any mitigation alternatives can be accepted, the wind industry and other entities need credible, quantitative modeling frameworks to predict the impact of specific mitigation actions on eagle numbers.

A framework for dealing with uncertainty in offset analysis.—Bull et al. (2013) called for research and development of a comprehensive framework for dealing with uncertainty in offset analysis. Our project provides an example of such a framework for quantifying mitigation gains and reaching defensible decisions in a realm of high uncertainty about underlying biological processes and mitigation effects, and high public interest: strategies to abate lead poisoning in Golden Eagles in the western United States due to ingestion of spent game hunting ammunition. This case illustrates how compensatory mitigation can be leveraged to address a widespread and high-priority conservation concern such as lead poisoning (Haig et al. 2014). We chose to investigate lead poisoning abatement as a mitigation option because lead exposure via spent ammunition is a well-documented source of anthropogenic eagle mortality (e.g., Hunt et al. 2006, Bedrosian et al. 2012, Haig et al. 2014). Methods for encouraging and supporting voluntary lead abatement by sport hunters, such as subsidizing the expense of non-lead ammunition and education programs, are available for near-term application (e.g., Sieg et al. 2009, Bedrosian et al. 2012, Epps 2014, Haig et al. 2014). Lead abatement actions could be completed directly by permit applicants (e.g., a wind energy company) and their contractors, by mitigation banking where the applicant funds governmental or third-party programs, or through collaborative efforts (USFWS 2013).

Our model incorporates scientific uncertainty about how eagles ingest spent lead and die from that exposure; additional uncertainty arises from "partial controllability" (Williams and Brown 2012) of abatement efforts (Epps 2014, Haig et al. 2014). In other words, the model accounts for uncertainty in the amount of offset "credits" per abatement level, but not uncertainty in actually achieving an abatement level. Our Wyoming examples illustrate how estimates of implementation success can be added to mitigation decision making, but we leave the task of predicting abatement levels due to alternative "voluntary" (meaning nonregulatory) strategies to future analysis.

Biodiversity offsetting is typically measured in terms of spatial area with associated ecological values (e.g., Moilanen et al. 2009, Quétier and Lavorel 2011, Maron et al. 2012, Bull et al. 2013, 2014, Regnery et al. 2013), sometimes including species count data (e.g., USFWS 2009*b*, *c*, Doherty et al. 2010). These methods do not transfer well to mitigation analysis under the Eagle Act since they do not account for losses and gains based on individual animals. Maron et al. (2012) suggested that mitigation based on "number of individuals" may be one of the easier mitigation cases because it can be "defined precisely, quantified well, and often measured (or at least estimated) accurately." Indeed, calculating mitigation to replace deaths in a discrete animal population seems a relatively tractable problem when contrasted with the challenges of quantifying losses and gains among multiple and complexly interacting ecological functions in disturbed and restored ecosystems. Yet even in comparatively well-studied wildlife populations the effects of particular mitigation actions may be fraught with scientific uncertainties and difficult to quantify.

Our framework for analyzing individual animal offsets builds upon best practices for modeling to solve wildlife management problems (e.g., Starfield and Bleloch 1991, Starfield 1997), eliciting expert judgments for risk analysis and modeling (e.g., Martin et al. 2012, Drescher et al. 2013), and making decisions under uncertainty (e.g., Burgman 2005, Williams and Brown 2012). Our approach to mitigation analysis (1) relies on expert opinion elicited in a thoughtful and structured process to design the analysis (models) and supplement available data, (2) builds computational models as hypotheses about cause–effect relationships (Runge et al. 2011), (3) represents scientific uncertainty in stochastic model simulations (Drescher et al. 2013), (4) provides probabilistic predictions of "relative" mortality (Beissinger and Westphal 1998) with and without mitigation, (5) presents results in clear formats useful to applying risk management preferences (Burgman et al. 1993) and selecting strategies and levels of mitigation for immediate action, and (6) defines predictive parameters in units that can be monitored effectively, to support experimental adaptive management and reduction in uncertainty (Williams and Brown 2012). Collectively, these components allow us to make useful and responsible estimates for compensatory mitigation.

Expert opinion and model development to support decision making.—In environmental risk assessment, the issue is not whether but how best to use expert judgment (Burgman 2005). Formalized applications of expert opinion are increasingly common in ecology and conservation (e.g., Martin et al. 2005, Marcot et al. 2006, Low-Choy et al. 2009, Kunhert et al. 2010, Burgman et al. 2011, Runge et al. 2011, Drescher et al. 2013). Expert opinion may be integral to various stages of environmental decision analysis, from initial problem framing and conceptual model development, to derivation of quantitative cause-and-effect relationships and probabilistic estimates of action effects, to planning for and conducting experimental implementation through active adaptive management (Burgman 2005, Marcot et al. 2006, Runge et al. 2011, Martin et al. 2012, McBride and Burgman 2012, Drescher et al. 2013).

Best practices for eliciting and applying expert knowledge are well established (Morgan and Henrion 1990, Cooke 1991, Ayyub 2001, Low-Choy et al. 2009, Speirs-Bridge et al. 2010, McBride and Burgman 2012, Perera et al. 2012, Drescher et al. 2013). As with other aspects of modeling or mitigation analysis (Starfield 1997, Bull et al. 2014), the use of expert opinion should be carefully designed to match particular problems and objectives. Key components include (1) selecting experts, (2) structuring their contributions to minimize bias and maximize accuracy, transparency, and utility, (3) measuring and documenting uncertainty, and (4) checking for plausibility.

In sum, our model estimates the resource equivalency value of mitigation that reduces eagle exposure to lead from ingesting spent ammunition, assuming a specified level of mitigation, e.g., the "credits" needed to offset predicted unavoidable losses of eagles at wind energy or other facilities. We demonstrate the model's utility with an example analysis of alternative strategies to abate lead poisoning in the state of Wyoming. While the model is specific to lead abatement in Golden Eagle populations, our approach illustrates a comprehensive framework for dealing with scientific uncertainty transparently and rigorously in compensatory mitigation analysis and decision-making.

Methods

The stages of model development were: (1) expert panel selection; (2) preliminary conceptual model development; (3) in-depth literature review; (4) conceptual model revision and preliminary parameter values selection; (5) deterministic spreadsheet model; (6) expert review and discussion (webinar); (7) stochastic spreadsheet model prototype; (8) expert review and discussion (webinar); (9) model revision, expansion and coding in Matlab; (10) formal elicitation of expert judgments for select parameter values; (11) prototype simulations and sensitivity analysis; (12) expert review and discussion (webinar); (13) repeat formal elicitation to update parameter values (note: steps 11–13 were completed twice, for a total of three formal elicitation rounds); (14) final runs and sensitivity analysis; (15) final reviews. We outline our methods here; see Appendix B for complete details of the expert elicitation methods and results, and Appendix C for detailed model equations and parameter values.

Expert opinion

Expert opinion served two critical and distinct roles in this modeling project. The first role was provided by a group of experts who advised the authors on all aspects of model development from initial concepts to the final simulations. The second role for expert judgment was providing quantitative estimates for specific model parameters where data from empirical research were limited or absent. Our goal was to work with a small group of experts who were not only deeply knowledgeable about relevant topics, but also effective communicators and willing contributors (Martin et al. 2012, Drescher et al. 2013). At various stages of the project we engaged with 16 scientists with expertise in one or more fields including (1) eagle behavior, ecology, and management, (2) raptor lead poisoning, (3) quantitative skills and modeling, (4) regulatory requirements and mitigation planning, and (5) field conditions in different regions of the western United States (see Appendix B for selection process and list of experts).

At an initial workshop we led an expert panel through exercises to describe and draw a conceptual model of how ingesting lead ammunition fragments poisons Golden Eagles and how abatement strategies may reduce ingestion rates. Conceptual model development is largely a subjective process (Burgman 2005, Marcot et al. 2006), but we employed best practices of expert elicitation to help maximize critical thinking and information sharing, while minimizing biases such as anchoring and "group think" (e.g., Martin et al. 2012, McBride and Burgman 2012, Drescher et al. 2013). We converted the experts' conceptual model diagram into a simple Bayes net (run in Netica, version 4.09 [Norsys Software Corporation, Vancouver, British Columbia, Canada]), and subsequently into a simple spreadsheet first-prototype model to facilitate further discussion of quantitative relationships. This iterative build–review–

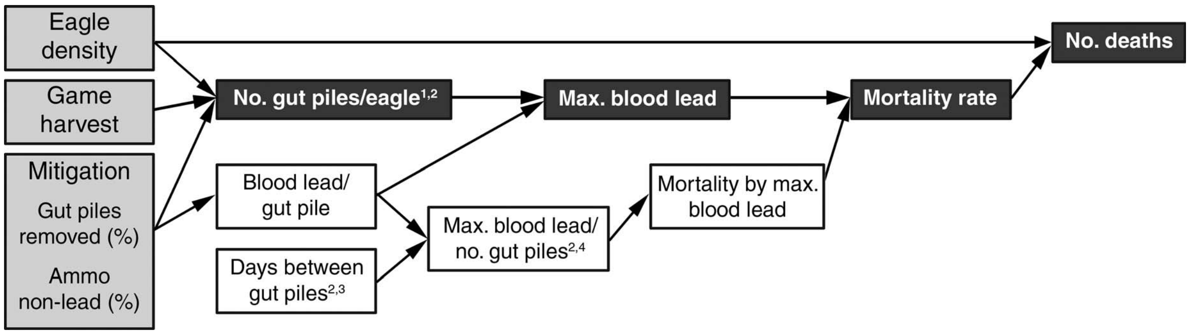

FIG. 1. Causal diagram illustrating the cause-to-effect relationships (directional arrows) between input and output parameters (boxes) in the Golden Eagle lead abatement model. The predictive variables or "inputs" (light-shaded boxes) are set for each scenario and geographical unit modeled. The subsequent parameters or response variables result from the modeling steps; of these, the dark-shaded boxes are location-specific responses (dependent upon the gut piles available per eagle). Four additional model inputs are indicated by superscript numbers where they influence a response parameter: (1) the game recovery rate, (2) maximum number of gut piles scavenged per month, (3) minimum days' lag between gut piles scavenged, and (4) daily blood lead decay rate derived from the blood concentration half-life. The model output is a probability distribution of Golden Eagle deaths produced from repeated stochastic simulations.

revise process was repeated with the addition of stochastic parameters and more example runs over a couple of months, before we settled on all the functional relationships to include in a fully computational model to be programmed in Matlab (see Appendix C for detailed diagram of the final computational model).

During early model development we prepared a literature summary on eagles and lead poisoning for the experts to read as background information (see Appendix A) and developed parameter values to use in the prototype simulations. For three parameters, we needed to elicit expert judgments more formally where we lacked empirical data to develop functional distributions for the model's cause–effect relationships. A group of four experts who are highly experienced in Golden Eagle behavior provided estimates for eagle scavenging rate (the average expected number of gut piles scavenged per eagle in association with specific levels of eagle and gut pile densities). A separate group of four experts in lead poisoning in raptors provided estimates for two parameters addressing lead toxicity (blood lead level increase per scavenge, and mortality per maximum blood lead level).

We elicited or encoded (McBride and Burgman 2012) these judgments following Speirs-Bridge et al.'s (2010) four-point method. We asked for the (1) lowest reasonable estimate, (2) highest reasonable estimate, (3) and most likely estimate for each value of interest, followed by (4) the expert's degree of confidence (from 50 to 100%) that the values for each parameter were within the lowest–highest range they provided. In addition, we elicited a discrete probability distribution for the incremental increase in blood lead per gut pile scavenged. For probability estimates, we employed direct elicitation while encouraging the experts to think about probabilities as frequencies or proportions of events they could envision from their experiences (e.g., indirect elicitation, Burgman 2005).

Each elicitation was preceded by review and clarification of the purpose, context, definitions, and relevant information for the predictions at hand. We employed a modified Delphi approach to the elicitation (Runge et al. 2011), eliciting responses from each expert independently, followed by tightly facilitated group discussions. An initial elicitation with the eagle experts was completed during the in-person workshop; all subsequent rounds occurred remotely. Following discussion and modifying any assumptions and questions as agreed upon by each team, we allowed each expert to update their responses as desired. We repeated this iterative cycle of response–review–revise until the experts stated they were satisfied that the elicited values represent their best available beliefs about the defined relationships.

We developed distributions for the three elicited parameters by looking at the patterns among the elicited values and subjectively applying functional relationships that best matched plots of elicited values (for details, see Appendix B). These functional curves are smoothed representations for a range of expert beliefs about underlying ecological processes (Burgman 2005). Preliminary model runs provided insights that helped the experts update their beliefs about the model parameters, identify missing elements, and improve the fit of distributions for elicited parameters.

Model design and steps

The model simulates step-by-step how scavenging Golden Eagles consume spent ammunition and accumulate lead in their blood, and how many die from acute lead exposure during a month of big game hunting season in any specified geographical region (see causal diagram in Fig. 1; also Appendix C: Fig. C1). The overarching relationship is that as the density of gut piles containing spent lead ammunition increases, the likelihood of eagle

TABLE 1. Parameter value ranges used in modeling the Wyoming scenarios, based on expert elicitation results (Appendix B).

Parameter	Values
Average maximum number of gut piles eaten per eagle in a month	1–5
Mode of the blood lead concentration increase (μg/dL) per gut pile scavenged	25–75
Blood lead concentration that would lead to 50% mortality (μg/dL)	150–700
Gut piles with no lead fragments (%)	10–50
Half-life of lead in blood (days)	10–20

Note: See the Supplement for game harvest and eagle density data by Wyoming hunting unit.

exposure and acute mortality increases proportionally (Hunt et al. 2006, 2009, Green et al. 2008, Bedrosian et al. 2012, Legagneux et al. 2014), accounting for variation in eagle and gut pile densities. The model is not a demographic model of the complete annual cycle (e.g., all births and deaths) for the eagle population. Instead, it is similar to an ecological web belief network model (Marcot et al. 2006) in predicting the outcome of interest (eagle deaths during hunting season) due only to a particular set of influential variables. For this first analysis of potential mitigation strategies, we chose not to include lead exposure from sources other than big game hunting, and did not address ancillary or cumulative effects of lead exposure beyond acute deaths.

We adopted these key assumptions in building the model:

1) The particular location of hunting and gut pile availability within geographical areas (hunting units in our examples) is not considered by the model; we assume eagles are adept at finding these food supplies in open terrain, such as typical Wyoming hunting habitats. Natural variation in food sites and detection is accounted for by modeling an average scavenging rate.
2) Average expected scavenging rates per Golden Eagle can be calculated from gut pile abundance and eagle density per unit area. Natural variation in gut pile characteristics and in scavenging due to the age, social status, residency or migrant, or other traits of eagles in a population are accounted for by modeling an average scavenging rate.
3) Estimated scavenging rates take into account that primary sciurid prey in Wyoming, ground squirrels (*Urocitellus* spp.), prairie dogs (*Cynomys* spp.), and marmots (*Marmota* spp.), may be hibernating during the fall–winter hunting season and are generally unavailable as food for eagles during this season.
4) Maximum blood lead is a useful index of lead exposure and potential mortality. Although field measurements of blood lead generally are not peak levels (Finkelstein et al. 2012, Hunt 2012), we can model expected maximum blood lead for prediction purposes. Subsequent field confirmation of blood lead levels would have to be adjusted to account for time between feedings, blood lead decay rates, and variation from peak blood lead.
5) Predicting the probability of acute lead-poisoning mortality in one-month time frames is reasonable and keeps our focus on direct rather than indirect and cumulative effects of lead ingestion.
6) Using population averages for model inputs based on either 100-km^2 or hunting-unit-sized regions provides estimates of "expected" (long-run average) eagle deaths that are appropriate for decision-making under the Eagle Act. Thus, we did not need to build and run a more complex or individual-based model and did not need to simulate natural temporal variation due to demography or environmental stochasticity.
7) The variation between high and low estimates for the model parameters derived from the literature and expert elicitation represents epistemic or scientific uncertainty about the "true" functional relationships (Kuhnert et al. 2010, Runge et al. 2011).
8) Scientific uncertainty in expected (long-run average) outcomes is estimated adequately by 5000 simulations with stochastic sampling of the input variable distributions (Table 1) for each modeled scenario.

Estimating the number of gut piles eaten per eagle.—While Golden Eagles frequently feed on carrion in the fall and winter (Kalmbach et al. 1964, Kochert et al. 2002, Watson 2010), including big game gut piles (Legagneux et al. 2014), data are not available for the scavenging rate parameter in our model. Thus, we apply foraging theory and elicited expert knowledge to project the number of gut piles eaten per Golden Eagle based on the relative density of gut piles available per eagle. We modeled this relationship as a Type III functional response (Holling 1959, Restani et al. 2000) that has an initial lag, increases rapidly, then plateaus or saturates at a maximum potential number of gut piles the eagles are able to scavenge per month (Fig. 2, top panel). We assume that gut piles are not divided between different eagles, and use a Poisson distribution to determine the discrete probability that an eagle ingests 0, 1, and up to the maximum possible number of gut piles an individual eagle could ingest in a month, which we set at five based on expert opinion. This means that the absolute largest number any Golden Eagle will eat is five gut piles in a month, although the actual (expected) maximum in any population may be lower than five (Appendix C: Eqs. C.1 and C.2).

Estimating blood lead concentration per gut pile.—We assume that scavenging eagles ingest lead in direct proportion to lead ammunition use and resulting fragment abundance in gut piles, in concurrence with Hunt et al. (2006, 2009) and Bedrosian et al. (2012) findings that blood lead levels in eagles were highly correlated with the absolute number of big game animals hunted with lead ammunition (see Plate 1). Lead fragments varied from none to hundreds in samples of gut piles from deer shot with lead ammunition (Hunt et al. 2006, 2009, Warner et al. 2014). Lacking direct empirical measures, we relied on expert elicitation to describe the probability distribution of the amount of lead an eagle absorbs when it scavenges a gut pile that contains lead bullet fragments, as measured by peak blood lead concentration. The experts reviewed relevant information (Appendix A) before providing professional judgments for this novel parameter.

We use the Cauchy distribution to model the scavenge–lead exposure relationship because it best approximates the logic expressed by our experts and provides "fat-tails" of the distribution, i.e., nonzero probabilities of relatively high or low amounts of lead exposure when gut piles contain lead bullet fragments (Fig. 2, middle panel; Appendix C: Eq. C.3). We modified this exposure probability to account for the estimated proportion of gut piles that do not contain lead (Appendix C: Eq. C.3b), which the experts estimated is between 10% and 50% (from Hunt et al. 2006, 2009, Warner et al. 2014). This produces a bimodal distribution for lead exposure with one peak at zero and a larger peak at the mode of the Cauchy distribution, which varied from 25–75 μg/dL, reflecting scientific uncertainty.

Estimating days between multiple gut piles scavenged.—Since blood lead concentrations decay between feeding events, we include the effects of time lags between meals in order to estimate the average maximum blood lead levels eagles experience during a month when they consume gut piles on different days. Gut piles of large game provide a full meal to a Golden Eagle (e.g., viscera comprise ~14% of large ungulate body mass [Wilmers et al. 2003]) and our experts believe a typical minimum lag or waiting time is at least three days between scavenging events. When eagles eat more than one carcass in a month, we model uncertainty in the average or expected lag time between meals with a simple formula that draws a uniform integer between a minimum of three days and a potential maximum where meals are evenly dispersed across a 30-day month (with meals on the first and last days) (Appendix C: Eq. C.4). Thus the potential maximum lag varied from 7 days with 5 meals per month, up to 30 days with two meals per month.

Estimating maximum blood lead by quantity of gut piles scavenged.—To incorporate dynamics of lead accumulating and diminishing in the blood over multiple scavenge events, we first calculate the daily decay rate for blood lead based on the average blood lead half-life (Appendix C: Eq. C.5), which our experts believe is between 10 and 20 days, based in part on studies of California Condors (*Gymnogyps californianus*) (Appendix A). Next we calculate the probability distribution of maximum blood lead concentration (Appendix C: Eq. C.6), given the number of gut piles ingested, lag time between meals, the daily blood lead decay rate, and the blood lead concentration increase per gut pile consumed, up to the expected maximum number of meals in a month.

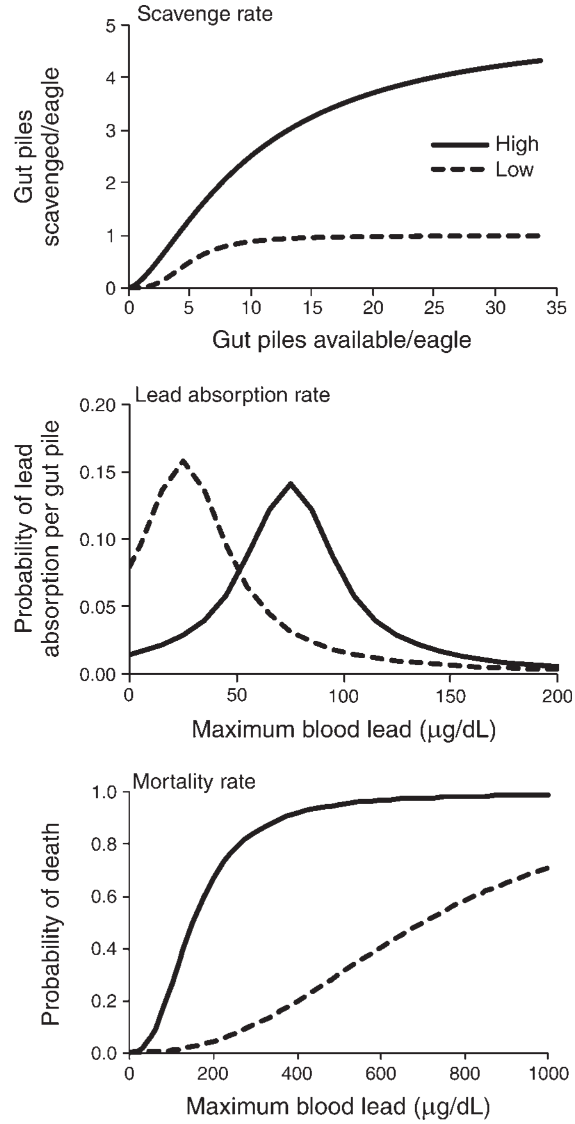

FIG. 2. Distributions sampled for three input parameters. Top: Golden Eagle scavenging rate, or average expected number of gut piles scavenged per eagle. Middle: blood lead absorption rate, or probability of an eagle having a peak concentration of lead in their blood per gut pile scavenged, based on a Cauchy function. Bottom: Golden Eagle mortality rate by blood lead concentration, or probability of acute death based on maximum blood lead concentration during a month. For each of these parameters, we used the low and high curves to define lower and upper bounds of uniform distributions that were sampled for each simulation. All three distributions are smoothed representations of the range of estimates elicited from eagle and lead effects experts (see Appendix B).

Estimating mortality by maximum blood lead.—As the maximum concentration of lead in the blood increases, Golden Eagles may suffer from lead poisoning, and the likelihood of mortality increases. Blood lead concentrations >100 or >120 μg/dL are generally associated with acute, fatal, or toxic lead poisoning in raptors, based on large numbers of birds treated in rehabilitation centers (e.g., Kramer and Redig 1997, Stauber et al. 2010, Kelly et al. 2011, Bedrosian et al. 2012 citing Redig 1984, Cruz-Martinez et al. 2012). Blood lead concentrations as low as 2–5 μg/dL affect avian physiology and may contribute to subsequent mortality (Pain et al. 2009, Finkelstein et al. 2012, Hunt 2012); however, the model does not account for cumulative indirect or sub-lethal effects. Our goal is to prototype a lead abatement model that estimates mitigation credits available by reducing acute mortality during the hunting season.

For simplicity and clarity, our model predicts mortality based on peak blood lead levels post-ingestion, and we elicited dose-mortality probability estimates from our experts in those terms after reviewing available data on blood lead concentrations and mortality (Appendix A). Since blood lead concentration for acute mortality is not known with certainty, we model mortality as a probabilistic function by maximum blood lead level during a month (Fig. 2, bottom). We used a saturating functional shape for mortality based on blood lead concentration (Appendix C: Eq. C.7) with half-saturation values between 150 and 700 μg/dL reflecting scientific uncertainty.

Integrating blood lead concentration and mortality: expected maximum blood lead and mortality rate for a site.—Given the probability distribution for the number of gut piles scavenged and the probability distribution of blood lead concentration per gut pile consumed, we can project the joint probability distribution describing the expected number of gut piles eaten and the blood lead concentration due to those gut piles (e.g., the expected maximum blood lead; Appendix C: Eq. C.8). To determine the expected mortality rate that accounts for multiple scavenge events, we simply need to multiply this joint probability distribution by the mortality consequence of that combination (Appendix C: Eq. C.9). The total expected mortality is thus influenced by the availability of carcasses per eagle and the amount of blood lead concentration increase per gut pile consumed. It follows that the number of Golden Eagles dying per area (hunting unit) is simply the mortality rate multiplied by the estimated population size (Appendix C: Eq. C.10). To estimate mortality rates at larger geographical scales, we sum the total deaths and divide by the total eagle abundance across all the units encompassed by the larger area.

Incorporating mitigation.—We model two mitigation options: removing gut piles from the landscape, or reducing the proportion of gut piles that have lead in them by replacing lead ammunition with non-lead ammunition. Our model predicts how eagle mortality would change *if* a specified level of either mitigation measure occurred. For each mitigation scenario we simulate, we input a proportional reduction in gut pile abundance or ammunition containing lead (Appendix C: Eqs. C.11–C.12) to represent a hypothetical level of voluntary mitigation and run the model to determine the change in expected eagle mortality. Thus, we model mitigation based on the adoption or success rate of the voluntary lead abatement, without addressing how to use educational programs or economic incentives to get there.

Implementing the model

The model is implemented as a simulation program run in Matlab (version R2010a, MathWorks; see Supplement for model code) with stochastic sampling from the distributions we assign to the input variables and their functional relationships. We gathered publicly available hunter harvest data for the number of elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginianus*), and pronghorn antelope (*Antilocapra americana*) harvested within each of the designated hunting units in Wyoming for 2012 (Wyoming Game and Fish Department 2013, public communication: 2012 annual report of big and trophy game harvest).[5] We assumed all game was shot with lead ammunition, so we can compare model performance with historical lead poisoning rates. We also assumed that 90% of shot animals would be retrieved and field-gutted by hunters based on Fuller (1990) and Nixon et al. (2001). Golden Eagle densities specific to Wyoming have not been published, so we used preliminary estimates of late summer abundance covering 139 of 141 Wyoming Game and Fish Department hunting units (Ryan Nielson, *personal communication* [Western EcoSystems Technology, Incorporated, Cheyenne, Wyoming, USA, 2014]) based upon USFWS late-summer surveys and methods reported in Nielson and Sawyer [2013] and Nielson et al. [2014]). While preliminary, we considered these abundance estimates sufficiently representative of potential eagle densities in Wyoming to be useful in determining whether our prototype model predicts plausible rates of lead poisoning for a Wyoming example. The 139 Wyoming hunting units we considered encompass 236 975 km^2, with 81 054 big game animals reported shot in 2012 and an estimated 6435 Golden Eagles in late summer, for a statewide average of 2.72 Golden Eagles/100 km^2 and potential availability of 11.34 gut piles per Golden Eagle (see the Supplement for game harvest and eagle density data). All other model parameter values were determined as described previously and in Appendix C. Prior to use in any actual permitting context, the model would need to be updated with the current, best available site-specific data, including eagle density estimates.

To incorporate scientific uncertainty in parameter values, we ran 5000 iterations of every modeled scenario drawing random sets of parameter values from the specified distributions for every parameter each time. We determined the average scavenging rate and

[5] http://wgfd.wyo.gov/web2011/Departments/Wildlife/pdfs/HR2012_FULLREPORT0005408.pdf

resulting blood lead concentration for each hunting unit, because these values depend upon unit-specific eagle and gut pile densities. All other input parameters were determined once at the start of every iteration to be applied across all hunting units.

Sensitivity analysis of parameter values.—We explored the effect of uncertainty in five model parameters that produced the most variation in model outcomes during preliminary runs: (1) the average maximum number of gut piles eaten per eagle (as used in the Type III scavenging function); (2) the blood lead concentration increase with each gut pile consumed (mode value of the Cauchy exposure function); (3) the mortality rate due to blood lead based on the concentration of lead in the blood that would lead to 50% mortality (half-saturation value in the dose-response mortality function); (4) proportion of gut piles containing no lead fragments (when the animal was shot with lead ammunition); and (5) the persistence of lead in blood (half-life of lead in the daily decay rate function). For the sensitivity analysis we held eagle density constant at 5.0 eagles/100 km^2 across all hunting units, which produced a wide range of levels in gut piles available per eagle and illustrated the impact of the five variables based upon gut pile availability. We completed 5000 simulations with the values of all five parameters varying randomly within their respective distributions, which covered the same range of values for each parameter as in the Wyoming modeling scenarios (Table 1), except that we extended the range for blood lead concentration for 50% mortality from 150–700 to 120–720 μg/dL. We sorted the results of each simulation into four or five incremental levels or "bins" for a range of values for each sensitivity analysis parameter, and calculated the mean mortality rate in that location given each bin level for each parameter while all other input parameters varied randomly. Thus, for sensitivity analysis, we report mortality rates from hunting units, rather than pooling eagle deaths to report statewide mortality rates.

Mitigation scenarios.—We explored the effect of non-lead ammunition by running the model under 11 scenarios, from 0 to 100% of harvested animals shot with non-lead ammunition, with a 10% step. We used the same set of scenarios to explore the effect of gut pile removal from eagle habitat. Each mitigation scenario (type and level) was run for 5000 simulations using the available data on eagle and gut pile densities by hunting unit, while all other input parameters varied randomly. We also completed sensitivity analysis to explore the effect of gut pile availability per eagle on mitigation success, running 5000 simulations for each mitigation scenario under each of nine combinations of eagle and gut pile density (fixed for all hunting units), while all other parameters varied randomly. We used combinations of eagle density at 0.5, 2.0, or 3.5 eagles/100 km^2 with gut pile density 5, 45, or 85 piles/100 km^2 (a total of nine combinations). Although higher densities of both eagles and gut piles occur in Wyoming, we explored density combinations up to the extent eagles were fully saturated with the gut piles available and additional combinations were not informative.

Example of compensatory mitigation analysis.—To illustrate how the modeling analysis can support an incidental take permit application process, we simulated a hypothetical example by determining the level of non-lead ammunition mitigation that would be needed to compensate for the incidental taking of Golden Eagles in a region around Casper, Wyoming, under different management preferences for addressing the uncertainty in eagle density estimates and the modeled mortality rates caused by lead ingestion. Specifically, we looked at hunter's voluntary adoption of non-lead rifle ammunition.

So, for example, if permit compliance would require compensating for the unavoidable incidental deaths of five Golden Eagles per year at proposed wind energy facilities (an unusual and very high take level for one facility), we can ask, "What portion of big game hunters would need to switch from lead to non-lead bullets in this region, on average, to reduce eagle deaths in this population by an expected five eagles per year?" (Question 1). The compensatory mitigation analysis may be tailored for alternative framing of the decision question. Perhaps the partners developing a voluntary mitigation program estimate that 25–50% of hunters would use non-lead ammunition across the project area, based on local knowledge and the initial success of programs attempted elsewhere (e.g., Sieg et al. 2009, Bedrosian et al. 2012). Given that expected level of lead abatement, we can ask, "How many eagles do we estimate will be saved?" (Question 2).

We illustrate how project developers and permit decision makers can apply risk management standards when assigning mitigation credits based on these uncertain estimates. They may be neutral to risks and determine mitigation credits from the average or expected predictions from the model. Perhaps instead they want to be cautious in the face of uncertainty, preferring to err toward a more conservative estimate for the number of eagles "saved" from lead poisoning until more data are gathered to support the modeled predictions. Such caution is frequently applied to biodiversity offsets via multipliers for compensatory area (Quétier and Lavorel 2011), although specific loss : replacement ratios are rarely linked to an explicit degree of uncertainty or biodiversity valuing (Moilanen et al. 2009, Maron et al. 2012, Pilgrim et al. 2013). By producing mortality estimates as a probability distribution, our model supports decision analysis at any level of regulatory risk tolerance (Burgman 2005), from caution to optimism. Our example illustrates cautionary decisions using the 20th percentile, because it mirrors the degree of regulatory caution employed by the USFWS (2013: Appendix D) when they use the 80th quantile or upper credible limit to predict eagle fatalities. (Both estimates err toward protecting the species in the face of prediction uncertainty.) Before determining credit for eagles saved, similar choices may be considered to address uncertainty in regional eagle density estimates.

We used the same model parameter values for the hypothetical examples of compensatory mitigation analysis as in our statewide analysis, applied to the game harvest data and eagle density estimates from the Casper region (Wyoming Game and Fish Department big game hunting units 22, 34, 66, 67, 88, 89) that encompasses ~16 303 km^2, with an estimated 679 Golden Eagles in late summer (4.17 eagles/100 km^2) and 6.46 big game gut piles per Golden Eagle.

Results

Under the status quo without mitigation, our stochastic simulations (including all our modeling assumptions and preliminary eagle density estimates) projected that the expected or median mortality of Golden Eagles dying from ingested lead in a month of big game hunting season was 3.2% of the Wyoming population (full simulation results in Appendix D: Table D1a, b). This estimate had considerable uncertainty; based on the 10th and 90th percentile simulations an 80% credible interval was 1.3–9.2% mortality. Fig. 3 illustrates the effect of uncertainty on the mortality projections. Most (70%) of the no-mitigation simulations resulted in cause-specific mortality rates below 5%. However, a small fraction of the stochastic parameter combinations (e.g., the top increment of simulations between 90% and 100%) produced mortality outcomes 3–10 times higher than the median.

Sensitivity analysis of parameter values.—Our sensitivity analysis revealed that mortality rate increased as the quantity of gut piles available per eagle and lead fragment ingestion increased, although the rate of increase diminished as the eagles became increasingly saturated (Fig. 4; the bend in the curves is dictated by the half-saturation parameter in our scavenging function, which we set at ~5–10 gut piles) (full results for sensitivity analysis in Appendix D: Table D2a, D2b). Without mitigation, mortality was only 1.3% if only 1.4 gut piles were available per eagle; at the other extreme, mortality increased to 6.5% at 170 gut piles per eagle.

Mortality was affected most noticeably by four model parameters in addition to gut pile availability. The parameter with the greatest influence on predicted mortality was blood lead concentration that leads to 50% mortality (Fig. 4A), followed by the average maximum number of gut piles Golden Eagles eat in a month (Fig. 4B), how much blood lead increased per scavenge (Fig. 4C), and the proportion of gut piles containing no lead fragments (Fig. 4D). In contrast, within the parameter ranges we evaluated, the half-life of lead in blood had very little effect on mortality rates (Appendix D: Fig. D1E).

When we repeated the complete sensitivity analysis at lower eagle densities (down to 0.5 eagles/100 km^2), the sensitivities of mortality rates to parameter levels were equivalent to those shown in Fig. 4. This confirmed that mortality rate predictions in our model are a function of gut piles available *per eagle* rather than eagle abundance per se, at least within the eagle abundance levels estimated for most Wyoming hunting units in late summer.

Mitigation scenarios.—Both gut pile removal and non-lead ammunition affected mortality rates in proportion to the amount of mitigation imposed, but the use of non-lead in place of lead bullets was consistently more effective than removing gut piles in reducing expected eagle mortality. On average (from our statewide analysis), median mortality dropped by half with 50% non-lead ammunition, but only by one-third with 50% gut pile removal (from 3.2% at no mitigation to 1.6% and 2.3%, respectively). In sensitivity analysis with varied gut pile and eagle densities, the difference between the types of mitigation became more pronounced as eagles became more saturated with gut piles and mortality rates increased (Fig. 5). In contrast, regardless of eagle and gut pile densities, eagle mortality declined in direct proportion to the percentage of game animals shot with non-lead bullets.

Example of compensatory mitigation analysis.—Results for the Casper region example exhibited the same patterns as the statewide results, although with lower average mortality rates (median 2.4% with no mitigation; full results in Appendix D: Table D3a, b), reflecting the lower abundance of gut piles per eagle in these six hunting units (6.46 vs. 11.34 gut piles) because eagle density here is relatively high for the state. Fig. 6 illustrates how these results may be used to answer our permitting analysis questions. To reduce eagle deaths by an expected five per year (Question 1), our "expectation" is that ~31% of big game hunters would need to switch from lead to non-lead bullets in this region. A compensatory mitigation credit of five eagles (marked by the circle in the left panel of Fig. 6) is the median or expected outcome from simulations that incorporated uncertainty about lead poisoning rates, given the mean eagle density estimate for the Casper region in late summer (679 eagles) and 31% non-lead mitigation. The cautionary choice for assigning mitigation credits, illustrated with the 20th percentile simulation, indicates that 55% of hunters in the Casper region would need to use non-lead ammunition to save five eagles annually (marked by the circle in the right panel of Fig. 6).

For the alternative framing of the decision question (Question 2), the model predicts an expectation, or 50:50 chance, that at least eight eagles would be saved based upon the median simulation with 50% non-lead ammunition (marked with a diamond in the left panel of Fig. 6). More cautiously, the model provides high confidence that at least two eagles would not die from lead poisoning, again determined with the example of using the 20th percentile simulation and cautiously anticipating 25% non-lead ammunition (marked with a diamond in the right panel of Fig. 6).

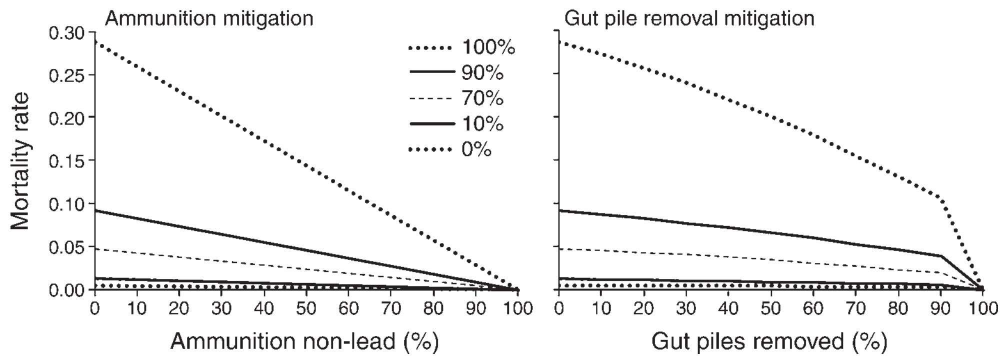

Fig. 3. Effect of parameter uncertainty on mortality estimates by mitigation level for non-lead ammunition (left panel) and gut pile removal (right panel). Statewide average mortality rates are shown by mitigation rate, which we varied from 0 to 100% with increments of 10%. The *y*-axis of each panel is the mortality rate (total Golden Eagle deaths/total Golden Eagles in 139 hunting units) and lines demark increments of 5000 total stochastic iterations under each mitigation type and level. The lowest and highest simulations (0–100th percentile of results) are shown with dotted lines, the 10th and 90th percentile simulations are shown with solid lines, respectively, such that 80% of total simulations fell between those lines, and the middle of the five lines (dashed) marks the 70th percentile simulation.

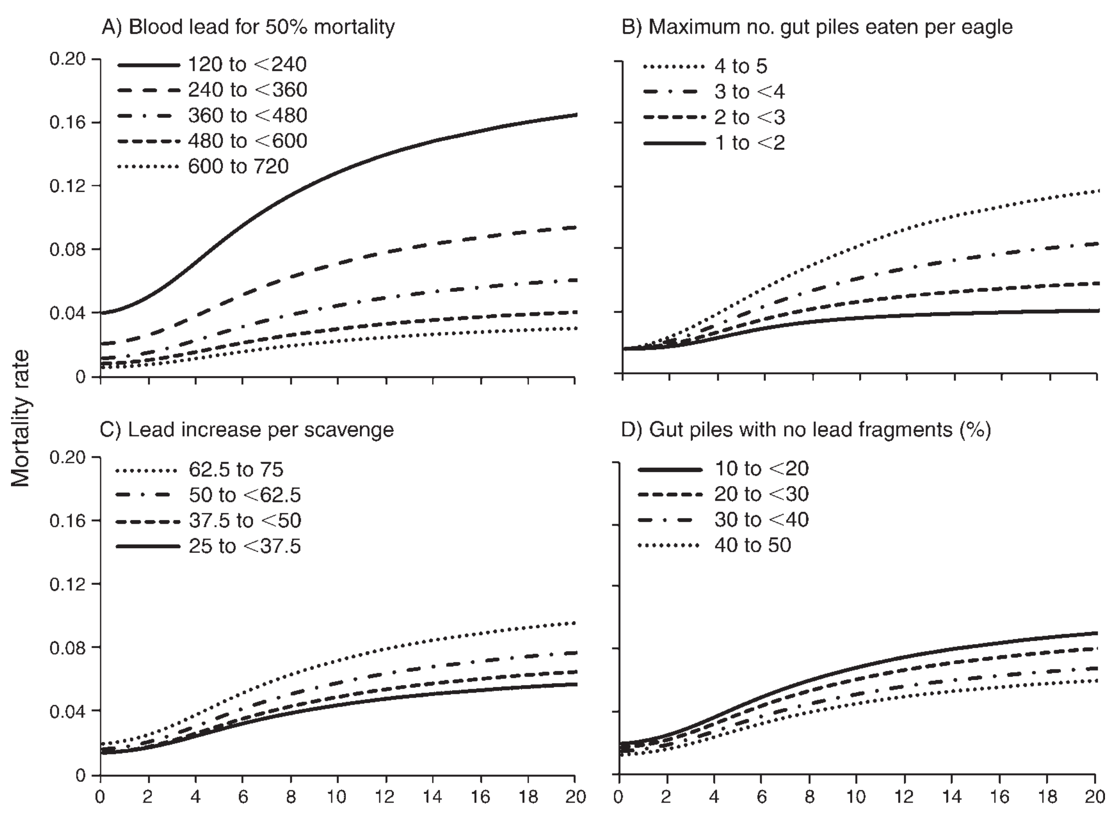

Fig. 4. Sensitivity of mortality to parameter values for (A) the blood lead concentration (μg/dL) that would lead to 50% mortality, (B) average maximum number of gut piles eaten per eagle (blood lead in μg/dL), (C) mode of the blood lead concentration (μg/dL) increase per gut pile scavenged, and (D) proportion of gut piles with no lead fragments. The *x*-axis is the availability of gut piles per Golden Eagle and the *y*-axis is the predicted mortality rate. All parameters varied randomly for 5000 model iterations. Mortality rates are the average calculated for the proportion of those simulations that fell into the indicated bin or incremental levels of the parameter in each graph (all other parameters randomly varied), for 139 individual Wyoming big game hunting units under the status quo or no mitigation. These results are from simulations at 5.0 eagles/100km^2.

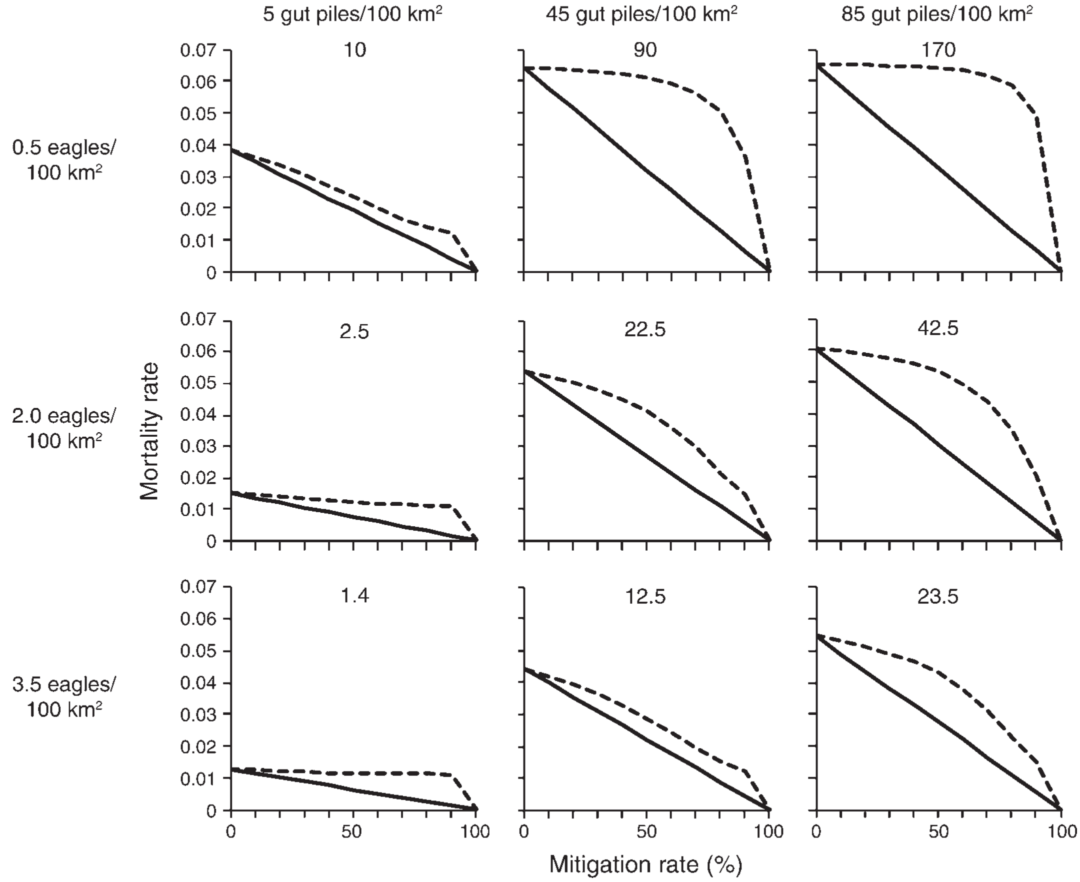

FIG. 5. Effectiveness of mitigation using non-lead bullets (solid lines) and removing gut piles (dashed lines) on Golden Eagle mortality rates under three levels of gut pile density (columns) and three levels of Golden Eagle density (rows). The average number of gut piles available per eagle for each density combination is shown at the top of the panels. The *x*-axis of each panel represents the mitigation rate, which we varied from 0%· to 100% with increments of 10%. The *y*-axis of each panel is the mortality rate and lines represent the median of 5000 iterations under each mitigation type and level.

DISCUSSION

Under the Eagle Rule, compensatory mitigation actions must be "scientifically credible and verifiable" (USFWS 2013) to be considered for permitting approval. We designed our model so that its assumptions and quantitative relationships will be "verifiable," or at least testable, through experimental implementation with monitoring. Scientific credibility accrues from the rigor of the methods we employed to develop and run the predictive models, especially how we elicited and incorporated expert opinion, and documented and addressed scientific uncertainties.

Specific modeling predictions should also pass a "plausibility test" (Drescher et al. 2013). The cause-specific mortality rates estimated by our model seem reasonable and consistent (McBride and Burgman 2012) with the general information available on Golden Eagle mortality and lead poisoning rates. Our modeled projections of mortality rates due to gut pile ingestion (median 3.2%, 1.3–9.2% estimated 80% credible interval under a status quo scenario in Wyoming with no mitigation and all other modeling assumptions) are consistent with information that ~2–3% of Golden Eagles die annually from lead poisoning (we derived this estimate by merging overall Golden Eagle mortality rates with lead poisoning rate estimates from multiple sources; see Appendix A). Our results reflect a broad range of uncertainty in key parameters, rising up to ~29% mortality with the most extreme parameter values. Considering that lead ingested from big game gut piles is only one source of lead poisoning in Golden Eagles, either the combination of parameter values we modeled (reflecting our uncertainty) tends to overestimate mortality somewhat, or lead poisoning rates may actually represent a larger portion of total mortality than indicated by available studies (e.g., Pattee et al. 1981, Scheuhammer and Norris 1996, Hunt 2012).

Since the eagle density estimates available to us were preliminary, they did not include uncertainty metrics to incorporate into our analysis. If eagle densities are found to be higher than the estimates we used, particularly during hunting season, then the model would project slightly lower rates of lead poisoning in

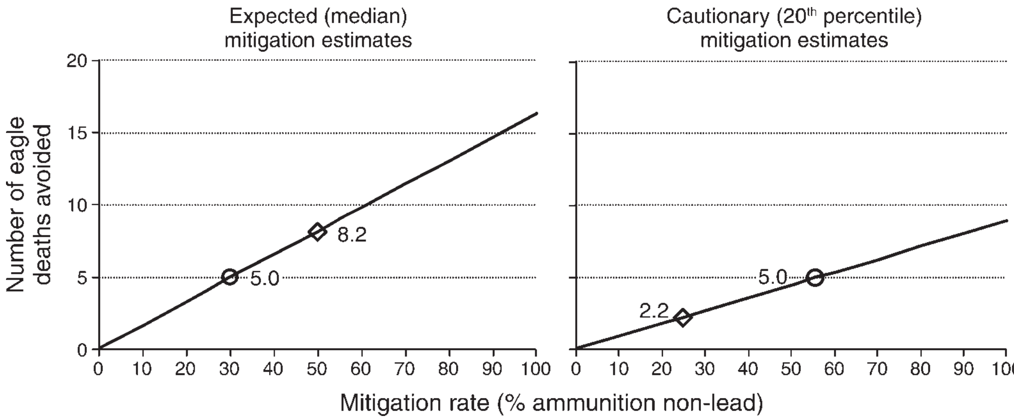

FIG. 6. Example of a hypothetical compensatory mitigation decision analysis for the Casper, Wyoming, region. The *x*-axis of each panel is the non-lead ammunition mitigation rate, which we varied from 0% to 100% with increments of 10%. The *y*-axis of each panel is the number of eagles that would *not* die from ingesting lead in big game gut piles compared with the status quo, based on multiplying the net change in mortality (the difference in mortality rate estimates between the no-mitigation baseline and the respective mitigation levels) multiplied by the mean eagle density estimate for the six hunting units in this region (679 Golden Eagles). The left panel illustrates the expected mitigation credits (eagles saved) from the median simulation and the right panel shows an example cautionary mitigation credit estimate using the 20th percentile of 5000 simulations. In each panel, the circles mark the mitigation rate (% ammunition non-lead) to reduce eagle deaths by five: 31% is expected (left panel) while 56% is a cautionary prediction (right panel). The diamonds mark the number of eagles that would be saved (potential mitigation credits) based on how many hunters switch to non-lead ammunition: assuming 50% mitigation rate, we expect at least eight eagles would not die (left panel), but more cautiously assuming only 25% mitigation rate combined with using the 20th percentile prediction, mitigation credit would be given for only two eagles (right panel).

the population (as happened with the Casper region example). Either way, our projections are within the ballpark of prior estimates and seem plausible given current knowledge.

As in any modeling, our analysis has multiple potential sources of bias and errors stemming from assumptions and parameter values. The single most influential parameter in our model is the input assigning mortality rates by maximum blood lead levels during a month. The beliefs experts hold about this relationship, including widely cited blood lead toxicity thresholds, derive largely from observations and testing of rescue birds brought in to rehabilitation clinics. Blood concentrations sampled a week or longer post-ingestion are certainly below the maximum blood lead concentrations eagles experience soon after ingesting lead fragments, by as much as 40% (e.g., assuming 10 days between meal, rescue, and sampling, and 5% daily blood lead decay rate). Further, birds found incapacitated and taken into captivity are a nonrandom sample; they may be more susceptible to lead poisoning due to other, underlying conditions (including body burden of lead from prior ingestion) compared with typical wild eagles. Given these and possibly other factors, the dose-response mortality relationship in our simulations may be biased somewhat high even though we omitted the highest of the experts' estimates when we developed the mortality rate curves (see Appendix B).

Another influential variable in the model is the lead exposure (peak blood lead concentration) per gut pile ingested. Almost no data exist to provide this parameter estimate for the model, other than limited information about frequencies and quantities of lead bullet fragments in gut piles and blood lead levels in rescued and randomly sampled wild eagles. While our experts believe that lead ingestion will almost always increase blood lead concentrations, their uncertainty about absorption levels per typical gut pile carries through the modeling and contributes to the wide range (credible interval) in expected lead poisoning mortality.

Additional parameters that will warrant review for future lead abatement mitigation analysis include the number of gut piles Golden Eagles can eat in a month, and the minimum lag time between ingestion of gut piles. Legagneux et al. (2014) monitored Golden Eagles scavenging on discarded moose gut piles in Quebec with remote cameras. Similar sampling in Wyoming would improve estimates of our model's scavenging rate parameters. The model may miss other nuances about scavenging that influence lead ingestion, such as considering the species and size of big game harvested. Similarly, few data provide estimates for the average proportion of gut piles that contain no lead fragments, so we set a wide bracket of 10–50%. Eagle density estimates also need to be updated, including accounting for fall migrants.

Our model is deliberately focused on only one aspect of lead exposure and effects: the numerical value of mitigation credits due to abating acute mortality from ingesting lead in gut piles from big game animals. By focusing only on acute effects from one primary source of lead exposure, the expert elicitation of parameters and treatment of uncertainty were tractable for this demonstration of a prototype for modeling lead

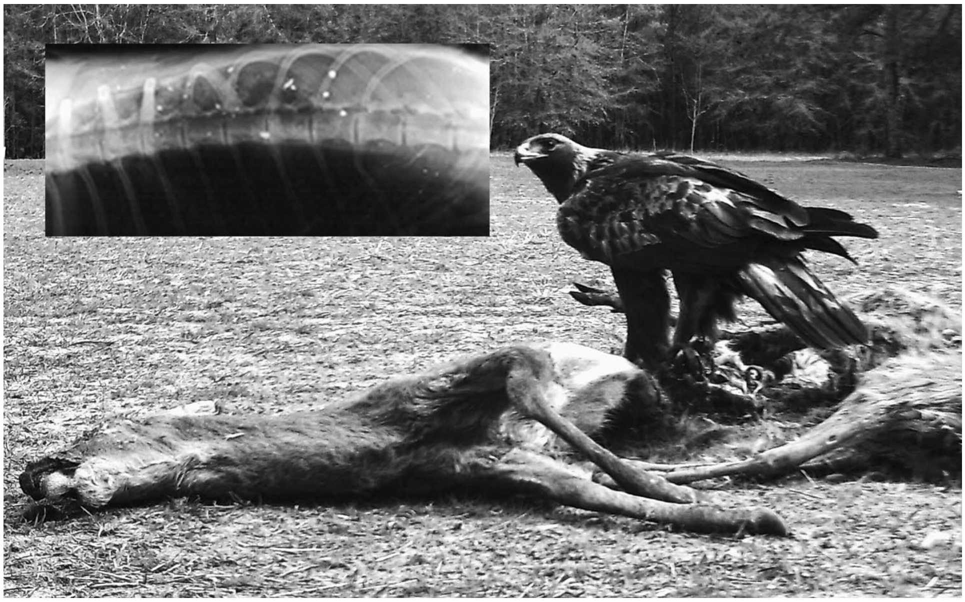

PLATE 1. Golden Eagle scavenging on deer carcasses placed as bait near a trail camera station. (Inset) Radiograph of a deer carcass body cavity showing metal bullet fragments as light spots. This deer was killed with a standard lead-core, copper-jacketed bullet. Photo credits: eagle, South Carolina Department of Natural Resources; inset, The Peregrine Fund.

abatement. When using our framework for take permitting analysis, regulators may also take into account the ancillary conservation benefits from reducing lead in the environment that are not represented or quantified in our model, including reducing exposure to spent lead in big game carcasses that are not retrieved and gutted by hunters, reducing mortality among other scavenging species, reducing sublethal, cumulative or delayed (non-acute) effects of lead ingestion among Golden Eagles that survive the hunting season (Green et al. 2008, Pain et al. 2009, Finkelstein et al. 2012), and more generally the possible increase in population growth rate due to removing a source of additive mortality. To quantify credits for additional benefits from lead abatement, the model could be expanded to include un-retrieved game carcasses, non-acute effects of lead ingestion, and other sources of lead exposure including small game or "varmint" hunting. Our framework for modeling and addressing uncertainty is also applicable at scales other than the breeding population areas in our case study.

A framework for dealing with uncertainty in offset analysis

Our approach to modeling provides a general framework to support regulatory decision-making under scientific uncertainty. We employed the best information available by combining published literature with carefully elicited expert judgments, accounted explicitly for uncertainty and carried it through the modeling calculations, and provided probabilistic predictions so decision makers can apply regulatory standards (risk management preferences) transparently and independently of the modeling.

Designing and completing a process for expert engagement and elicitation is a craft requiring its own expertise. We relied on our previous experience and training, and followed steps to motivate, condition, encode beliefs, and feedback consequences to the experts in order to reduce biases and elicit useable opinions (Low Choy et al. 2009, McBride and Burgman 2012). The quantitative functions we derived might be improved if we elicited estimates from more than four experts (for each parameter), although group size generally does not predict aggregate performance (Drescher et al. 2013). More constraining to our effort was the time available for in-depth engagement with the experts, who contributed their time to the project. Even though the project extended 20 months, with an in-person workshop and many remote meetings and e-mails, the experts likely still did not have sufficient feedback to recognize the full implications of their parameter-specific judgments (McBride and Burgman 2012). All the more reason to treat the model as a hypothesis about cause–effect relationships and implement lead abatement actions experimentally; then the experts can update their beliefs about eagle scavenging, lead poisoning, and abatement relationships, in addition to updating the model directly with empirical data.

Simulation modeling is a valuable tool for analyzing mitigation equivalency under high uncertainty (Drescher et al. 2013). By simulating the difference in mortality rates under "with and without" or alternative mitigation scenarios (e.g., relative mortality [Beissinger and Westphal 1998]), the predictions may be more robust to potential errors and biases, and allow managers to select strategies and levels of mitigation for immediate action consistent with their risk management preferences. Further, we are satisfied that making predictions from population-level averages and variance due to scientific uncertainty, rather than simulating a fully random process that tracks individual bird behavior and demography, is appropriate to the permitting decision context. Given the extent of scientific uncertainty about the quantitative functions in play, building a more complex model would not improve the ability of decision makers to address uncertainty transparently and assign mitigation credits.

While mitigation decisions can be made with probabilistic predictions, we reiterate that future adopters of our model should treat the parameter values, including the dose-response functions for scavenging rates, lead absorption, and mortality, as hypotheses subject to field testing (Quétier and Lavorel 2011, Runge et al. 2011). Predictions may be improved most by reducing uncertainty about the relationship between blood lead concentration and mortality, and maximum gut pile scavenging, since these parameters were most influential in our sensitivity analysis. Other parameters may be relatively easy to update with field sampling, such as the occurrence of lead fragments in gut piles and the rate at which hunters retrieve wounded game animals. However, in active adaptive management, research priorities should be based on the greatest anticipated return-for-investment in improving predictions and decisions. Our model provides the decision-relevant predictions and explicit treatment of uncertainty needed to analyze the "expected value of new information" from proposed options for scientific research, within an experimental adaptive management program (Runge et al. 2011).

Our model does not address uncertainty in the extent to which voluntary lead abatement strategies will be successful (e.g., predicting the percentage of hunters using alternative ammunition as a function of educational or subsidy programs [Epps 2014]). In our Casper, Wyoming, example we illustrated how uncertainty in predicted abatement levels could be included in the decision analysis with adjustments to mitigation credits. Rather than attempting to predict abatement levels in advance with a detailed model (with social and economic parameters), monitoring during implementation could provide direct measures of hunters' ammunition use or gut pile removals to determine adjusted or final mitigation credits. Since some hunters may begin switching to non-lead ammunition before or independently from the mitigation program (Epps 2014), site-specific mitigation analysis would require estimates of both status quo and program-related non-lead ammunition use for "with and without" comparison (e.g., through adaptive management design). Experimental implementation could also be designed to measure uncertainty in success by abatement strategy, in addition to the scientific uncertainty we address in our model.

In conclusion, we developed a model that estimates how many Golden Eagle deaths may be avoided through specific lead abatement actions in specific locations, using the best available scientific information and carefully elicited expert beliefs. We designed the model to support decision-making even under high levels of uncertainty, as we illustrate with two alternative risk management standards in the Casper example, including a more cautionary choice for attributing compensatory credit for lead abatement. We also designed the model so its parameters and assumptions can be evaluated over time through an experimental adaptive management program. As such, we believe it meets the expectations of the Eagle Guidance for compensatory mitigation modeling that "ensures that the USFWS can provide appropriate review of the results . . . " (USFWS 2013:93) and provides a useful framework for estimating compensatory mitigation despite scientific uncertainty in a wide array of biodiversity offsetting cases (Bull et al. 2014).

Acknowledgments

We thank the experts in eagle biology, lead toxicology, and mitigation assessment who provided their time and expertise in assisting with the development and parameterization of the model: Bryan Bedrosian, Pete Bloom, Mike Collopy, Chris Franson, Grainger Hunt, Todd Katzner, Terra Kelly, Mike Kochert, Brian Millsap, Bob Murphy, Leslie New, Patrick Redig, Bruce Rideout, and Leslie Wilkinson. Thanks to USFWS, Ryan Nielson, and WEST for allowing us to run the model with their preliminary eagle density estimates. The paper benefited from suggestions from two anonymous reviewers. We are grateful to the National Renewable Energy Laboratory and U.S. Department of Energy for providing financial support. Finally, we thank the AWWI's wind, science, and conservation partners, whose support made this project possible.

Literature Cited

Ayyub, B. M. 2001. Elicitation of expert opinions for uncertainty and risks. CRC Press, Boca Raton, Florida, USA.

BBOP (Business and Biodiversity Offsets Programme). 2012. Standard on biodiversity offsets. Business and Biodiversity Offsets Programme, Washington, D.C., USA.

Bedrosian, B., D. Craighead, and R. Crandall. 2012. Lead exposure in Bald Eagles from big game hunting, the continental implications and successful mitigation efforts. PLoS ONE 7(12):e51978.

Beissinger, S. R., and M. I. Westphal. 1998. On the use of demographic models of population viability in endangered species management. Journal of Wildlife Management 62:821–841.

Bull, J. W., E. J. Milner-Gulland, K. B. Suttle, and N. J. Singh. 2014. Comparing biodiversity offset calculation methods with a case study in Uzbekistan. Biological Conservation 178:2–10.

Bull, J. W., K. B. Suttle, A. Gordon, N. J. Singh, and E. J. Milner-Gulland. 2013. Biodiversity offsets in theory and practice. Oryx 47(3):369–380.

Burgman, M. A. 2005. Risks and decisions for conservation and environmental management. Cambridge University Press, Cambridge, UK.

Burgman, M. A., S. Ferson, and H. R. Akçakaya. 1993. Risk assessment in conservation biology. Chapman & Hall, London, UK.

Burgman, M. A., M. F. McBride, R. Ashton, A. Speirs-Bridge, L. Flander, B. Wintle, F. Fidler, L. Rumpff, and C. Twardy.

2011. Expert status and performance. PLoS ONE 6(7):e22998.

Cooke, R. M. 1991. Experts in uncertainty: opinion and subjective probability in science. Oxford University Press, New York, New York, USA.

Cruz-Martinez, L., P. T. Redig, and J. Deen. 2012. Lead from spent ammunition: a source of exposure and poisoning in bald eagles. Human-Wildlife Interactions 6:94–104.

Doherty, K. E., D. E. Naugle, and J. S. Evans. 2010. A currency for offsetting energy development impacts: horse-trading sage-grouse on the open market. PLoS ONE 5(4):e10339.

Drescher, M., A. H. Perera, C. J. Johnson, L. J. Buse, C. A. Drew, and M. A. Burgman. 2013. Toward rigorous use of expert knowledge in ecological research. Ecosphere 4(7):83.

Epps, C. W. 2014. Considering the switch: challenges of transitioning to non-lead hunting ammunition. The Condor: Ornithological Applications 116:429–434.

Finkelstein, M. E., D. F. Doak, D. George, J. Burnett, J. Brandt, M. Church, J. Grantham, and D. R. Smith. 2012. Lead poisoning and the deceptive recovery of the critically endangered California condor. Proceedings of the National Academy of Sciences USA 109:11449–11454.

Fuller, T. K. 1990. Dynamics of a declining white-tailed deer population in north-central Minnesota. Wildlife Monograph 110.

Gardner, T. A., et al. 2013. Biodiversity offsets and the challenge of achieving no net loss. Conservation Biology 27(6):1254–1264.

Green, R. E., W. G. Hunt, C. N. Parish, and I. Newton. 2008. Effectiveness of action to reduce exposure of free-ranging California Condors in Arizona and Utah to lead from spent ammunition. PLoS ONE 3(12):e4022.

Haig, S., J. D'Elia, C. Eagles-Smith, J. M. Fair, J. Gervais, G. Herring, J. W. Rivers, and J. H. Schulz. 2014. The persistent problem of lead poisoning in birds from ammunition and fishing tackle. The Condor: Ornithological Applications 116:408–428.

Holling, C. S. 1959. The components of predation as revealed by a study of small-mammal predation of the European pine sawfly. Canadian Entomologist 91:293–320.

Hunt, W. G. 2012. Implications of sublethal lead exposure in avian scavengers. Journal of Raptor Research 46:389–393.

Hunt, W. G., W. Burnham, C. Parish, K. Burnham, B. Mutch, and J. L. Oaks. 2006. Bullet fragments in deer remains: implications for lead exposure in avian scavengers. Wildlife Society Bulletin 34:167–170.

Hunt, W. G., C. N. Parish, K. Orr, and R. F. Aguilar. 2009. Lead poisoning and the reintroduction of the California Condor in Northern Arizona. Journal of Avian Medicine and Surgery 23:145–150.

Kalmbach, E. R., R. H. Imler, and L. W. Arnold. 1964. The American eagles and their economic status, 1964. Circulars 27 and 30. U.S. Fish and Wildlife Service and Bureau of Sport Fisheries and Wildlife, Washington, D.C., USA.

Kelly, T. R., P. H. Bloom, S. G. Torres, Y. Z. Hernandez, R. H. Poppenga, W. M. Boyce, and C. K. Johnson. 2011. Impact of the California lead ammunition ban on reducing lead exposure in Golden Eagles and Turkey Vultures. PLoS ONE 6(4):e17656.

Kochert, M. N., K. Steenhof, C. L. Mcintyre, and E. H. Craig. 2002. Golden Eagle (*Aquila chrysaetos*). *In* E. Poole, editor. The Birds of North America Online. Cornell Laboratory of Ornithology, Ithaca, New York, USA.

Kramer, J. L., and P. T. Redig. 1997. Sixteen years of lead poisoning in eagles, 1980–95: an epizootiologic view. Journal of Raptor Research 31:327–332.

Kuhnert, P. M., T. G. Martin, and S. P. Griffiths. 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. Ecology Letters 13:900–914.

Legagneux, P., P. Suffice, J.-S. Messier, F. Lelievre, J. A. Tremblay, C. Maisonneuve, R. Saint-Louis, and J. Bêty. 2014. High risk of lead contamination for scavengers in an area with high moose hunting success. PLoS ONE 9(11):e111546.

Low-Choy, S., R. A. O'Leary, and K. L. Mengersen. 2009. Elicitation by design in ecology: using expert opinion to inform priors for Bayesian statistical models. Ecology 90:265–277.

Marcot, B. G., J. D. Steventon, G. D. Sutherland, and R. K. McCann. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Canadian Journal of Forest Research 36:3063–3074.

Maron, M., R. J. Hobbs, A. Moilanen, J. W. Matthews, K. Christie, T. A. Gardner, D. A. Keith, D. B. Lindenmayer, and C. A. McAlpine. 2012. Faustian bargains? Restoration realities in the context of biodiversity offset policies. Biological Conservation 155:141–148.

Martin, T. G., M. Burgman, F. Fidler, P. M. Kuhnert, S. Low-Choy, M. McBride, and K. Mengersen. 2012. Eliciting expert knowledge in conservation science. Conservation Biology 26:29–38.

Martin, T. G., P. M. Kuhnert, K. Mengersen, and H. P. Possingham. 2005. The power of expert opinion in ecological models using Bayesian methods: impact of grazing on birds. Ecological Applications 15:266–280.

McBride, M. F., and M. A. Burgman. 2012. What is expert knowledge, how is such knowledge gathered, and how do we use it to address questions in landscape ecology. Pages 11–38 *in* A. H. Perera, C. A. Drew, and C. J. Johnson, editors. Expert knowledge and its application in landscape ecology. Springer, New York, New York, USA.

McGowan, C. P., M. R. Ryan, M. C. Runge, J. J. Millspaugh, and J. F. Cochrane. 2011. The role of demographic compensation theory in incidental take assessments for endangered species. Biological Conservation 144:730–737.

Moilanen, A., A. J. A. Van Teeffelen, Y. Ben-Haim, and S. Ferrier. 2009. How much compensation is enough? A framework for incorporating uncertainty and time discounting when calculating offset ratios for impacted habitat. Restoration Ecology 17:470–478.

Morgan, M. G., and M. Henrion. 1990. Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press, New York, New York, USA.

Nielson, R., L. McManus, T. Rintz, L. L. McDonald, R. K. Murphy, W. H. Howe, and R. E. Good. 2014. Monitoring abundance of Golden Eagles in the Western United States. Journal of Wildlife Management 78:721–730.

Nielson, R. M., and H. Sawyer. 2013. Estimating resource selection with count data. Ecology and Evolution 3:2233–2240.

Nixon, C. M., L. P. Hansen, P. A. Brewer, J. E. Chelsvig, T. L. Esker, D. Etter, J. B. Sullivan, R. G. Koerkenmeier, and P. C. Mankin. 2001. Survival of white-tailed deer in intensively farmed areas of Illinois. Canadian Journal of Zoology 79:581–588.

Pagel, J. E., K. J. Kritz, B. A. Millsap, R. K. Murphy, E. L. Kershner, and S. Covington. 2013. Bald Eagle and Golden Eagle mortalities at wind energy facilities in the contiguous United States. Journal of Raptor Research 47(3):311–315.

Pain, D. J., I. J. Fisher, and V. G. Thomas. 2009. A global update of lead poisoning in terrestrial birds from ammunition sources. Pages 99–118 *in* R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, editors. Ingestion of lead from spent ammunition: implications for wildlife and humans. The Peregrine Fund, Boise, Idaho, USA.

Pattee, O. H., S. N. Wiemeyer, B. M. Mulhern, L. Sileo, and J. W. Carpenter. 1981. Experimental lead-shot poisoning in Bald Eagles. Journal of Wildlife Management 45:806–810.

Perera, A. H., C. A. Drew, and C. H. Johnson, editors. 2012. Expert knowledge and its application in landscape ecology. Springer, New York, New York, USA.

Pilgrim, J. D., et al. 2013. A process for assessing offsetability of biodiversity impacts. Conservation Letters 6:376–384.

Quétier, F., and S. Lavorel. 2011. Assessing ecological equivalence in biodiversity offset schemes: key issues and solutions. Biological Conservation 144(12):2991–2999.

Regnery, B., D. Couvet, and C. Kerbiriou. 2013. Offsets and conservation of the species of the EU habitats and birds directives. Conservation Biology 27(6):1335–1343.

Restani, M., A. R. Harmata, and E. A. Madden. 2000. Numerical and functional responses of migrant bald eagles exploiting a seasonally concentrated food source. The Condor 102:561–568.

Ruhl, J. B. 2012. Harmonizing commercial wind power and the Endangered Species Act through administrative reform. Vanderbilt Law Review 65(6):1769–1799.

Runge, M. C., S. J. Converse, and J. E. Lyons. 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. Biological Conservation 144:1214–1223.

Scheuhammer, A. M., and S. L. Norris. 1996. The ecotoxicology of lead shot and lead fishing weights. Ecotoxicology 5:279–295.

Sieg, R., K. A. Sullivan, and C. N. Parish. 2009. Voluntary lead reduction efforts within the northern Arizona range of the California Condor. Pages 341–349 *in* R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, editors. Ingestion of lead from spent ammunition: implications for wildlife and humans. The Peregrine Fund, Boise, Idaho, USA.

Speirs-Bridge, A., F. Fidler, M. McBride, L. Flander, G. Cumming, and M. Burgman. 2010. Reducing overconfidence in the interval judgments of experts. Risk Analysis 30:512–523.

Starfield, A. M. 1997. A pragmatic approach to modeling for wildlife management. Journal of Wildlife Management 61(2):261–270.

Starfield, A. M., and A. L. Bleloch. 1991. Building models for conservation and wildlife management. Second edition. Burgess International Group, Edina, Minnesota, USA.

Stauber, E., N. Finch, P. A. Talcott, and J. M. Gay. 2010. Lead poisoning of bald (*Haliaeetus leucocephalus*) and golden (*Aquila chrysaetos*) eagles in the US inland Pacific Northwest region—an 18-year retrospective study: 1991–2008. Journal of Avian Medicine and Surgery 24:279–287.

USFWS (U.S. Fish and Wildlife Service). 2009*a*. Final Environment Assessment–Proposal to Take Provided Under the Bald and Golden Eagle Protection Act. U.S. Fish and Wildlife Service, Division of Migratory Bird Management, Branch of Policy, Permits and Regulations, Arlington, Virginia, USA. April 2009.

USFWS (U.S. Fish and Wildlife Service). 2009*b*. Amended guidance on determining mitigation for the Florida scrub jay. March 16, 2009. U.S. Fish and Wildlife Service, Jacksonville Ecological Services Field Office, Jacksonville, Florida, USA.

USFWS (U.S. Fish and Wildlife Service). 2009*c*. Guidelines for the establishment, management, and operation of gopher tortoise conservation banks. Alabama, Louisiana, and Mississippi. January 27, 2009. U.S. Fish and Wildlife Service, Mississippi Ecological Services Field Office, Jackson, Mississippi, USA.

USFWS (U.S. Fish and Wildlife Service). 2013. Eagle Conservation Plan Guidance. Module 1–Land-based Wind Energy Version 2. U.S. Fish and Wildlife Service, Division of Migratory Bird Management, Branch of Policy, Permits and Regulations, Arlington, Virginia, USA.

Warner, S., E. Britton, D. Becker, and M. Coffey. 2014. Bald eagle lead exposure in the Upper Midwest. Journal of Fish and Wildlife Management 5(2):208–216.

Watson, J. 2010. The Golden Eagle. Second edition. A & C Black, London, UK.

Williams, B. K., and E. D. Brown. 2012. Adaptive management: the U.S. Department of the Interior applications guide. U.S. Department of the Interior, Adaptive Management Working Group, Washington, D.C., USA.

Wilmers, C. C., R. L. Crabtree, D. Smith, K. M. Murphy, and W. M. Getz. 2003. Trophic facilitation by introduced top predators: gray wolf subsidies to scavengers in Yellowstone National Park. Journal of Animal Ecology 72:909–916.

Supplemental Material

Ecological Archives

Appendices A–D and the Supplement are available online: http://dx.doi.org/10.1890/14-0996.1.sm