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A SPATIALLY EXPLICIT MODEL TO PREDICT THE RELATIVE RISK OF GOLDEN EAGLE ELECTROCUTIONS IN THE NORTHWESTERN PLAINS, USA

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Abstract.—Electrocution of Golden Eagles (*Aquila chrysaetos*) on overhead power poles is a conservation concern in the western United States. The US Fish and Wildlife Service recommends retrofitting power poles to minimize electrocution risk as one mechanism for compensatory mitigation to offset permitted take for Golden Eagles. Because densities of Golden Eagles and power poles vary spatially, identifying where poles should be retrofitted to best meet compensatory mitigation goals is of conservation importance. We developed a model that predicts relative risk of eagle electrocution based on the overlap between spatial models of Golden Eagle nest-site density and power pole density within the Northwestern Plains ecoregion. Risk was unevenly distributed: areas with the highest electrocution risk were rare (1.1% by area), while lowest risk areas were common (53.6% by area). We tested model predictions with independent data consisting of locations of Golden Eagle electrocution mortalities ($n = 342$). Mortalities were distributed among six risk classes proportional to model predictions, with 87.7% of mortalities occurring in the top three risk categories. Prioritizing pole retrofitting in the highest-risk areas could prevent >3 × the electrocutions expected by selecting areas at random and would be 89 × more effective than retrofitting in the lowest risk areas. Our risk model offers a consistent method to spatially prioritize retrofitting to increase effectiveness of electrocution reduction for Golden Eagle conservation and provides an efficient approach for utilities. This method of quantifying spatial overlap between indices of exposure and hazard is repeatable and accurate, and can be adapted to various forms of data whenever quantification and visualization of spatial prioritization is desired.

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KEY WORDS: *Golden Eagle*; Aquila chrysaetos; *power pole*; *prediction*; *raptor electrocution*; *risk analysis*; *spatially explicit model*.

UN MODELO ESPACIALMENTE EXPLÍCITO PARA PREDECIR EL RIESGO RELATIVO DE ELECTROCUCIONES DE *AQUILA CHRYSAETOS* EN LAS LLANURAS DEL NOROESTE DE EEUU

RESUMEN.—La electrocución de *Aquila chrysaetos* en postes eléctricos aéreos es causa de preocupación para su conservación en el oeste de Estados Unidos. El Servicio de Pesca y Vida Silvestre de este país recomienda reacondicionar los postes eléctricos para minimizar el riesgo de electrocución, como un mecanismo de mitigación compensatoria para equilibrar la extracción permitida de individuos de esta especie. Debido a que las densidades de *A. chrysaetos* y de los postes eléctricos varían espacialmente, identificar dónde reacondicionar estos postes es de importancia para conservar esta especie así como para lograr los objetivos de mitigación compensatoria. Desarrollamos un modelo que predice el riesgo relativo de electrocución de las águilas basado en la superposición entre los modelos espaciales de densidad de sitios de nidificación de *A. chrysaetos* y de densidad de postes eléctricos dentro de la ecorregión de las Llanuras del Noroeste. El riesgo se distribuyó de manera desigual: las áreas con el riesgo de electrocución más alto fueron raras (1.1% por área), mientras que las áreas con el riesgo más bajo fueron comunes (53.6% por área). Evaluamos las predicciones del modelo con datos independientes de sitios con mortalidad por electrocución de *A. chrysaetos* ($n = 342$). Las muertes estuvieron distribuidas entre seis clases de riesgo de modo proporcional a las predicciones del modelo, con un 87.7% de las muertes ocurriendo en las tres categorías principales de riesgo. Priorizar el reacondicionamiento de los postes en las áreas de alto riesgo podría prevenir tres veces más las electrocuciones que las esperadas mediante la selección de áreas al azar y sería 89 veces más efectivo que reacondicionar tendidos en las áreas de riesgo más bajo. Nuestro modelo de riesgo ofrece un método consistente para priorizar espacialmente el reacondicionamiento, que aumenta la efectividad de la reducción de electrocución para la conservación de *A. chrysaetos* y proporciona un enfoque eficiente para las compañías. Este método de cuantificación de la superposición espacial entre índices de exposición y peligro es repetible y preciso, y puede ser adaptado a varios tipos de datos siempre que se desee cuantificar y visualizar la priorización espacial.

[Traducción del equipo editorial]

Conservation planning for raptors and other species with broad geographic ranges presents challenges for decision makers tasked with maintaining viable wildlife populations. Incomplete knowledge of the regional and landscape-scale variation in the distribution and abundance of individuals, and potential threats to those individuals, often requires a predictive model-based framework to identify priority areas for protection or management action (e.g., Dunk et al. 2019b). Spatial conservation prioritization uses spatial analysis of quantitative data to identify priority areas and may be used to guide efficient allocation of scarce conservation resources (Bottrill et al. 2008, Ferrier and Wintle 2009, Wilson et al. 2009). When focused on the spatial distribution and severity of threats, conservation prioritization shares many attributes with risk analysis (Tulloch et al. 2015, Suter 2016). As part of a western United States (US)–wide effort to support conservation planning for Golden Eagles (*Aquila chrysaetos*), we describe the approaches we developed to quantify variation in electrocution risk within a portion of the species' western US range.

Spatial prioritization of conservation action is particularly valuable for conservation planning when the distribution of a species and its threats vary geographically (Wilson et al. 2009). Golden Eagles are widely distributed, have large home ranges, and can move long distances (>500 km) during dispersal and migration (Brown et al. 2017, Murphy et al. 2017). As a result, Golden Eagles can be exposed to numerous hazards across broad geographic areas (McIntyre 2012, US Fish and Wildlife Service [USFWS] 2016), and those hazards vary in type and intensity across the species' range. Quantifying the distribution of hazards in relation to the distribution of Golden Eagles at regional and landscape scales therefore provides a decision support tool for efficient allocation of conservation and management resources.

Electrocution of Golden Eagles on overhead power structures is a global conservation concern (Avian Powerline Interaction Committee [APLIC]

2006, Lehman et al. 2007, Mojica et al. 2018). For example, in North America, where most avian electrocutions occur on distribution power poles (2.4–60 kilovolts; APLIC 2006), the USFWS estimated that 504 Golden Eagles are electrocuted annually (95% credible interval: 124–1494; USFWS 2016). Numerous factors are thought to influence electrocution risk, including pole configuration, surrounding habitat characteristics, abundance and distribution of prey, season, weather, amount of human disturbance, and proximity of poles to nests (APLIC 2006, Dwyer and Mannan 2009, Dwyer et al. 2014, Mojica et al. 2018).

Electrocution risk can be effectively mitigated through retrofitting distribution poles to "avian-friendly" standards (Dwyer et al. 2017a). Power pole retrofitting (hereafter, retrofitting) has been widely used by electric utilities to reduce electrocution mortality of Bald Eagles (*Haliaeetus leucocephalus*) and Golden Eagles within utility service areas to comply with the Bald and Golden Eagle Protection Act (16 U.S.C. 668-668d), which prohibits the unauthorized take of eagles. Retrofitting is also used as compensatory mitigation to offset authorized (permitted) take (mortality) of Golden Eagles due to collision with wind turbines (USFWS 2013) and other permittable activities. Wind energy production in the US increased >400% in the last decade (2008–2018; US Energy Information Administration [USEIA] 2019) and will likely continue to increase over the next two decades (USEIA 2016). The USFWS recently authorized an *in-lieu* fee program intended to facilitate and incentivize a strategic approach to retrofitting as a compensatory mitigation tool (USFWS 2018). This program specifies that retrofitting should be implemented on poles with (1) hazardous equipment configurations and (2) in areas where concentrations of Golden Eagles are exposed to these hazards. A pole-specific model is available to estimate electrocution risk based on equipment configuration and general habitat characteristics immediately surrounding (within 200 m) individual poles (Dwyer et al. 2014), but this pole-specific model is not amenable to quantifying electrocution risk at broader spatial scales. We sought to complement local-scale evaluations of pole-level risk by providing an improved understanding of how Golden Eagle electrocution risk varies spatially at regional and landscape scales.

To prioritize relative risk across broad areas, spatial data on the distributions of a hazard (e.g., power poles) and species (e.g., Golden Eagles) can be combined in a geographic information system (GIS) to quantify areas of spatial overlap (Miller et al. 2014, Tack and Fedy 2015, Mojica et al. 2016, Pérez-García et al. 2017). Because the exact locations of all hazards are generally unknown at broad spatial scales, spatially explicit models can be used to predict distributions of hazards (Dwyer et al. 2016).

We developed and evaluated a model for predicting spatial variation of the relative risk of electrocution for Golden Eagles within an ecological region of the western USA, the Northwestern Plains. Our goals were to: (1) create a spatially explicit model of relative risk of Golden Eagle electrocution, and (2) demonstrate a method that is reproducible using GIS and is applicable to efforts to prioritize conservation across varied taxa, hazards, and spatial extents.

METHODS

Study Area. We conducted our study within the Northwestern Plains, a 474,170-km^2 region adapted from the Northwestern Great Plains and Northwestern Glaciated Plains Level-III ecoregions defined by the Commission for Environmental Cooperation (2011), with modifications to improve alignment with Golden Eagle habitat (Dunk et al. 2019a; Fig. 1). The region includes portions of five states: Montana, Wyoming, North Dakota, South Dakota, and Nebraska. The Northwestern Plains is characterized by rolling topography, a dry mid-latitude steppe climate, and shortgrass and mixed grass prairie vegetation with areas of sagebrush steppe (Wiken et al. 2011).

We tested our risk model's predictions within the Powder River Energy Corporation (PRECorp) service area in northeastern Wyoming and southeastern Montana. PRECorp is an electric service provider with 17,204 km of distribution lines within a 41,484 km^2 area, and is almost entirely within the Northwestern Plains (93.5%; 38,793 km^2). The PRECorp service area covers 8.18% of the Northwestern Plains and includes a wide variety of habitats (prairie grasslands, sagebrush steppe, montane forests) and land uses (oil and gas developments, ranches, isolated urban areas).

Risk Analysis Approach. To conceptualize broad-scale risk of Golden Eagle electrocution on electric distribution systems, we adapted the risk framework used by Smith (2013) and Connelly et al. (2018) where risk results from the interaction of: (1) a hazard and the likelihood or degree of its occur-

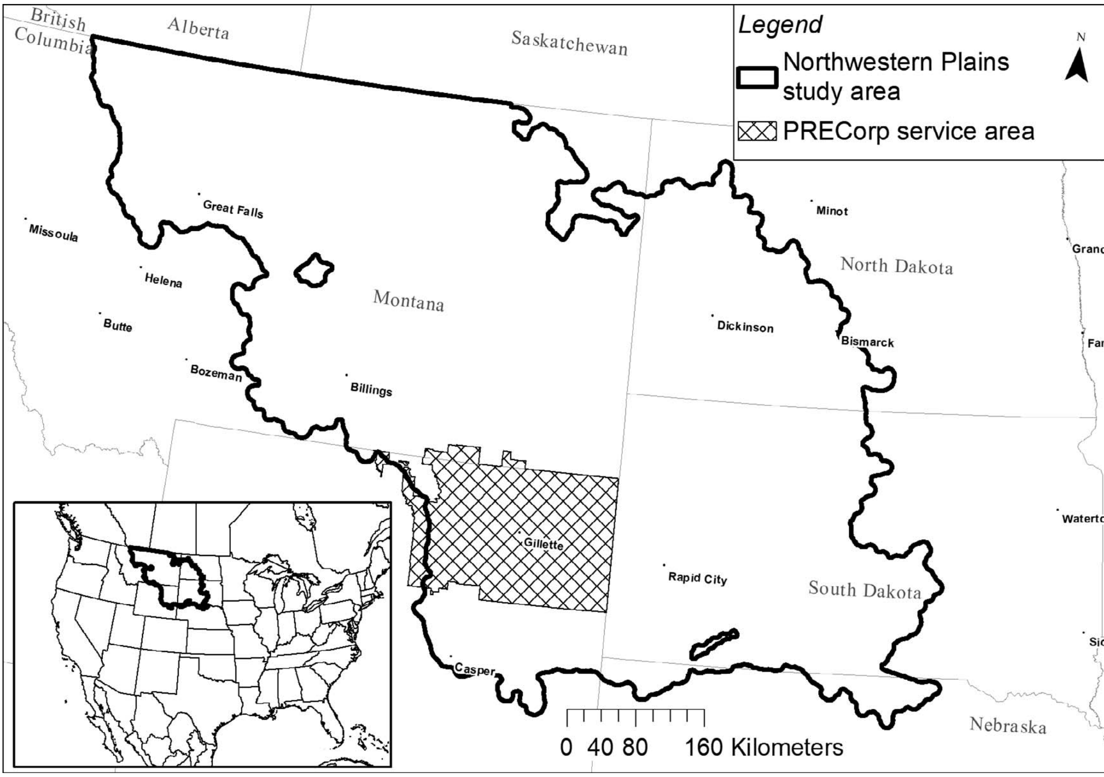

Figure 1. The Northwestern Plains study area and the PRECorp service area.

rence, (2) exposure to the hazard, and (3) vulnerability of individuals upon exposure to a hazard.

For our study, a **hazard** is a natural or anthropogenic object, condition, or event that could cause the death or significant reduction of fitness of individuals in a population of Golden Eagles. We focus on electrocution hazard, which occurs when overhead power line equipment is energized and exposed (not insulated) in configurations that allow Golden Eagles to make simultaneous contact with equipment at different electric potentials, thereby becoming part of a high voltage electric circuit (APLIC 2006, Dwyer et al. 2015, 2017a). We used power pole density as an index of electrocution hazard (Dwyer et al. 2016). **Exposure** is the degree of opportunity to encounter hazards, in terms of spatial and temporal overlap; we estimated only spatial overlap as the relative density of Golden Eagles predicted to occur in an area. **Vulnerability** of Golden Eagles to electrocution is a function of factors such as weather, season, age class, sex (i.e., size), and behavior that influence the likelihood of electrocution mortality (Mojica et al. 2018) at a given level of hazard and exposure. Because these factors are highly variable and difficult to quantify or predict, we made the simplifying assumption that vulnerability was constant across the gradient of hazard and exposure.

Predictive Models of Golden Eagle Exposure and Electrocution Hazard. We used a predictive model of Golden Eagle relative nest-site density for the Northwestern Plains ecoregion as an index of exposure (Fig. 2a; Dunk et al. 2019a). Using MaxEnt (Phillips et al. 2006), Dunk et al. (2019a) related Golden Eagle nest locations to environmental covariates (e.g., landcover, topography, climate) at multiple spatial scales and generated predictions of relative nest-site density at a 120-m $\times$ 120-m spatial resolution. Dunk et al. (2019a) interpreted their estimated quantity as relative nest density (RND), based on Dudík (2004) and Aarts et al. (2012) who noted that models such as MaxEnt represent relative density of the estimated quantity. Relative density alone, however, is equivalent to ranking, where the

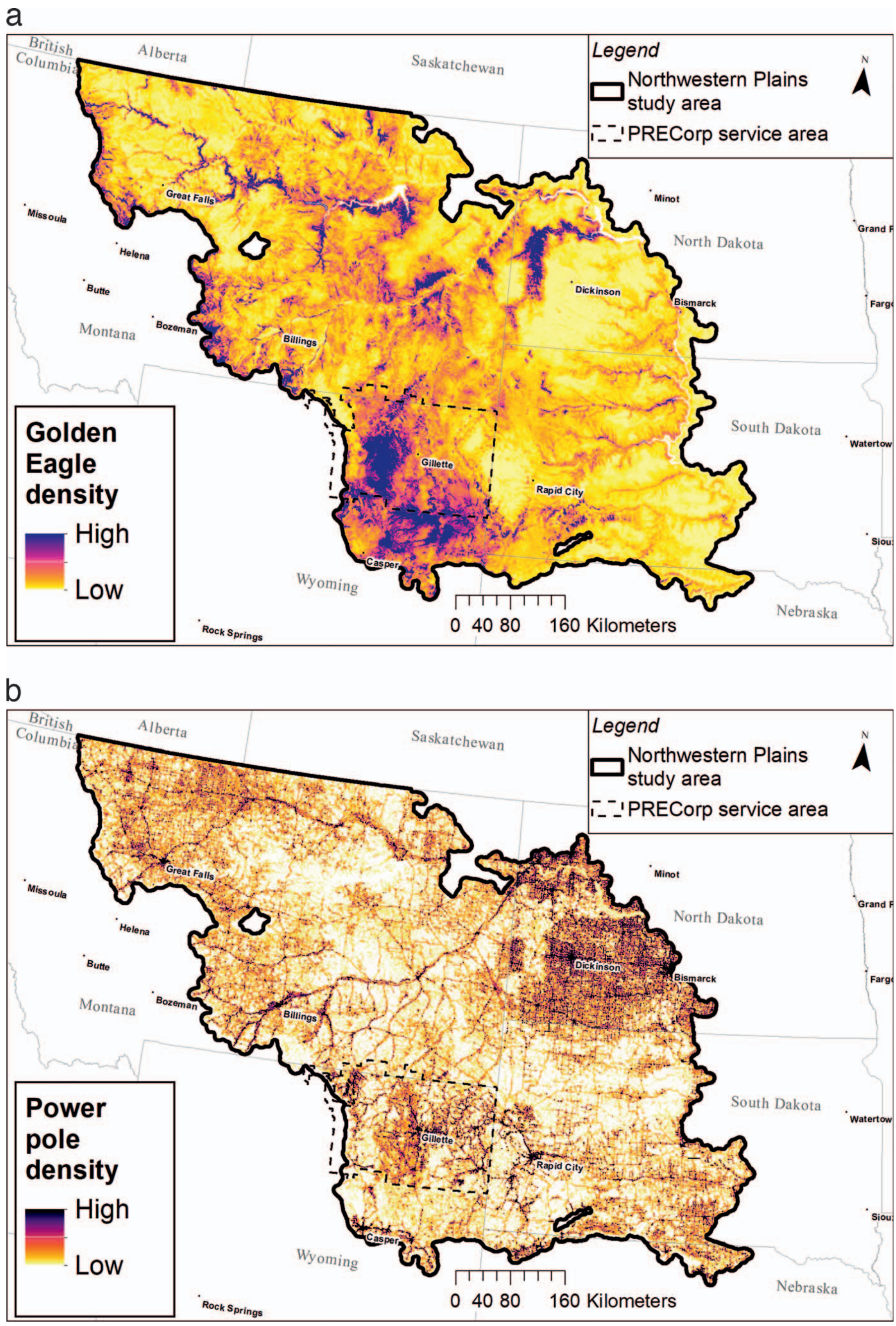

Figure 2. Predictive models of (a) Golden Eagle nest-site density (area-adjusted frequency; Dunk et al. 2019a), and (b) distribution power pole density (poles per km^2; Dwyer et al. 2018).

magnitude of differences between areas of differing RND is unknown. In order to estimate the magnitude of differences between RND categories, Dunk et al. (2019a) calculated area-adjusted frequencies (AAF; Boyce et al. 2002) of RND classes as the frequency of cross-validated nest locations divided by the area of that range of RND values across the Northwestern Plains. AAF is a measure of the extent to which predicted nest-site densities varied from a random distribution (i.e., proportional to the areal extent of each habitat suitability bin, which would have an AAF of 1.0). For example, if areas with RND values between 0.70–0.80 occurred on 3% of the landscape and contained 30% of the nest locations, AAF would be 10.0 (i.e., 10 times more nests occurred in this area than expected by chance). AAF was estimated for overlapping, equal-interval bins of RND values (0–0.10, 0.01–0.11, ... 0.90–1) across the full range of values in each RND raster, and the resulting table of AAF estimates was then used to reclassify the RND raster to AAF values. We used the AAF map to represent variation in Golden Eagle nest-site densities, where nest site refers to a more general area surrounding a breeding pair's nests and does not incorporate spatial variation in the size and shape of behaviorally defined territories (Crandall et al. 2015).

The Golden Eagle nest-site model that we used accurately predicted RND within the Northwestern Plains (based on model cross-validation; Dunk et al. 2019a). We recognize, however, that Golden Eagle exposure to electrocution hazards more likely corresponds to the distribution of eagle space-use at the broader scale of nesting territories (Steenhof et al. 2017). Therefore, we rescaled the nest-site density model to reflect the area of disproportionately high use (i.e., core area: Bingham and Noon 1997, Vander Wal and Rodgers 2012) surrounding high RND pixels. To do this, we smoothed the AAF surface using a weighted Gaussian kernel ($\sigma = 4.0$) where the size of the kernel (27×27 120-m pixels) approximated the 80% upper confidence interval (UCI) of the mean monthly core-area size (8.686 km^2) estimated for 109 territorial adult Golden Eagles from across North America, with most being in the western conterminous USA (R. Crandall pers. comm.). The 80% UCI was selected as a conservative estimate of Golden Eagle space use and subsequent exposure. The weighted smoothing is a moving window analysis, in which each pixel receives a new smoothed AAF value based on a weighted focal mean of AAF values of nearby pixels. Weights are inversely proportional to distance, meaning that AAF values nearest to a focal pixel are more influential in calculating its smoothed value. We chose $\sigma = 4.0$ because it was the smallest distance that achieved the desired smoothing effect of eliminating narrow bands or "valleys" of low AAF that were otherwise encompassed by areas of high AAF. The core-area scaled smoothing provided a more biologically realistic spatial representation of relative likelihood of Golden Eagle presence (i.e., exposure) associated with nesting territories.

As an index of hazard, we used a spatially explicit predictive model of power pole density developed by Dwyer et al. (2016) with predictor variables including road length, number of oil and gas wells, slope, presence of pivot irrigation, and presence of development at a 1-km $\times$ 1-km spatial resolution (Fig. 2b). These models did not explicitly incorporate information on pole-level hazard associated with complexity of energized components (Dwyer et al. 2014). Instead, Dwyer et al. (2016) asserted that power pole density is positively correlated with per-pole structural complexity (and subsequent higher hazard), which results from connecting service lines to end-users such as irrigation pumps, oil and gas wells, and residential development. The power pole density model developed for Colorado and Wyoming was applied to the remaining area of the Northwestern Plains (Montana, western North Dakota and South Dakota) and evaluation indicated a high correlation between counts of predicted vs. observed numbers of poles in this area (Dwyer et al. 2017b, 2018). We used bilinear interpolation to resample the pole density model surface to match the 120-m $\times$ 120-m spatial resolution of the Golden Eagle exposure model.

Ranking Areas by Relative Risk. We quantified relative risk as the interaction of exposure and hazard. Hence, the riskiest areas had both high exposure (i.e., Golden Eagle nest-site density) and high hazard (i.e., power pole density). To rank relative risk across the Northwestern Plains study area, we applied the general methodology of Tack and Fedy (2015) and reclassified Golden Eagle nest-site density (AAF) and pole density (number of poles per km^2) into seven bins (Table 1). We used quantile binning, so each bin contained the same amount ($1/7^{th}$ or 14.3%) of land area. Each raster pixel in the study area was assigned an exposure value (relative ranking after binning; 1–7) and a hazard value (1–7), creating a risk matrix representing all 49

Table 1. Binned values of modeled Golden Eagle nest-site density (area-adjusted frequencies; AAF) and power pole densities used to assess relative risk of electrocution. We calculated the range for each bin as equal-area quantiles of the model predictions (i.e., each bin included 1/7th or 14.3% of the study area).

BIN	GOLDEN EAGLE NEST-SITE DENSITY (AAF)	POWER POLE DENSITY (POLES/km^2)
1	0.00–0.13	0.00–0.05
2	0.14–0.19	0.06–0.16
3	0.20–0.30	0.17–0.40
4	0.31–0.46	0.41–1.04
5	0.47–0.75	1.05–2.28
6	0.76–1.47	2.29–4.61
7	1.48–24.02	4.62–281.89

combinations of exposure and hazard values (Tack and Fedy 2015).

We grouped the 49 risk matrix cells into six risk categories. One reason for this reduction was that values of 1 or 2 on either the electrocution hazard or exposure axis represented areas that either had very few power poles or very few Golden Eagle nest sites, regardless of the amount of the other risk component. In such cases, creating a composite index of risk by adding or multiplying the component bin numbers (Ferrier and Wintle 2009) would misrepresent the low level of risk resulting from any combination with a low value for either exposure or hazard. Hence, our six refined risk categories were as follows: (1) *lowest risk* included matrix cells that contained either a 1 or 2 on either axis; (2) *very low risk* included matrix cells with a 3 as the lowest bin on either axis; (3) *low risk* included matrix cells with a 4 as the lowest bin on either axis; (4) *moderate risk* included matrix cells with a 5 as the lowest bin on either axis; (5) *high risk* included matrix cells with a 6 as the lowest bin on either axis; and (6) *very high risk* was the single matrix cell with 7 on both axes. Following Tack and Fedy (2015), we calculated the area (km^2) and percentage of the Northwestern Plains within each of the 49 exposure-by-hazard combinations, and within each of the six risk categories.

Testing Risk Model Predictions with Independent Data. To test our model's spatial predictions of electrocution risk, we used location data for 342 Golden Eagle electrocutions within the PRECorp service area. PRECorp staff discovered these Golden Eagle mortalities from 2001 through 2018 as part of routine operations, line inspections, outage investigations, or when mortalities were reported by contract biologists, agency personnel, or private citizens. From 2013 through 2017, PRECorp reviewed every structure in their system, including searching for avian carcasses, during which they discovered 84 Golden Eagle carcasses (25% of the total sample). Thus, we made the assumption that these data represent an unbiased sample although we recognize that search effort and detection rates likely varied spatially and temporally. We did not filter electrocution location data by the day they were discovered or season because eagle remains can persist for months and thus discovery date may not accurately reflect when an electrocution occurred. Information on age class was not collected for all carcasses, and was thus unavailable for analysis. Although these locations were not the result of a designed study or sampling procedure, none of the Golden Eagle electrocution mortalities played a role in model development or predictions, so they represent independent data.

Risk predictions that performed no better than random chance would result in the number of known electrocutions within each of the six risk categories being proportional to the area covered by that risk category (i.e., observed-to-expected ratio = 1.0, the null-model expectation). We would consider our risk predictions to perform well if we observed more electrocutions than the null-model expectation in areas with higher risk values (observed-to-expected ratio >1.0), fewer electrocutions than the null-model expectation in areas with lower risk values (observed-to-expected ratio <1.0), and if the ratios of observed-to-expected mortalities were monotonically increasing (i.e., a significant positive rank correlation; Boyce et al. 2002).

We calculated the geographic area and proportion of the total area (represented by each of the six risk categories) and multiplied each category's proportion by the sample size of electrocution locations (n = 342) to estimate the number of expected electrocutions under the null hypothesis that electrocutions were distributed proportional to area within the PRECorp service area. We then used chi-square goodness of fit tests to compare the expected values within each: (1) bin of Golden Eagle nest-site density; (2) bin of power pole density; and, (3) risk category, to the observed distribution of the 342 electrocutions in each bin/category throughout the entire service area. We summarized differences as observed-to-expected ratios of electrocutions by bin of Golden Eagle density, power pole density, and risk category, and we evaluated the rank correlation between risk category and observed-to-expected ratios within each bin of Golden Eagle density, power pole density, and risk category. Lastly, we calculated the magnitude of difference in relative risk between risk categories by dividing observed-to-expected ratios.

We used Program R to conduct analyses (R Core Team 2018). We used the "sp" (Pebesma and Bivand 2005), "raster" (Hijmans 2016), "rgdal" (Bivand et al. 2017), and "rgeos" (Bivand and Rundel 2017) packages for spatial data handling, summary, and analysis. We made figures using the "ggplot2" (Wickham 2009), "RColorBrewer" (Neuwirth 2014), and "viridis" (Garnier 2017) packages and ArcGIS 10.6 (Esri 2018).

RESULTS

The six risk categories of the Golden Eagle electrocution risk model were unevenly distributed, with a high concentration of moderate, high, and very high risk areas in south-central portions of the Northwestern Plains (Fig. 3a). In contrast, the lowest and very low risk areas were more broadly distributed throughout the region. At the scale of the Northwestern Plains, our risk prediction map suggested a highly variable and nonrandom spatial distribution of risk, with very small areas of very high (1.1%) and high (3.8%) risk, large areas of lowest (53.6%) and very low (20.2%) risk, and intermediate areas of low (13.7%) and moderate (7.7%) risk (Fig. 3b).

Model Evaluation with Independent Data. The amount and distribution of relative risk categories within PRECorp's service area were markedly different from those of the Northwestern Plains as a whole. The PRECorp service area had a larger percentage of its area with higher values of risk, and a smaller percentage of its area with lower values of risk, than the Northwestern Plains region (Fig. 4a). Specifically, PRECorp's service area had 2.2 times more moderate risk, 4.2 times more high risk, and 6.3 times more very high risk (based on proportion of the area) than in the Northwestern Plains overall (Fig. 4b). Similarly, PRECorp's service area contained approximately half the amount (by proportion) of lowest risk and 3/4 the amount of very low risk compared to the Northwestern Plains.

Within the PRECorp service area, 87.7% of the 342 Golden Eagle electrocution locations were in 39.7% of the area, including areas our model classified in the moderate, high, or very high risk categories (Fig. 4c). By contrast, the lowest and very low risk categories included only 3.8% of electrocutions occurring within 43.0% of the area, and areas classified in the low risk category had 8.5% of electrocutions in 17.3% of the area. Electrocutions were much more likely to occur than expected in the top three risk categories and much less likely to occur in the lowest risk categories (Fig. 5a; $\chi^2 = 427.5$, df = 5, $P < 0.0001$). Furthermore, we found a perfect and positive rank correlation between risk category level (1–6) and observed-to-expected ratios ($r_s = 1.00$, $P < 0.01$). The magnitudes of difference between the observed-to-expected ratios of the very high, high, and moderate risk categories to the lowest risk category were 89.8, 63.0, and 33.8, respectively.

Electrocutions were much more likely to occur than expected in the top two bins of Golden Eagle density (Fig. 5b; $\chi^2 = 91.6$, df = 6, $P < 0.0001$), with an increasing positive rank correlation across most but not all bins ($r_s = 0.99$, $P = < 0.0001$). Electrocutions were more likely to occur than expected in the top three bins of power pole density with a positive trend across most but not all bins (Fig. 5c; $\chi^2 = 510.4$, df = 6, $P < 0.0001$), and there was increasing positive rank correlation across most but not all bins ($r_s = 0.93$, $P < 0.01$). Electrocutions were more common than expected above relatively low values of both Golden Eagle density (ca. 1.0 AAF; Fig. 6a) and power pole density (ca. 0.5 poles per km^2; Fig. 6b).

DISCUSSION

Our method of estimating a spatially explicit index of electrocution risk to Golden Eagles is repeatable and proved effective at predicting relative risk based on evaluation of our model with independent data. The risk model classified approximately half (53.6%) of the Northwestern Plains as lowest risk, with a small proportion (1.1%) classified as very high risk. Identifying how electrocution, or any other risk, varies in a spatially explicit manner can improve efficiency of conservation and management. For example, if predictions are accurate, areas within the lowest and very low risk categories could be considered as candidates for less intensive pre-project evaluation requirements by regulatory agencies, and excluded as appropriate areas for conservation actions (i.e., power pole retrofitting), at least until after the moderate, high, and very high risk areas were thoroughly addressed. Similarly, areas identified as high and very high risk could be specifically targeted as areas for conservation ac-

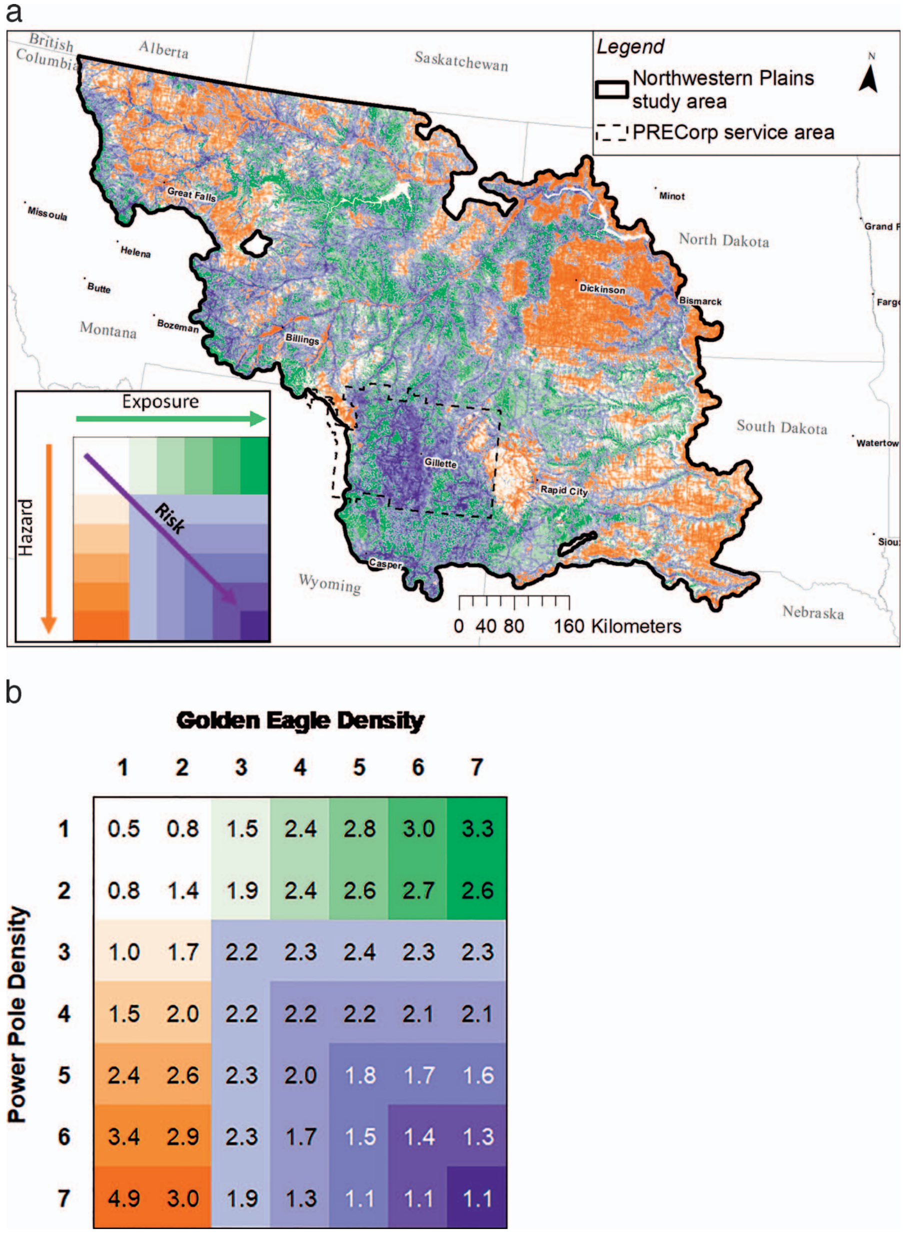

Figure 3. (a) Relative risk of electrocution for Golden Eagles in the Northwestern Plains. Map colors correspond with relative risk categories shown in the risk matrix (b). Risk matrix values are the percentage of the total assessed area (474,170 km^2) in each risk combination.

tions, with a high likelihood of positive conservation outcomes.

Our evaluation of the locations of 342 Golden Eagle electrocution mortalities collected independent of our model building revealed very high predictive accuracy of our electrocution risk model, with nearly all (87.7%) of the electrocution locations occurring in areas predicted to be moderate, high, and very high risk and only 3.8% occurring in areas predicted to be in the lowest and very low risk

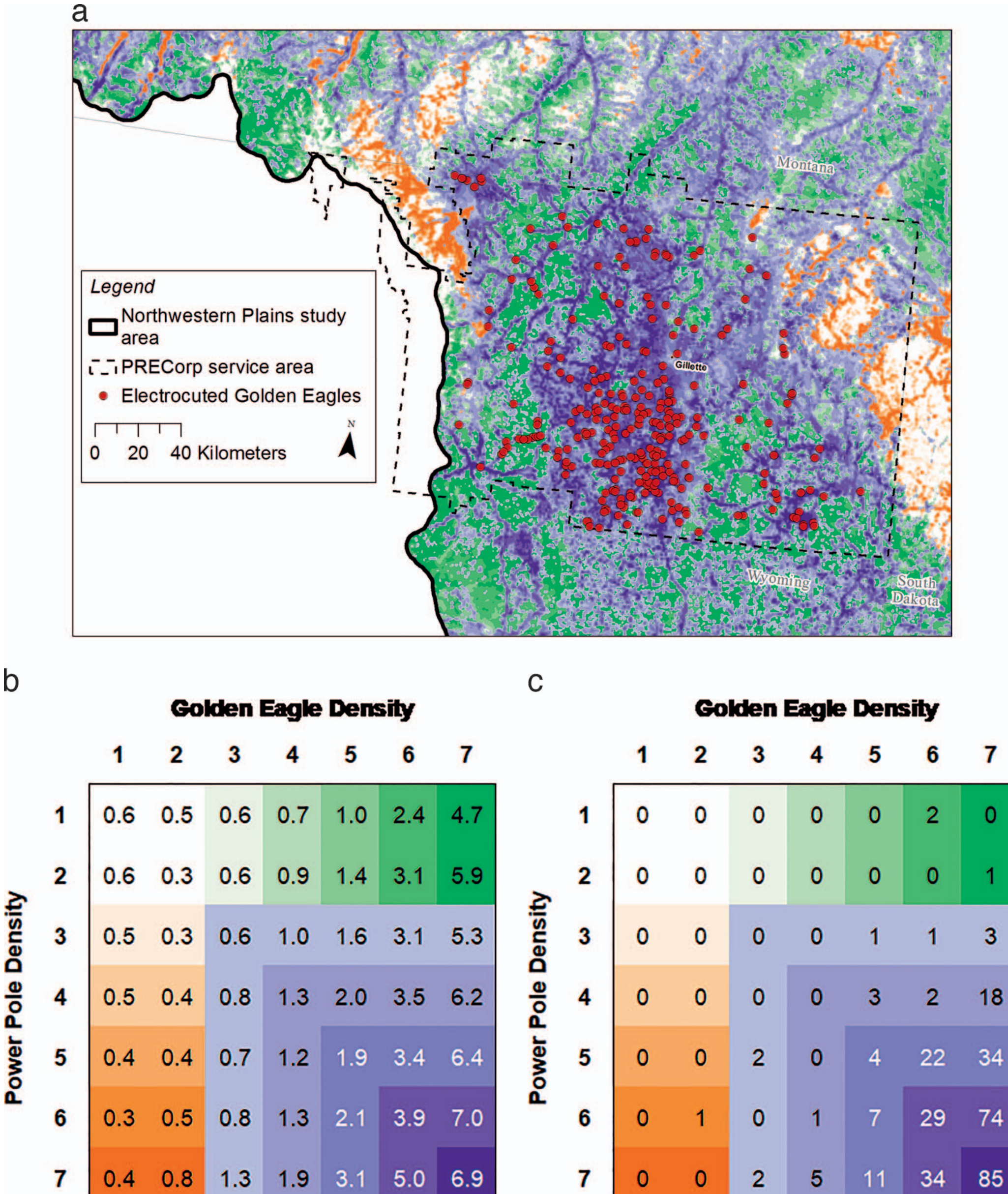

Figure 4. (a) Relative risk of electrocution for Golden Eagles in the PRECorp service area. Map colors correspond with relative risk categories shown in risk matrices (b) and (c). Values are (b) the percentage of the total assessed area (38,793 km^2) and (c) counts of Golden Eagle electrocutions ($n = 342$) in each risk combination.

categories. We found that combining the Golden Eagle and power pole models accurately predicted areas with disproportionately more and fewer electrocutions than would be expected by chance. All models are imperfect and have errors, and combining two models as we did could propagate error resulting in inaccurate estimates. However, our evaluation of the model's predictive accuracy using independent mortality data suggested that this was not occurring in our Golden Eagle electrocution risk

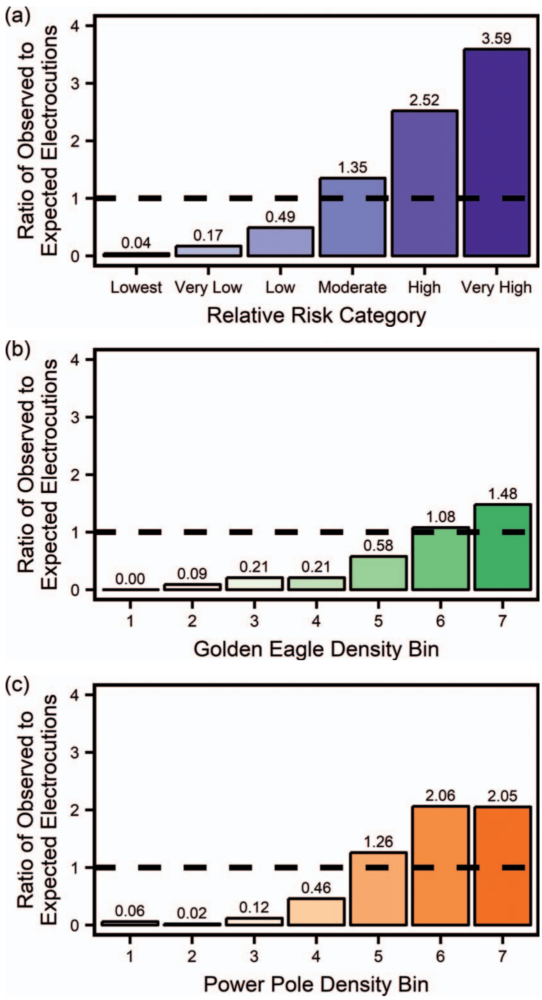

Figure 5. Ratio of observed-to-expected Golden Eagle electrocution mortalities by (a) relative risk category, (b) Golden Eagle density bin, and (c) power pole density bin. The number of expected mortalities was based on the assumption that electrocutions occurred uniformly throughout the PRECorp service area. Colored bars correspond with the color matrices in Figure 4 and are labeled with observed-to-expected ratio values. The dashed line represents the null hypothesis (ratio of observed to expected electrocutions = 1).

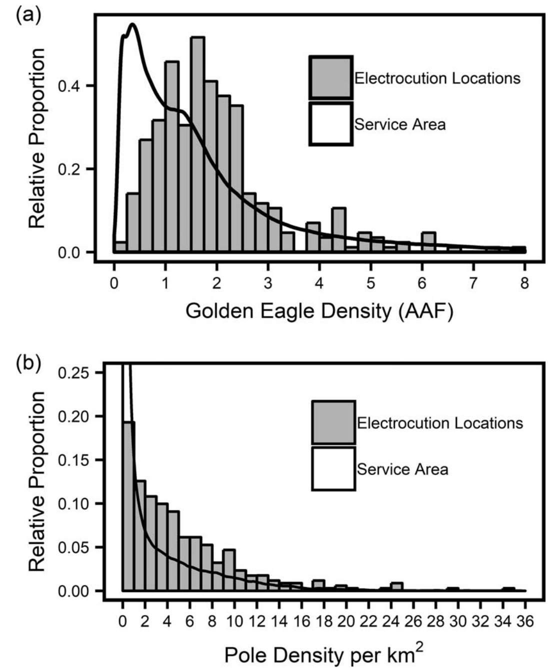

Figure 6. Relative proportion of predicted (a) Golden Eagle nest-site density (area-adjusted frequency [AAF]) and (b) power pole density per km^2 in the PRECorp service area (black line) compared with 342 Golden Eagle electrocution locations (gray bars). The y-axis of (b) was limited to y = 0.25 to display at this scale; the maximum value was ca. 0.70.

model. Additionally, the fact that the ranks of observed-to-expected ratios scaled strongly (r_s = 1.0) and positively with electrocution risk ranks suggested that our risk categories have on-the-ground ecological relevance, and thus value for land managers.

The independent mortality data used to evaluate our predictions of relative risk should be interpreted with some caution due to potential issues with sampling bias because mortality monitoring by utilities is typically retrospective and only a proportion of electrocutions are detected (Kemper et al. 2013, Mojica et al. 2018). However, searches for avian carcasses were conducted at all electrical structures in the PRECorp service area at least once during the study period, which should reduce the bias of increased detections occurring near roads and developed areas. Ongoing efforts to develop standardized survey protocols to detect electrocutions will enable more rigorous evaluations in the future (APLIC 2018). It is also possible that the risk model's performance in PRECorp's service area is not representative of the model's predictive abilities throughout the Northwestern Plains. However, the fact that the distribution and abundance of risk categories differed substantially between PRECorp's service area and the Northwestern Plains as a whole, and that the estimated distribution of mortalities conformed closely with the actual distribution of mortalities among risk categories suggests that our model is useful for informing Golden Eagle conservation and management decisions. The strength and consistency of the relationships between categories of Golden Eagle density, pole density, and relative risk with electrocution mortality supports the conclusion that our approach accurately represents spatial variation in risk of Golden Eagle electrocution in the study area.

Vulnerability is an important component to quantifying absolute risk, but a factor that we did not incorporate because it is highly stochastic and difficult to quantify or predict. Quantile-binning provided a means of ranking habitat and hazard values without prior knowledge of the relationship between Golden Eagle vulnerability and electrocution hazard. Although our measure of risk is relative, we found that it was proportional to the actual risk as evidenced by our evaluation of independent electrocution mortality data (e.g., rank correlation of risk category and observed-to-expected mortality ratios was 1.0).

High densities of predicted Golden Eagle nest sites and power poles were relatively rare in the Northwestern Plains. For example, pole density predictions ranged from 0.00–281.89 poles/km^2 but only approximately 3% of the values were >10.0 poles/km^2. Thus, quantile binning resulted in the highest bins containing a disproportionately large range of the values, while the lower bins more finely differentiated among the smaller predicted values. Similarly, <20% of the study area had Golden Eagle nest-site density values >1.0 AAF, yet contained >80% of known Golden Eagle nests (Dunk et al. 2019a). Although other binning methods might be reasonable and useful, our method of binning model values using quantiles worked very well, based on our evaluation of independent mortality data, which indicated that even small increases in Golden Eagle density (e.g., bin 5 vs. bin 6; Fig. 5b) or pole density (e.g., bin 4 vs. bin 5; Fig. 5c) resulted in meaningful increases in electrocution risk. We consider this approach conservative and appropriate for Golden Eagles due to their protected status and sensitivity to even small increases in anthropogenic mortality (USFWS 2016).

The Dwyer et al. (2016) power pole density model was a useful surrogate for electrocution hazard and was strongly positively related to observed electrocution mortalities. This result contrasts with the findings of Pérez-García et al. (2017), who found a quadratic relationship between power pylon density and the incidence of electrocution for multiple avian species in Spain. This difference may be explained by comparatively low levels of anthropogenic development, and subsequently lower power pole densities, in our study area. In contrast, the area studied by Pérez-García et al. (2017) was extensively developed, with high densities of pylons occurring in urban areas that were avoided by birds. A second important distinction is that power distribution systems in the US are usually constructed of wood poles with wood crossarms (APLIC 2006, Dwyer et al. 2014) where electrocution hazard is strongly influenced by the complexity of energized components, which typically increase at higher pole densities (Dwyer et al. 2016). In Spain, however, distribution pylons usually consist of steel lattice pylons with steel crossarms (Martín et al. 2015, 2017). Electrocution hazards are higher on the steel lattice pylons, even relatively simple pylons, because energized conductors occur in close proximity to grounded structural components. Despite these and numerous methodological differences between our study and that of Pérez-García et al. (2017), both models successfully revealed priority conservation areas based on the spatial distribution of focal species habitat, power pole density, and the distribution of electrocution mortalities.

Our use of Golden Eagle nest-site density to represent exposure in our electrocution risk model may underrepresent areas occupied by winter migrants or other eagles not associated with breeding territories. Despite this potential shortcoming, our electrocution risk model accurately predicted relative electrocution risk in the independent test area, indicating that the nest-site density model adequately represented the overall distribution of Golden Eagle exposure in the study area. To the degree that non-territorial and migrant Golden Eagles use different habitats than territorial residents and their offspring, we anticipate that integrating predictive models of Golden Eagle density in winter and movement periods into our exposure model would increase the accuracy of our relative risk predictions by accounting for temporal variation in eagle exposure.

Our model provided spatially explicit predictions of relative electrocution risk while maintaining information on the individual components of risk (Golden Eagle density and power pole density). This information-rich method can be interpreted visually on a map and support quantitative analysis for prioritization of conservation actions; in this case, power pole retrofitting for electrocution prevention. Moreover, the magnitude of difference between ratios of observed-to-expected mortalities by risk category represents the relative value of retrofitting efforts depending on risk categories mapped across the study area. For example, the magnitude of difference in the observed-to-expected ratio of mortalities between the high (2.52) and lowest risk categories (0.04) equals 63.0. We recognize that this calculation is highly sensitive to small differences in the number of mortalities within and among risk categories and the number of significant figures in the areal measurement. Our presentation and discussion of these relative differences is primarily to elucidate the major differences between and among risk categories, which have real-world implications for conservation prioritization.

We integrated indices of hazard and exposure to represent model predictions of Golden Eagle electrocution risk across a broad extent. Other than representing variation in nest-site densities, quantifying the ecological mechanisms underlying the relationships among predictor variables and electrocution risk was beyond the scope of this study. Better models of habitat suitability, distribution of hazards, and Golden Eagle exposure or vulnerability to hazards could refine our predictions of the spatial distribution of relative risk. However, management decisions are regularly made with imperfect information, and we therefore suggest it is appropriate to consider risk analysis to be an iterative process that can respond to changing resource conditions and available information. Additional test data within the Northwestern Plains will also elucidate how well the model works in other areas. We encourage wildlife biologists, land managers, and utility companies to evaluate the accuracy and usefulness of risk analyses using real-world data, whenever possible. Given the model's accurate predictions in the PRECorp service area, we believe the model will be immediately useful to land managers, utilities, and conservationists throughout the Northwestern Plains region. Because we previously developed models of Golden Eagle and power pole density for the majority of ecoregions occupied by Golden Eagles in the western USA (Dunk et al. 2019a, Dwyer et al. 2018), the analysis presented here is a case study in only one of many regions where such risk analyses are possible.

Management Applications. We designed our risk analysis approach to complement existing efforts to reduce electrocution mortality, including compensatory mitigation for permitted take of Golden Eagles. Our risk analysis provides a consistent and repeatable methodology to rank Golden Eagle and power pole densities to identify and target areas for utility retrofitting efforts, among other possible conservation actions. Our analysis of independent data suggests that focusing retrofitting efforts in areas with high densities of power poles and high densities of Golden Eagle nest sites (very high risk areas) could prevent more than 3 times the electrocutions expected by selecting areas at random, and prevent >89 times more electrocutions compared to the lowest risk areas. Hence, initially focusing retrofitting actions within the highest risk categories within a region (or utility service area) would be a much more efficient and effective expenditure of time and money, in terms of reducing Golden Eagle electrocutions. We recommend the application and use of this model at relatively large spatial scales (e.g., >100 km^2 or larger). Use at smaller scales is less likely to result in accurate predictions. In cases where utilities have high-quality spatial data on their electric equipment, including information on pole locations and equipment type (e.g., Hernández-Lambraño et al. 2018), such information could be substituted for the pole density model and used in combination with the Golden Eagle density model in a spatially explicit risk analysis.

Power pole retrofitting programs can integrate our Golden Eagle electrocution risk model into a hierarchical process consisting of risk analyses conducted at two or more scales of resolution. Our risk model is useful as a consistent coarse-filter tool for "desk-top" analyses conducted to identify higher risk (priority) areas at regional and landscape scales. This would facilitate strategic prioritization of retrofitting for mitigation projects that span multiple utility service areas, such as the Bald Eagle and Golden Eagle Electrocution Prevention *In-lieu* Fee Program (USFWS 2018). Because service areas of many US electric utilities are landscape-sized, our risk model can also be used to develop, evaluate, and coordinate programs for minimizing risk of avian mortality associated with power lines within and among electric utilities. The details of utility retrofitting programs are documented in Avian Protection Plans (APPs; APLIC and USFWS 2005), and the inclusion of our risk model into APPs as a means of prioritizing retrofitting could increase compliance with utilities' legal obligations under the Bald and Golden Eagle Protection Act (16 U.S.C. 668-668d).

When a higher risk (priority) area has been identified, finer-scale coordination is needed between resource managers and electric utilities to determine if retrofitting has previously occurred and what additional retrofitting is needed (Dwyer et al. 2016). We recommend retrofitting electric equipment to avian-friendly standards be prioritized on high-risk poles in high-risk areas with correct application of retrofitting techniques (APLIC 2006, Dwyer et al. 2017a, Mojica et al. 2018). Because electrocution risk depends on pole configuration, identification of high-risk poles should be determined by evaluating each pole individually (APLIC 2006, Harness and Wilson 2001, Lehman et al. 2010, Dwyer et al. 2014).

Our risk analysis approach has the potential to offer insights for a wide range of species, hazards, and conservation actions, including management planning, targeted mitigation, land acquisition, and energy development. The spatial data products from this regional-scale risk analysis (areal tables and maps) are most appropriate for spatial prioritization of conservation actions aimed at ameliorating future electrocutions of Golden Eagles at relatively broad spatial scales—a recognized and growing conservation concern for this species. Binning of input layers can be adjusted to correspond to thresholds established in *a priori* management goals and the analysis area can be determined based on the scale at which prioritization actions will be taken. Considering the range of potential hazards and conservation needs for Golden Eagles more broadly, we encourage the use of our general approach to estimate other sources of risk to Golden Eagles (e.g., lead poisoning, conventional and renewable energy development, vehicle collision). While this study focused on Golden Eagle electrocutions, our method of spatial prioritization for strategic conservation planning is adaptable to other species and hazards for which relevant spatial data are available.

Geospatial data and tabular results are publically available for our electrocution risk model for the Northwestern Plains, as well as 14 other regions of the western USA corresponding to the Dunk et al. (2019a) Golden Eagle nest-site models: https://ecos.fws.gov/ServCat/Reference/Profile/112488.

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