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POWER POLE DENSITY AND AVIAN ELECTROCUTION RISK IN THE WESTERN UNITED STATES

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Abstract.—Avian electrocutions on power poles affect raptor populations globally. Mitigation strategies in the USA are typically bottom-up, combining risk assessments for individual poles into a utility-specific avian protection plan. This approach is usually reactive, relying on incidental documentation of electrocutions for initiation, and can allow uncoordinated mitigation strategies among adjacent utilities. A top-down strategy may help solve both problems if maps identifying where distribution power poles occur were available for comparison to range maps for species at risk of electrocution. Range maps exist but pole location data are rarely publicly available in the USA. Pole-density models were previously created for Colorado and Wyoming, the Great Basin, and the Columbia Plateau because pole density can serve as a surrogate for electrocution risk. We used each of these models to predict pole densities throughout four additional areas: the Northwestern Plains, Southwestern Plains, Southwestern Plateaus, and parts of New Mexico not included in other modeled areas. We also applied the Colorado and Wyoming model to portions of the Uinta Basin and Wyoming Basin projecting from Colorado and Wyoming into Idaho and Utah. The Colorado and Wyoming model fit all areas better than other models, except parts of New Mexico not included in other modeled areas, where the Great Basin model fit best. Our model predictions facilitate assessment of pole density across much (2,573,746 km^2) of the western USA. To assess whether the models are useful in predicting electrocutions, we compared predicted pole densities throughout White Sands Missile Range to locations of 59 avian electrocutions. Electrocutions occurred at low rates in cells with low predicted pole densities, and at higher rates in cells with moderate and high predicted pole densities. Because the models do not include species-specific information, they have the potential to be applicable to the conservation of a wide variety of species.

Key Words: *Golden Eagle*; Aquila chrysaetos; *electric utility*; *model*; *random forest*; *raptor*.

DENSIDAD DE POSTES ELÉCTRICOS Y RIESGO DE ELECTROCUCIÓN DE AVES EN EL OESTE DE ESTADOS UNIDOS

Resumen.—La electrocución con postes eléctricos es un problema que afecta a las poblaciones de rapaces globalmente. Las estrategias de mitigación aplicadas en los Estados Unidos siguen un modelo de abajo hacia arriba, combinando las evaluaciones de riesgo de los postes individuales dentro de un plan específico de protección de las aves propio de cada empresa de servicios. Este enfoque es usualmente reactivo, dependiente de la documentación de incidentes de electrocución para ponerse en marcha, y da lugar a la implementación de estrategias de mitigación descoordinadas entre empresas adyacentes. Una estrategia de arriba hacia abajo podría ayudar a solucionar ambos problemas si los mapas que identifican la ubicación de los postes eléctricos estuvieran disponibles para compararlos con mapas de áreas de distribución de especies en riesgo de electrocución. Los mapas de áreas de distribución existen, pero los datos de localización de los postes pocas veces están disponibles públicamente en EEUU. Se generaron modelos de densidad de postes para Colorado y Wyoming, la Gran Cuenca y la Meseta de Columbia, ya que la densidad de postes puede servir como un modelo del riesgo de electrocución. Usamos cada uno de estos modelos para predecir la

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densidad de postes a través de cuatro áreas adicionales: las Llanuras del Noroeste, las Llanuras del Sudoeste, las Mesetas del Sudoeste y partes de Nuevo México no incluidas en otras áreas modeladas. También aplicamos el modelo de Colorado y Wyoming a porciones de la Cuenca de Uinta y la Cuenca de Wyoming, proyectando desde Colorado y Wyoming hacia Idaho y Utah. El modelo de Colorado y Wyoming se adaptó mejor a todas las áreas que los otros modelos, excepto para partes de Nuevo México no incluidas en otras áreas modeladas, donde el modelo de la Gran Cuenca resultó más adecuado. Nuestras predicciones del modelo facilitan las evaluaciones de densidad de postes a través de la mayor parte (2,573,746 km^2) del oeste de EEUU. Para evaluar si los modelos son útiles y predicen la electrocución, comparamos las densidades esperadas de postes a lo largo del Campo de Misiles de Arenas Blancas con las ubicaciones de 59 electrocuciones de aves. Las electrocuciones ocurrieron a tasas bajas en las celdas con una baja densidad esperada de postes, y a tasas más altas en celdas con moderadas y altas densidades esperadas. Debido a que los modelos no incluyen información específica para cada especie, tienen el potencial de ser aplicables a la conservación de una amplia variedad de especies.

[Traducción del equipo editorial]

Avian electrocutions are of long-term and ongoing global conservation concern (Avian Power Line Interaction Committee [APLIC] 2006, Lehman et al. 2007, Loss et al. 2014). These incidents disproportionately affect larger species. For example, electrocutions appear particularly detrimental to Golden Eagles (*Aquila chrysaetos*), with over 3800 electrocutions of Golden Eagles reported in scientific literature from 1940 through 2016 (Mojica et al. 2018). Electrocutions in western North America include approximately 500 Golden Eagle fatalities annually (95% CI: 124–1494; US Fish and Wildlife Service [USFWS] 2016). These electrocutions occur widely across the species' range in North America from Canada (Kemper et al. 2013), through the USA (Harness 2004, Dwyer 2006, Dwyer et al. 2014, Bedrosian et al. 2020), and into Mexico (Cartron et al. 2000, 2005). Of these electrocutions, approximately 20% involve adults, 27% involve subadults, and 53% involve juveniles (Mojica et al. 2018).

Electrocutions have been implicated in population-level declines for Spanish Imperial Eagles (*Aquila adalberti*) and Booted Eagles (*Hieraaetus pennatus*) in Spain (González et al. 2007, López-López et al. 2011, Martinez et al. 2017), Wedge-tailed Eagles (*Aquila audax*) in Australia (Bekessy et al. 2009), Eurasian Eagle-Owls (*Bubo bubo*) in Italy (Sergio et al. 2004), Saker Falcons (*Falco cherrug*) in Mongolia and China (Dixon et al. 2013), Egyptian Vultures (*Neophron percnopterus*) in Egypt (Angelov et al. 2013), Cape Vultures (*Gyps coprotheres*) in South Africa (Boschoff et al. 2011), and Chaco Eagles (*Buteogallus coronatus*) in Argentina (Galmes et al. 2018).

In addition to effects on raptors, electrocution has been identified as a cause of death in numerous non-raptors, particularly corvids, parrots, and parakeets. For example, in North America, electrocutions have affected American Crows (*Corvus brachyrhynchos*; Dwyer et al. 2014), Common Ravens (*Corvus corax*; Dwyer and Mannan 2007, Dwyer et al. 2014), and Chihuahuan Ravens (*Corvus cryptoleucus*; Cartron et al. 2000, 2005). In Europe, Demerdzhiev (2014) and Demeter et al. (2018) reported electrocutions of Eurasian Magpies (*Pica pica*), Eurasian Jays (*Garrulus glandarius*), Carrion Crows (*Corvus corone*), Rooks (*Corvus frugilegus*), and Eurasian Jackdaws (*Corvus monedula*), with each author also reporting other corvids not reported by the other. Corvids, including House Crows (*Corvus splendens*), and numerous other taxa have also been electrocuted in Asia (Harness et al. 2013). In Argentina, parrots and parakeets are frequently involved in electrocutions (Galmes et al. 2018).

Despite the global occurrence of avian electrocutions, mitigation occurs primarily at relatively small scales of individual electric utilities (e.g., Harness and Wilson 2001, Dwyer and Mannan 2007), which generally do not coordinate with one another (J. Dwyer and R. Harness unpubl. data). These localized approaches may not focus mitigation where conservation efforts are most needed (Dwyer et al. 2016) and may not consistently apply the most effective mitigation techniques, allowing dangerous conditions to persist on retrofitted poles (Dwyer et al. 2017b). Lack of coordination persists in part because distribution power pole (pole) locations in the United States are often protected for security reasons, which limits the ability of conservation biologists to consistently identify avian electrocution risk across the landscape. To address this, the state of Colorado and some larger electric utilities have implemented broad-scale coordination and retrofitting (Harness and Nielsen 2006). To better inform coordination and prioritization of retrofitting, the density of distribution poles (≤60 kV; APLIC 2006) was modeled in Colorado and Wyoming (Dwyer et al. 2016), and in the Great Basin and the Columbia Plateau (Dwyer et al. 2017a).

Pole density may not be intuitively linked to electrocution risk for raptors. To assume pole density as a surrogate for avian electrocution risk, we rely on two important features of overhead electric systems. First, within high-quality habitats, electrocution risk per pole increases with increasing pole complexity (Dwyer et al. 2014, Harness et al. 2013). Second, pole complexity increases with increasing pole density, though the specific relationship remains unquantified (Dwyer et al. 2016, 2017a). Combining these two features, pole density can be used as a general surrogate for avian electrocution risk. This is supported by findings of Tintó et al. (2010) in which 95% of electrocutions were found in human-impacted areas where pole density was high, by findings of Perez-García et al. (2011) who identified a correlation between pole numbers and the likelihood of electrocution, and by Bedrosian et al. (2020) who reported correlations between pole numbers and Golden Eagle electrocutions, and also by the assessment of electrocutions in western New Mexico described herein.

In Colorado and Wyoming, pole density increased primarily with the number of oil and gas wells, the presence of development of any type, and the presence of roads of any type (Table 1; Dwyer et al. 2014). In the Great Basin, pole density increased primarily with the presence of any type of development, especially low-density development, and with the presence of roads of any type (Dwyer et al. 2017a). In the Columbia Plateau, pole density increased primarily with low-density development, the presence of pivot irrigation, and the presence of anthropogenic land cover (Dwyer et al. 2017a). Importantly, inclusion of gas and oil well density (the most influential variable in the Colorado and Wyoming models) reduced the fit of the Great Basin and Columbia Plateau models, underscoring the caveat that projection of pole-density models beyond their initial scopes of inference should be done with caution.

We hypothesized that existing pole-density models might be more broadly useful if applied to other parts of western North America, but given the variation in the three models, we could not assume *a priori* which model might best fit each area. To evaluate our hypothesis, we applied each of the models to the Northwestern Plains, the Southwestern Plains, the Southwestern Plateaus, and parts of New Mexico not included in other modeled areas (see Study Area). We then compared the fit of each model to each other model in each area by comparing counts of the number of distribution poles visible in satellite imagery to model predictions. Here we report (1) the best-fitting model for each area, (2) a comparison of predicted distribution pole densities to actual avian electrocutions in a New Mexico service area, and (3) how cautious application of these models might be used to guide avian electrocution mitigation. We also applied the Colorado and Wyoming model to portions of the Uinta Basin and Wyoming Basin projecting from Colorado and Wyoming into Idaho and Utah. Given the consistency of habitat for these areas with the adjacent modeled area, we did not test the fits of all three models in these areas.

Table 1. Variable importance ranks across models of distribution power pole density for Colorado and Wyoming, the Great Basin, and the Columbia Plateau (from Dwyer et al. 2014, 2017a).

	Models		
Variable	Colorado and Wyoming	Great Basin	Columbia Plateau
Number of oil and gas wells	1	15	15
Any type of development	2	1	6
Road length (all roads)	3	3	8
Mean slope	4	5	7
Road length (private)	5	12	14
Pivot irrigation present	6	11	2
Standard dev. of slope	7	6	5
Land-cover type	8	4	3
Road length (local)	9	7	4
Road length (4WD)	10	10	11
Road length (secondary)	11	9	12
Medium-density development	12	8	10
Road length (primary)	13	13	9
Low-density development	14	2	1
High-density development	15	14	13

METHODS

Study Area. The original scopes of inference for the pole-density models were Colorado and Wyoming, the Great Basin, and the Columbia Plateau (Dwyer et al. 2016, 2017a). These areas were characterized by elevations ranging from 85 m below sea level in the Great Basin to >4000 masl in all three modeled areas. Land cover varied widely across all three modeled areas, and included agricultural areas, alpine tundra, deserts, forests, grasslands, urban areas, and shrub-steppe environments, with vegetation varying accordingly. Urban areas varied widely in size and location, but often occurred along travel corridors, riparian corridors, and in major metropolises. Collectively, the variation in the areas of the original scopes of inference of the three models reflected many of the possible combinations of modeled variables in the areas onto which we projected the models.

The areas where we projected each of the models (see Results for maps) were (A) the Northwestern Plains (NWPL) in western portions of North Dakota, South Dakota, and Nebraska, (B) the Southwestern Plains (SWPL) in western portions of Nebraska, Kansas, Oklahoma, Texas, and New Mexico, (C) the Southwestern Plateaus (SWPT) in portions of Arizona, Colorado, and New Mexico Plateaus, (D) other parts of New Mexico (OPNM) not included in either SWPL or SWPT (Wiken et al. 2011), and (E) portions of the Uinta Basin and Wyoming Basin (UBWB) extending beyond the western edges of Colorado and Wyoming. In some cases, the edges of new areas overlapped previously modeled areas. Where this occurred, we clipped the new areas to exclude overlap.

The NWPL were mostly farmland cultivated from flat to gently rolling plains historically vegetated by grasslands, shrubs, and forests. The semi-arid climate was characterized by short, warm summers, and long, cold winters. The SWPL were widely used for agriculture and grazing, having been converted mostly from native grasslands. The dry mid-latitude steppe climate received relatively little precipitation during hot summers or cool winters, resulting in scarce, ephemeral, and intermittent water bodies throughout much of the area. The SWPT were used for ranching, grazing, and natural resources. The SWPT were higher in elevation than other areas we studied, so hot summers with low humidity created generally arid environments which trended progressively cooler with increasing elevation. OPNM were characterized primarily by desert landscapes with relatively little human land use and relatively little vegetative cover (Wiken et al. 2011). Land cover in the UBWB was consistent with land cover in the western portions of Colorado and Wyoming.

Model Fitting. Each of the three previously created models was constructed by populating 1-km^2 cells with information on oil and gas wells, development, pivot irrigation, roads, land cover, and topography (Dwyer et al. 2016, 2017a). Modeled variables were selected specifically for their potential to influence distribution power pole density. For example, oil and gas wells and pivot irrigation were explored because wells and pivots typically were supplied with electric power, and in many cases were the sole reason electric power was delivered to an otherwise undeveloped site. Roads and topography variables were investigated because these often dictated how distribution power lines were routed. Land cover, including various levels of development, was explored because where human influences dominate landscapes, electric power is often present. Where human influences were limited or absent, distribution of electric power also tended to be limited or absent (Dwyer et al. 2016, 2017a).

Previous research (Dwyer et al. 2016, 2017a) used a nonparametric random forest machine-learning classification procedure (random forest; Breiman 2001, Cutler et al. 2007) to model the density of power poles in Colorado and Wyoming, the Great Basin, and the Columbia Plateau in program R (R Core Team 2013). A key benefit of the random forest approach was that complex nonlinear interactions among collinear, nonindependent predictors could be accommodated (Cutler et al. 2007, Hastie et al. 2009). The random forest procedure also was robust for the high number of 1-km^2 cells where the number of poles was known to be zero, e.g., in large areas of undeveloped forest and alpine environments.

To evaluate the usefulness of applying the three previously developed models of distribution pole density beyond their original scopes of inference, we constructed 1-km^2 grids throughout the NWPL, the SWPL, the SWPT, and the OPNM. We then populated each cell in those grids with the same data types used in the three models. Specifically, within each cell, we identified numbers of oil and gas wells, presence and types of development, presence of pivot irrigation, road lengths, the mean and standard deviation of slope, and land-cover type.

We used a map including all types of oil and gas wells (e.g., producing, plugged, injection) in the western United States as of 2016 (IHS Energy 2016) to identify oil and gas well locations. We used Landfire (2016) to identify development and land-cover type in each 1-km^2 cell. Within 30-m^2 cells, Landfire used development intensity classes from the National Land Cover Database (Jin et al. 2013) to classify urban areas and used an Existing Vegetation Type–System Group Physiognomy (EVT_PHYS) attribute to classify land-cover categories other than urban areas. In this system, high-intensity development was defined as areas where impervious surfaces accounted for 80–100% of total cover (e.g., apartment complexes, row houses, commercial or industrial sites). Medium-intensity development was defined as areas where impervious surfaces accounted for 50–79% of total cover (e.g., single-family residences). Low-intensity development was defined as areas where impervious surfaces accounted for 20–49% of total cover, and areas with <20% impervious surfaces were categorized as land-cover types other than developed (e.g., agriculture, forested, open water). To assign a land-cover category to each 1-km^2 cell, we selected the most common 30-m^2 land-cover attribute within each 1-km^2 cell and assigned that value to the entire cell. For example, if a 1-km^2 cell contained 70% forest, 20% open water, and 10% high density developed, we characterized the cell as forest. Because this approach could mask developments such as small neighborhoods, which also require electric power, we separately recorded the number of 30-m^2 cells within each 1-km^2 cell identified by Landfire (2016) as developed high intensity, developed medium intensity, and developed low intensity, and included that quantification of development intensity as a variable in modeling.

We quantified the presence of pivot irrigation by visually evaluating each 1-km^2 cell on satellite imagery to identify the presence of large crop circles or partial circles characteristic of pivot irrigation. Other types of pump irrigation also require electric power but are indistinguishable through remote sensing from flood irrigation, which is not necessarily electrically powered. We accounted for these irrigated areas through incorporation of roads in our analyses because where pump irrigation was present, roads tended to occur in regular grids with spurs that could be used to access terminal poles (Dwyer et al. 2016, 2017a).

We used Topologically Integrated Geographic Encoding and Referencing (TIGER) products (Census Bureau 2015) to identify the length of primary, secondary, local, 4-wheel-drive, and private roads in each cell because poles typically run along road rights-of-way. TIGER identified primary roads as divided limited-access highways with access ramps and interchanges, secondary roads as main arteries with ≥1 lane of traffic in each direction, local roads as paved non-arterial streets with a single lane of traffic in each direction, four-wheel-drive roads as unpaved dirt trails, and private roads as those privately maintained for service, extractive industries, or other purposes (e.g., logging, oil fields, and ranches). We followed methods from Jarvis et al. (2008) to quantify slope and standard deviation of slope in each 1-km^2 cell.

Generally, application of models beyond their original scopes of inference is a risky endeavor, potentially misleading or misdirecting users of model results. In this case however, four features of our process and our application mitigate this concern. First, each of the pole models (Colorado and Wyoming, Columbia Plateau, and Great Basin) was already projected beyond the geospatial boundaries of their training and testing data because each model was developed from limited numbers of electric utilities in each area. Despite this, the models were effective throughout their original geographic extents (Dwyer et al. 2016, 2017a). Second, the boundaries of the original scopes of inference for the models were politically derived state lines or ecologically derived ecoregions, neither of which determine the human population's need for distribution power across a landscape, and thus the density of poles per km^2. Third, we did not simply accept the new models, but compared their performance to each other in each area and tested their performance against a sample of known avian electrocutions (described below). Fourth, Dwyer et al. (2016) emphasized these models are a beginning point, not an endpoint, in identifying areas where power pole mitigation could occur. Once pole model predictions are viewed in a geographic information system (GIS) together with habitat models for species of interest, such as Golden Eagles, these data should be shared with electric utilities to support their avian protection programs. During this communication, electric utilities may provide fine-scale feedback on distribution power pole locations within the broader area of interest identified by the models described here.

Model Evaluation. The three previously developed models were constructed by using samples of cells with known numbers of power poles to train and test models (Dwyer et al. 2016, 2017a). Given the environmental and landscape similarities between Wyoming and Montana, the Colorado and Wyoming model was projected to Montana and then the fit was evaluated by comparing predicted pole counts to actual poles visible in satellite imagery. In this case, actual counts of 72% of 100 cells evaluated were within one pole of modeled predictions for each 1-km^2 cell assessed (Dwyer et al. 2017a). Based on this percentage the Colorado and Wyoming model was identified as fitting generally well enough to be useful in predicting where small or large numbers of power poles were likely to be in Montana (Dwyer et al. 2017a). This established that comparing predicted pole counts to counts of poles visible in satellite imagery was a viable method of evaluating model performance.

In this study, we formalized quantitative assessment of model fit by conducting Spearman's rank correlation tests. In rank correlation tests, converting counts to ranks helps address concerns associated with nonnormally distributed data, obviates the need for an assumption of a linear relationship in the data, and avoids any assumption of cause-and-effect in interpreting the results (Krebs 1999). We generated Spearman's rho (ρ) and a *P*-value for each of the three models (Colorado and Wyoming, Columbia Plateau, and Great Basin) in each of the four areas where models where projected (NWPL, SWPL, SWPT, and OPNM). To do so, we evaluated 150 cells in each modeled area except OPNM where we evaluated only 50 cells due to the smaller extent of the modeled area. We then selected the model with the ρ value farthest from zero as the best-fitting model, where ρ exists on a scale from -1 to 1, and where -1 indicates a perfect negative correlation and a 1 indicates a perfect positive correlation. We report ρ values, *P*-values, and degrees of freedom for each model in each area. We also report the proportion of test cells where predicted pole counts were within one pole of actual pole counts for the best-fitting model.

Importantly, we did not expect ρ values of -1 or 1 indicating perfect or near-perfect correlations between predicted and counted values. Rather, in interpreting our results we follow conventional interpretation of absolute values of ρ where ρ values of 0.00–0.19 indicate very weak relationships, ρ values of 0.20–0.39 indicate weak relationships, ρ values of 0.40–0.59 indicate moderate relationships, ρ values of 0.60–0.79 indicate strong relationships, and ρ values of 0.80–1.00 indicate very strong relationships.

We expected predictions and counts to generally correlate where few poles or many poles occurred, so we supported quantitative assessments of model fit with qualitative assessment of predicted pole densities in four bins. That is, to be useful in 1-km^2 cells where few poles (<5 poles/km^2; Dwyer et al. 2016) were counted, the best-fitting model should generally predict few poles. In cells where moderate numbers of poles were counted (5–9 poles; Dwyer et al. 2016), moderate numbers of poles should be predicted. The same is true for cells with moderately high counts (10–15 poles), and with high counts (>15 poles). Exact correspondence of counts to predictions within low, moderate, moderately high, and high cells was unnecessary to accomplish the overall goal of identifying areas where high numbers of power poles occurred because of the way poles tend to be clustered within landscapes. We focused our assessment on pole counts in four bins: low (<5 poles), medium (5–9 poles), medium-high (10–15 poles), and high (>15 poles). These values were selected for consistency with previously published models (Dwyer et al. 2016, 2017a). In addition to reporting binned values, we report raw numbers to provide additional detail for users interested in considering alternative binning possibilities.

We also assessed the usefulness of pole density in predicting raptor electrocutions by comparing predicted pole densities in White Sands Missile Range (WSMR) in western New Mexico to the locations of 59 actual avian electrocutions of a variety of raptors and other birds occurring in WSMR from May 2005 through September 2012. We chose WSMR in part because WSMR had a history of documenting avian electrocutions when they occurred, and in part because the electric system was assembled by various utilities over many years, providing a broad cross section of construction standards for distribution power lines that the best-fitting model would need to effectively predict across if it were to be useful. In this analysis, we used a Fisher's exact chi-square (χ^2) 2×2 table with a Yates' continuity correction to compare electrocution frequencies in cells with low numbers of poles (<5) to all other cells (≥ 5 poles). Consolidating across moderate to high categories was necessary for this analysis due to expected frequencies of zero in some pole-density categories. Inclusion of the Yates' continuity correction to adjusted *P*-values for low expected values (>0; <5) in some cells. In the interest of protecting security, we did not evaluate and do not report any information on actual pole locations within WSMR, nor do we

Table 2. Spearman's rank correlation test results from comparing the fit of three distribution pole-density models in four areas not previously modeled. See text for descriptions of models and areas.

	Northwestern Plains	Southwestern Plains	Southwestern Plateaus	Other Parts of New Mexico
Colorado and Wyoming				
Spearman's ρ	0.68	0.52	0.42	0.53
ρ interpretation	strong	moderate	moderate	moderate
df	148	148	148	48
P-value	<0.001	<0.001	<0.001	<0.001
Columbia Plateau				
Spearman's ρ	0.14	0.34	0.33	0.53
ρ interpretation	very weak	weak	weak	moderate
df	148	148	148	48
P-value	0.09	<0.001	<0.001	<0.001
Great Basin				
Spearman's ρ	0.14	0.45	0.36	0.68
ρ interpretation	very weak	moderate	weak	strong
df	148	148	148	48
P-value	0.09	<0.001	<0.001	<0.001

provide the locations of the avian electrocutions used in this analysis.

Results

The Colorado and Wyoming, Great Basin, and Columbia Plateau pole-density models effectively predicted density of distribution power poles on a 1-km^2 grid throughout much of the western United States. However, the different models performed differently in the various regions. The Colorado and Wyoming model fit the NWPL in western portions of North Dakota, South Dakota, and Nebraska better

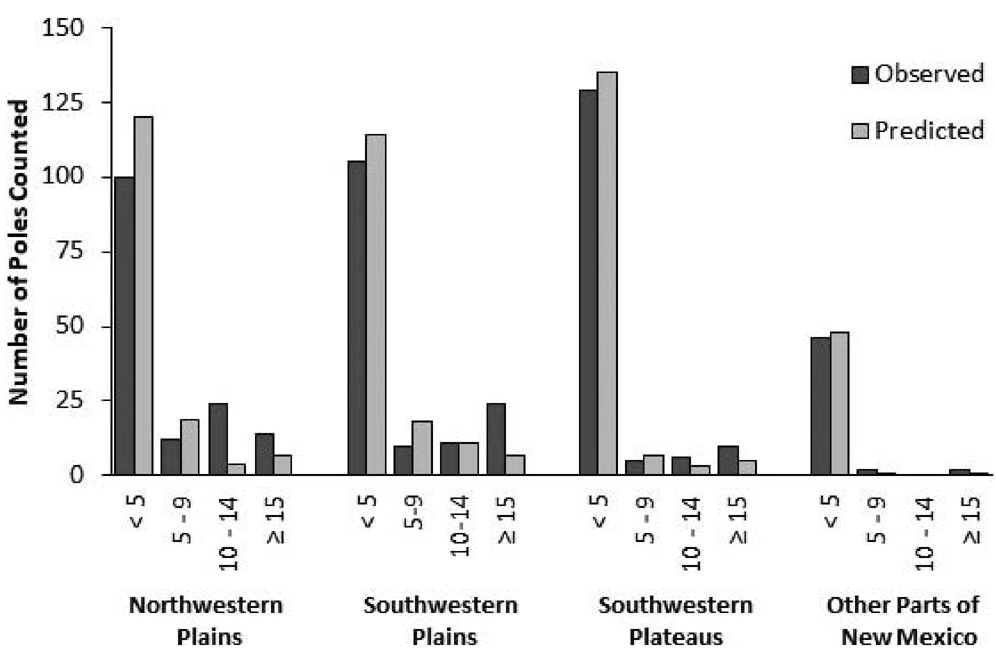

Figure 1. Binned (low, moderate, moderate-high, and high) observed and predicted numbers of poles counted in test cells.

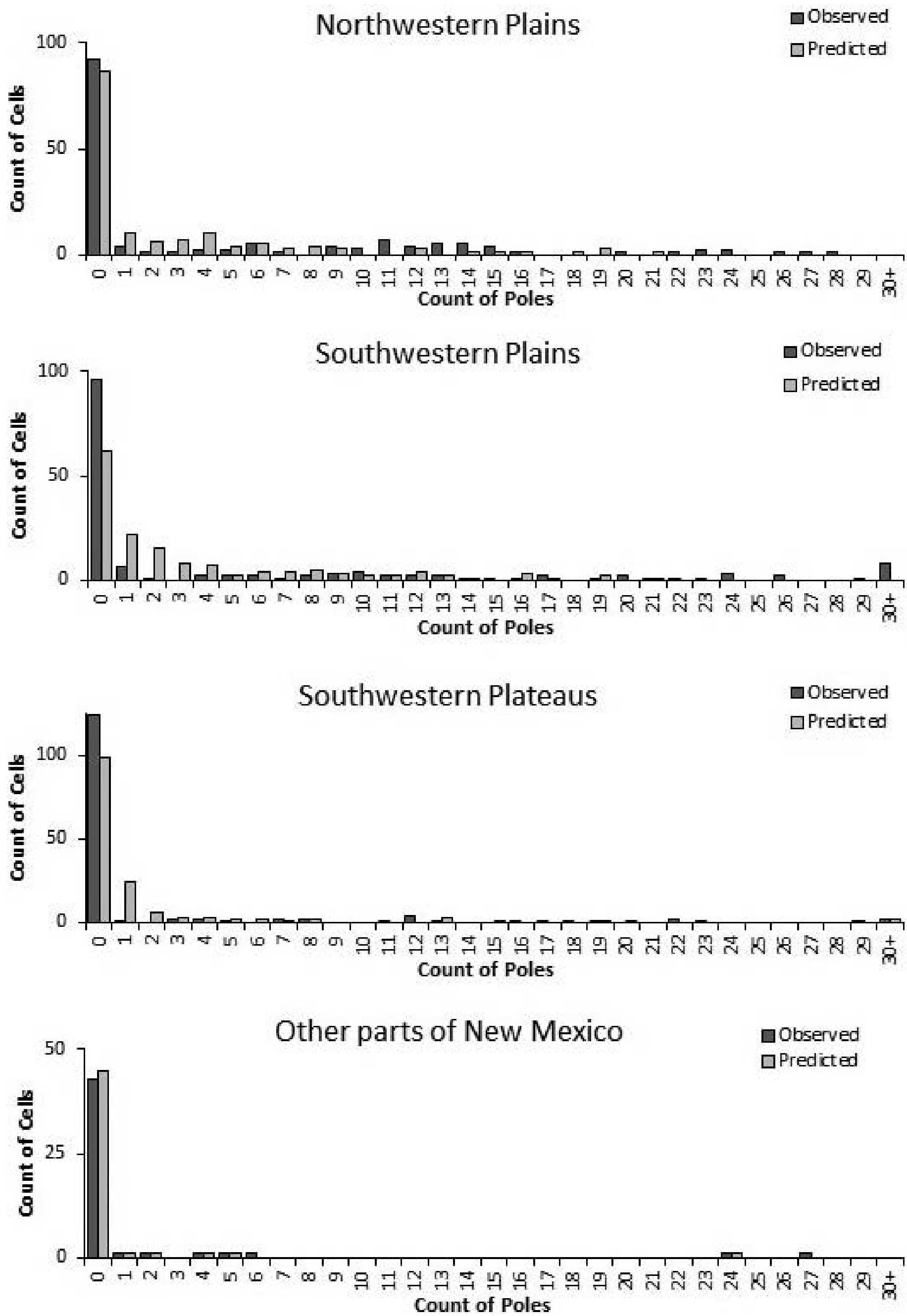

Figure 2. Raw (not binned) observed and predicted numbers of poles counted in test cells.

than the Columbia Plateau model or Great Basin model (Table 2). In the NWPL, the Colorado and Wyoming model predicted 60% of test cells within 1 pole of counted values and predicted 82% of test cells within the correct bin (low <5, medium 5–9, medium-high 10–14, and high ≥15; Fig. 1). The model was generally effective in distinguishing cells without poles from cells with poles but was less

Table 3. Species included in χ^2 comparisons of observed and expected electrocutions at White Sands Missile Range.

SPECIES	SCIENTIFIC NAME	COUNT
Barn Owl	*Tyto alba*	4
Cactus Wren	*Campylorhynchus brunneicapillus*	1
Chihuahuan Raven	*Corvus cryptoleucus*	6
Ferruginous Hawk	*Buteo regalis*	1
Golden Eagle	*Aquila chrysaetos*	12
Greater Roadrunner	*Geococcyx californianus*	2
Great Horned Owl	*Bubo virginianus*	13
Lesser Nighthawk	*Chordeiles acutipennis*	1
Red-tailed Hawk	*Buteo jamaicensis*	12
Swainson's Hawk	*Buteo swainsoni*	3
Unidentified Buteo	*Buteo* spp.	4
Total		**59**

effective in accurately predicting the number of poles present when poles occurred (Fig. 2).

The Colorado and Wyoming model also fit the SWPL in western portions of Nebraska, Kansas, Oklahoma, Texas, and New Mexico better than the

Table 4. Numbers of cells and avian electrocutions; χ^2 tests were conducted with number of cells and actual count data. Expected count data are provided for context.

		AVIAN ELECTROCUTIONS	
PREDICTED POLE DENSITY (PER km^2)	NUMBER OF CELLS	ACTUAL COUNT	EXPECTED COUNT[a]
Great Basin			
<5	9348	45	59
≥5	49	14	0
Colorado and Wyoming			
<5	9279	44	58
≥5	118	15	1
Columbia Plateau			
<5	9276	41	58
≥5	121	18	1

[a] Expected counts are proportional, i.e., 99% of Colorado and Wyoming cells are <5, so 99% of avian electrocutions are expected in cells with <5.

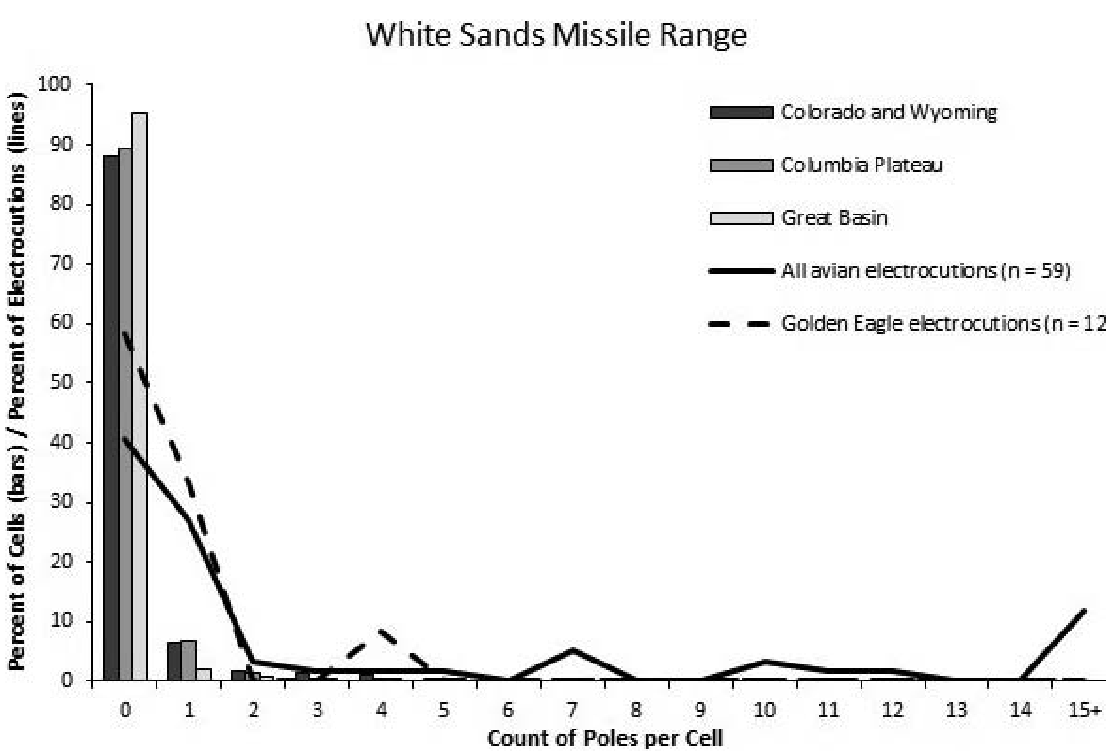

Figure 3. Percent of pole counts and avian electrocutions in 1-km^2 cells throughout White Sands Missile Range. The Golden Eagle electrocutions are a subset of all avian electrocutions.

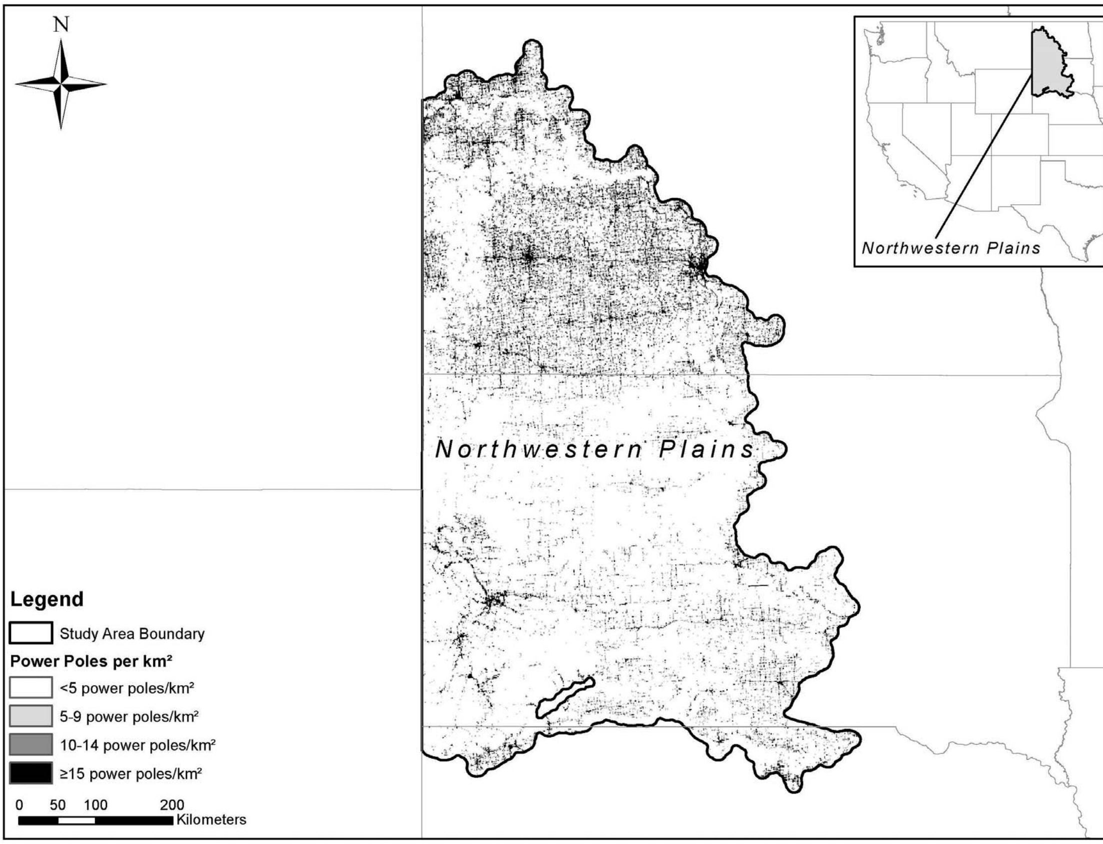

Figure 4. Predicted power pole density from the Colorado and Wyoming model projected to the Northwestern Plains.

Columbia Plateau model or Great Basin model. In the SWPL, the Colorado and Wyoming model predicted 52% of test cells within 1 pole of counted values and predicted 89% of test cells within the correct bin. Although the Colorado and Wyoming model was the best fit for SWPL, the model was not as effective in accurately predicting the absence of poles in SWPL as it was in NWPL.

The Colorado and Wyoming model fit the SWPT better than the Columbia Plateau model or Great Basin model. In the SWPT, the Colorado and Wyoming model predicted 76% of test cells within 1 pole of counted values and predicted 95% of test cells within the correct bin. The Colorado and Wyoming model was better at predicting the absence of poles in SWPT than in SWPL, but not as effective as in NWPL.

The Great Basin model fit OPNM better than the Colorado and Wyoming model or the Columbia Plateau model. In the OPNM, the Great Basin model predicted 88% of test cells within 1 pole of counted values and predicted 96% of test cells within the correct bin. As in the NWPL, the best-fitting model in OPNM was generally effective in distinguishing cells without poles from cells with poles.

Although WSMR was within OPNM where the Great Basin model fit best, we evaluated avian electrocution data at WSMR relative to predicted pole densities from all three models. All models predicted 98–99% of cells within WSMR had low (<5) predicted densities of power poles. If electrocutions occurred at random across the WSMR landscape regardless of pole density, then 58–59 of 59 electrocutions considered (Table 3) would have occurred in cells with low numbers of poles. This was not the case. Instead, electrocutions were less likely than would be expected by chance in cells with low predicted densities of power poles, and higher than expected in cells with moderate to high predicted densities when evaluated with the Great Basin model

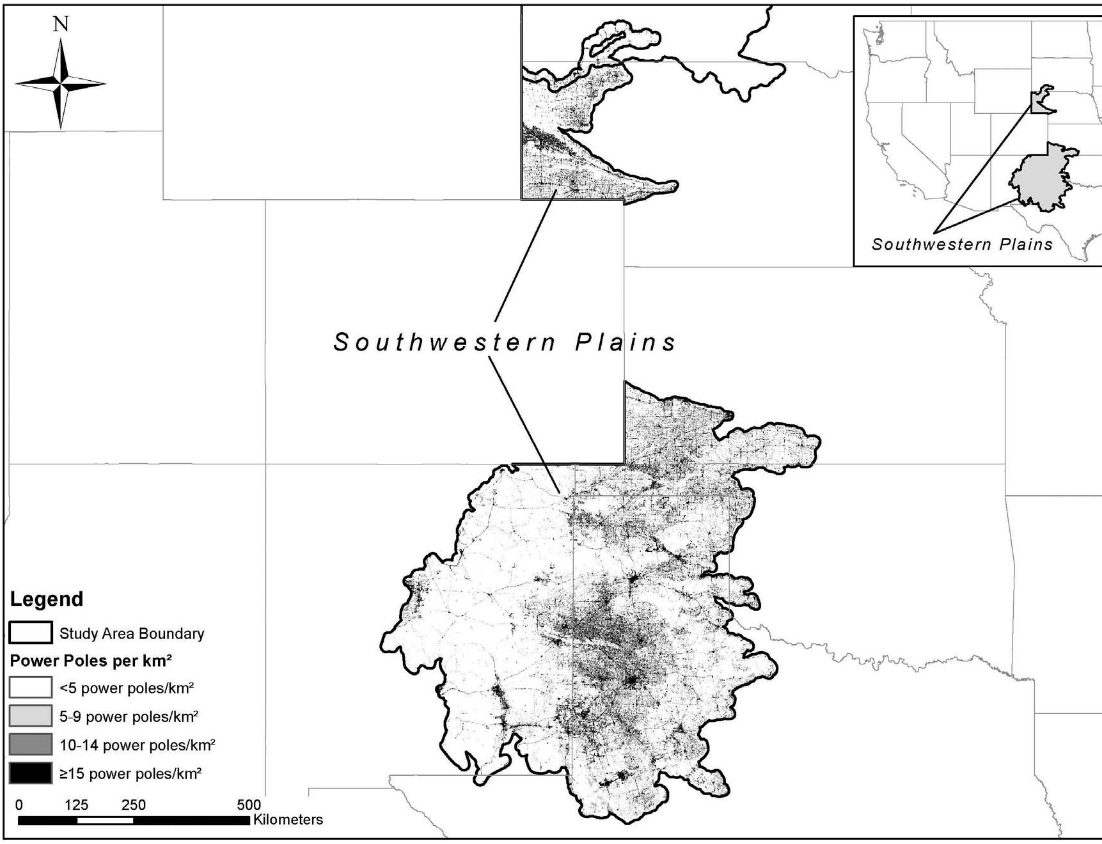

Figure 5. Predicted power pole density from the Colorado and Wyoming model projected to the Southwestern Plains.

(Yates' $\chi^2 = 442.73$, df = 1, $P < 0.001$; Table 4), the Columbia Plateau model (Yates' $\chi^2 = 325.77$, df = 1, $P < 0.001$), or the Colorado and Wyoming model (Yates' $\chi^2 = 229.84$, df = 1, $P < 0.001$). In contrast to this pattern across species, all 12 Golden Eagle electrocutions in the data set occurred in cells with low predicted pole densities across all three models (Fig. 3).

Model Predictions. Application of the best-fitting model to each projected area indicated distinct regions where power pole density was predicted to be high. For example, in the NWPL, pole density was predicted to be highest in the agricultural areas of North Dakota and along the interstate highway (I-90) corridor in South Dakota (Fig. 4). In the SWPL, pole density was predicted to be highest along the state highway (SR-26) corridor in Nebraska, and similar travel corridors in Kansas, Oklahoma, Texas, and New Mexico. High pole densities were also predicted in urban areas of the SWPL, particularly in western Texas and southeastern New Mexico (Fig. 5). In the SWPT, pole density was predicted to be highest wherever urban areas, travel corridors, or agricultural areas occurred within the largely desert landscape (Fig. 6). The same was true of predictions for power poles in the OPNM (Fig. 7). In UBWB, pole density extended smoothly across state lines (Fig. 8). Collectively, the models facilitate predicting distribution power pole density on a 1-km^2 grid throughout much of the western United States (2,573,746 km^2; Fig. 9).

DISCUSSION

We were able to model distribution power pole density throughout much of the western USA. The Colorado and Wyoming model contributed disproportionately to this outcome, likely because the Colorado and Wyoming model was based on the greatest amount of input data, making this model more robust to a wide range of combinations of

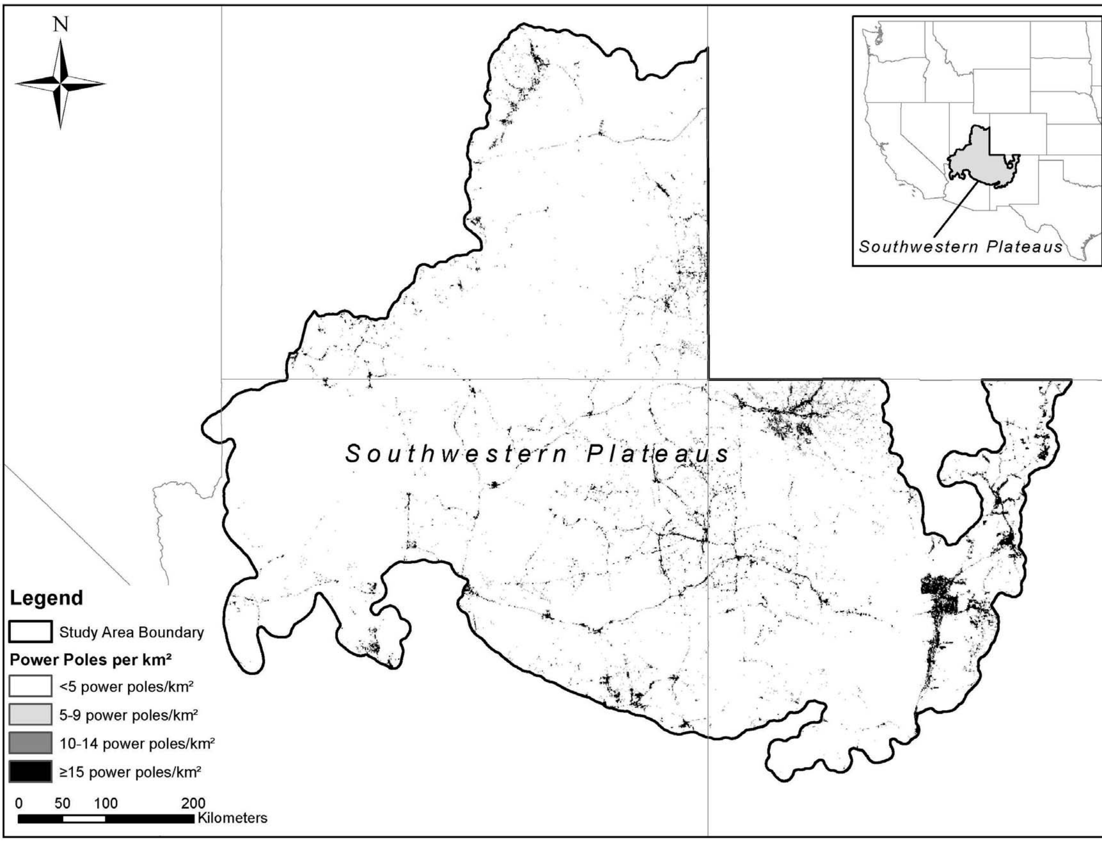

Figure 6. Predicted power pole density from the Colorado and Wyoming model projected to the Southwestern Plateaus.

variables in other areas. Specifically, the Colorado and Wyoming model included pole-density data from 17 electric utilities covering 163,395 km^2 (31%) of Colorado and Wyoming. In contrast, the Columbia Plateau model was developed from a single electric utility covering only 7410 km^2 (6%) of the Columbia Plateau. The Great Basin model also was developed from a single electric utility, although that utility covered 114,000 km^2 (20%) of the Great Basin, and that model fit OPNM best when evaluated across all areas of New Mexico not included in other models, and when focused specifically on avian electrocutions at White Sands Missile Range.

Although none of the ρ values derived from comparing predicted pole counts to actual pole counts indicated very strong correlations ($\rho \geq 0.80$), two were in the strong range ($\rho = 0.60–0.79$), indicating quantitatively supported correlations, and all but two very weak correlations yielded *P*-values of <0.001. The models fit well, but not perfectly. Understanding where and how predicted pole counts differed from actual pole counts is crucial to interpreting the real-world implications for model scores, and critical to distinguishing statistical significance from biological significance in terms of predicting areas of high avian electrocution risk. As in Dwyer et al. (2016, 2017a), the models were generally effective in distinguishing cells with poles from cells without poles but were less effective in accurately predicting actual numbers of poles in cells. Practically, this shortcoming matters little because much of the modeling uncertainty occurred along boundaries between areas without poles and areas with poles. Uncertainty about exact edge locations does not affect the large-scale usefulness of the models because the models are intended as an intermediary step in a process of identifying on a broad scale where conservation actions may be

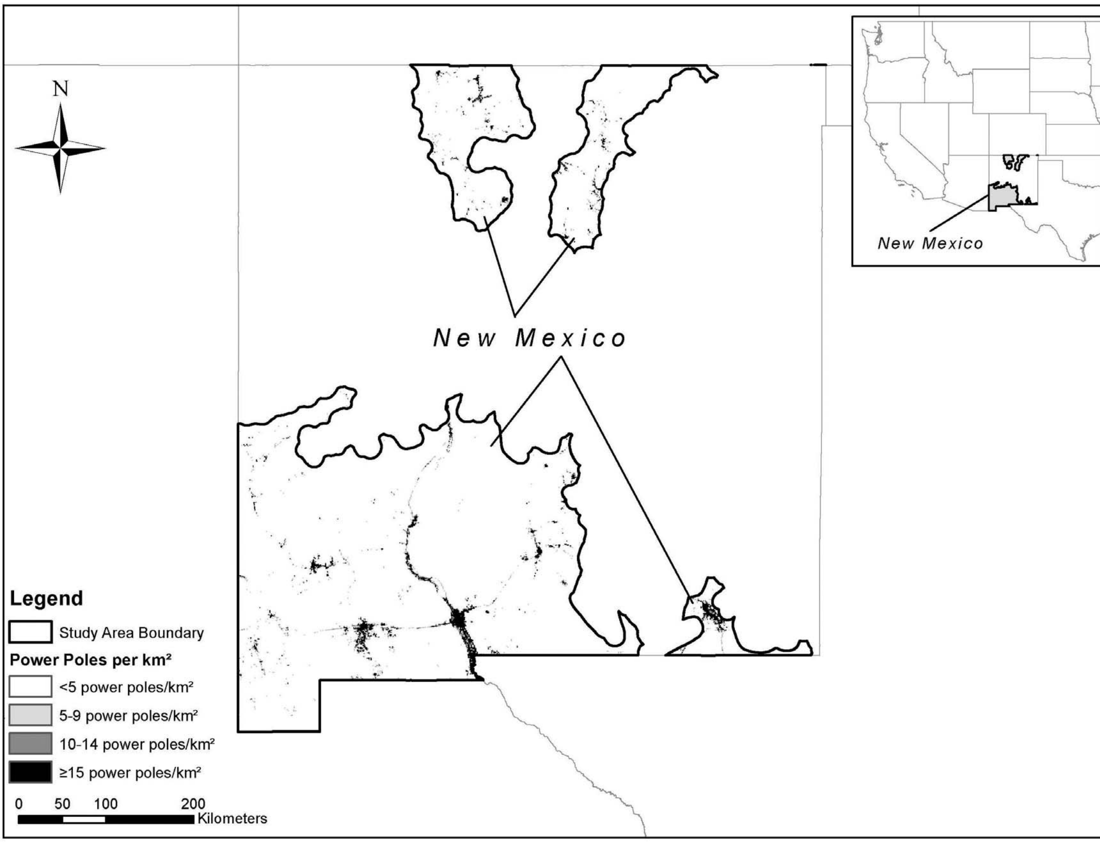

Figure 7. Predicted power pole density from the Great Basin model projected to parts of New Mexico not included in other modeled areas.

needed (Dwyer et al. 2016, 2017a). This step must be followed by coordination with electric utility managers who will know on a local scale the precise boundaries of their electric systems, will know whether poles within local electric systems are already raptor-friendly (Dwyer et al. 2017b), and will know whether local electric systems need to be retrofitted to meet the recommendations of the Avian Power Line Interaction Committee (APLIC 2006).

The results of our comparison of predicted pole densities in White Sands Missile Range to actual electrocutions indicated more electrocutions than would be expected due to chance in cells with moderate and high predicted pole densities, i.e., avian electrocution risk increased with increasing pole density. This was useful in evaluating our modeling approach, and in confirming the relationship between pole density and electrocution risk previously identified by Tintó et al. (2010) and Perez-García et al. (2011) and previously assumed by Dwyer et al. (2016, 2017a). However, the relationship between electrocution risk and pole density did not hold for Golden Eagles at WSMR. This may have occurred because of the unique mission-based design of the electric system at WSMR, where isolated power poles often occur far from other infrastructure and, in an otherwise undeveloped desert habitat, far from other natural elevated perch locations in a way that is inconsistent with power poles used in civilian applications like urban areas, farm lands, or energy extraction facilities. In contrast, Bedrosian et al. (2020) found a strong correlation for electrocution risk of Golden Eagles when pole density and habitat were considered together, and Crespo-Luengo et al. (2020) found a

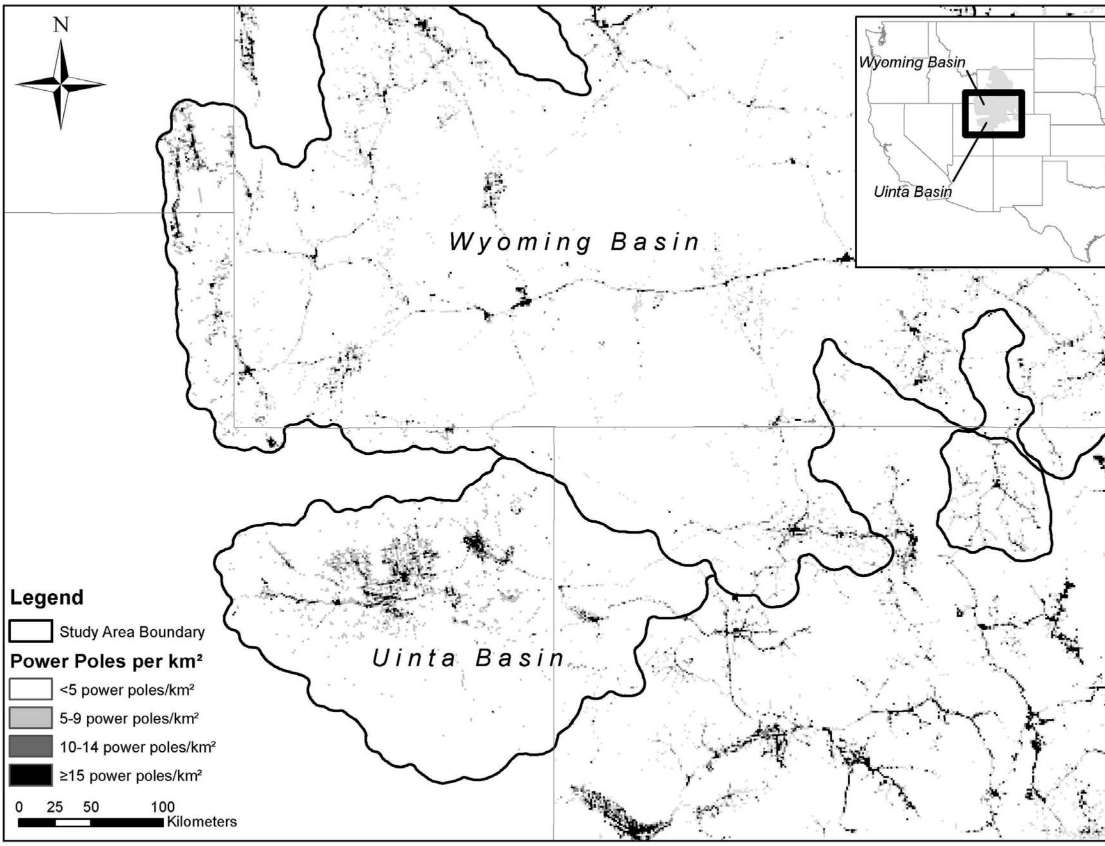

Figure 8. Predicted power pole density from the Colorado and Wyoming model projected to parts of the Uinta Basin and Wyoming Basin extending beyond Colorado and Wyoming state lines.

strong correlation between electrocution risk and poles in breeding habitat. This illustrates the importance of understanding the behavior and ecology of the particular species of concern when seeking to apply our pole-density models to conservation. For example, viewing these models together with information on Bald Eagle (*Haliaeetus leucocephalus*) or Osprey (*Pandion haliaetus*) habitat would likely indicate an entirely different set of areas around water bodies where electrocution of these species might be occurring (as in Mojica et al. 2009).

Given the success of the pole-density models, future research should consider mapping all of the western United States with the Colorado and Wyoming model to fill in gaps between existing modeled areas. This could occur in any of at least three ways. First, a similar process to that described here could be applied elsewhere. Second, the data used to create the three models described here could be used to create one meta-model that might apply better throughout the western United States. Third, new data could be used to create new models of distribution pole density. We suggest that a combination of these approaches consolidating new data from California with existing data from Colorado and Wyoming, the Great Basin, and the Columbia Plateau into a single seamless model might provide the best path forward for protecting birds from electrocution throughout the western United States.

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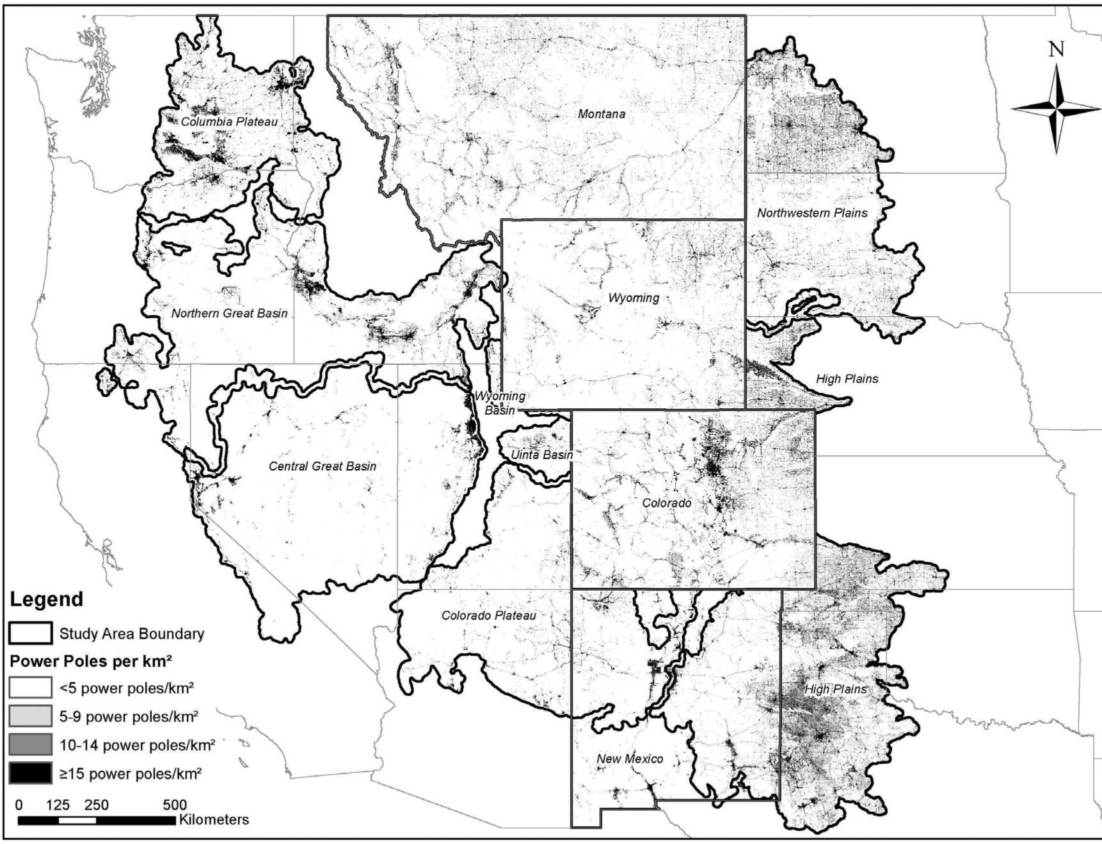

Figure 9. Predicted power pole density across much (2,573,746 km^2) of the western United States using the Colorado and Wyoming; the Great Basin; and the Columbia Plateau models.

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