



Predictive Model of Avian Electrocution Risk on Overhead Power Lines

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Abstract: *Electrocution on overhead power structures negatively affects avian populations in diverse ecosystems worldwide, contributes to the endangerment of raptor populations in Europe and Africa, and is a major driver of legal action against electric utilities in North America. We investigated factors associated with avian electrocutions so poles that are likely to electrocute a bird can be identified and retrofitted prior to causing avian mortality. We used historical data from southern California to identify patterns of avian electrocution by voltage, month, and year to identify species most often killed by electrocution in our study area and to develop a predictive model that compared poles where an avian electrocution was known to have occurred (electrocution poles) with poles where no known electrocution occurred (comparison poles). We chose variables that could be quantified by personnel with little training in ornithology or electric systems. Electrocutions were more common at distribution voltages (≤ 33 kV) and during breeding seasons and were more commonly reported after a retrofitting program began. Red-tailed Hawks (*Buteo jamaicensis*) ($n = 265$) and American Crows (*Corvus brachyrhynchos*) ($n = 258$) were the most commonly electrocuted species. In the predictive model, 4 of 14 candidate variables were required to distinguish electrocution poles from comparison poles: number of jumpers (short wires connecting energized equipment), number of primary conductors, presence of grounding, and presence of unforested unpaved areas as the dominant nearby land cover. When tested against a sample of poles not used to build the model, our model distributed poles relatively normally across electrocution-risk values and identified the average risk as higher for electrocution poles relative to comparison poles. Our model can be used to reduce avian electrocutions through proactive identification and targeting of high-risk poles for retrofitting.*

Keywords: avian protection plan, California, corvid, logistic regression, raptor

Modelo Predictivo del Riesgo de Electrocución de Aves en Líneas Eléctricas Elevadas

Resumen: *La electrocución en estructuras de energía elevadas afecta negativamente a poblaciones de aves en diversos ecosistemas en todo el mundo, contribuye al riesgo de poblaciones de rapaces en Europa y África, y es una causa importante de acción legal contra empresas eléctricas en Norte América. Investigamos los factores asociados con la electrocución de aves para que postes que posiblemente electrocuten a una ave sean identificados y sean acondicionados antes de que causen mortalidad de aves. Utilizamos datos históricos del sur de California para identificar patrones de electrocución de aves por voltaje, mes y año para identificar las especies que mueren más frecuentemente por electrocución en nuestra zona de estudio y desarrollar un modelo predictivo que comparó postes en los que se sabía había ocurrido una electrocución (postes de electrocución) con postes en los que no hubo electrocución (postes de comparación). Seleccionamos variables que pudieran ser cuantificadas por personal con poco entrenamiento en ornitología o sistemas eléctricos. Las electrocuciones fueron más comunes en voltajes de distribución (≤ 33 kV) y durante épocas reproductivas y fueron reportadas más comúnmente después de que comenzó un programa de acondicionamiento. Las especies electrocutadas más frecuentemente fueron *Buteo jamaicensis* ($n = 265$) *Corvus brachyrhynchos* ($n = 258$). En el modelo predictivo, se requirieron 4 de 14 variables consideradas para distinguir los postes de comparación de los postes de comparación: número de puentes (cables cortos que conectan equipo energizado), número de conductores primarios, presencia de conexiones a tierra y presencia de áreas deforestadas y no pavimentadas*

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dominantes en la cobertura de suelo cercana. Al probarlo con una muestra de postes no utilizados para construirlo, nuestro modelo distribuyó los postes normalmente en los valores de riesgo de electrocución e identificó el riesgo promedio más alto para postes de electrocución en relación con los postes de comparación. Nuestro modelo puede ser usado para reducir electrocuciones de aves mediante la identificación proactiva de postes con alto riesgo.

Palabras Clave: California, córvido, plan de protección de aves, rapaz, regresión logística

Introduction

Anthropogenic structures including buildings, cell-phone towers, and electrical infrastructure cause millions of bird deaths annually (Longcore et al. 2012; Loss et al. 2012). Conservation efforts can reduce effects but must be carefully targeted to be cost-effective. Avian protection plans (APPs) are used to identify high-risk electrical infrastructure (APLIC & USFWS 2005; APLIC 2006). Raptors often are the focus of APPs because the large size of many raptors increases their electrocution risk and because persistent electrocution mortality has been implicated in raptor population declines in Europe (Real et al. 2001; Sergio et al. 2004), Asia (Harness et al. 2008; Karyakin et al. 2009; Goroshko 2011), and Africa (Angelov et al. 2012) and in disruptions to social structure in North America (Dawson 1988). Avian electrocutions have been extensively documented in North America (e.g., Harness & Wilson 2001; APLIC 2006; Dwyer & Mannan 2007) Europe (Tintó et al. 2010; Guil et al. 2011; López-López et al. 2011), Asia (Harness et al. 2008; Karyakin et al. 2009; Goroshko 2011), Africa (Van Rooyen et al. 2003; Boshoff et al. 2011), and New Zealand (Fox & Wynn 2010). Electrocution incidents can affect an electric system's reliability by causing outages (Harness & Wilson 2001; APLIC 2006), equipment damage (Van Rooyen et al. 2003; APLIC 2006), and fires (Lehman & Barrett 2002).

Avian electrocutions occur where horizontal separation between conductors with different energy levels, including adjacent conductors at the same voltage on a single pole, or conductors and grounds are less than the distance between the distal tips of the carpal bones on each wing when the wings are spread (APLIC 2006). Avian electrocutions also occur where vertical separation of conductors, or conductors and grounds, are less than the head-to-foot length of a bird (APLIC 2006). Electric utilities retrofit high-risk poles to minimize electrocution risks (e.g., Harness & Wilson 2001; Dwyer & Mannan 2007). Retrofitting typically involves installing insulating covers on or increasing separation around energized equipment (APLIC 2006). Typically, poles most in need of retrofitting support energized equipment such as transformers and surge arresters and occur in areas where raptors forage and nest (Harness & Wilson 2001; APLIC 2006; Dwyer & Mannan 2007). Identification of high-risk poles often relies on gestalt-based evaluations conducted by experts familiar with both avian ecology and overhead electric systems. Quantitative modeling of electrocution

risk is less common but has been undertaken in some areas (Schomburg 2003; Tintó et al. 2010; Guil et al. 2011), and it offers increased consistency and transparency in identification of high-risk poles (BRC 2008).

Historical data provided by electric utilities can be useful in identifying patterns in avian electrocutions (Pérez-García et al. 2011). We used historical data provided by Southern California Edison (SCE) to identify patterns in avian electrocutions and to develop a logistic-regression model designed to predict electrocution risk on individual utility poles. We used simple descriptor variables in our model to increase the utility of the model to personnel lacking extensive ornithological or electrical backgrounds. We hypothesized that SCE's historical data would reveal significant differences in avian electrocutions by voltage, year, and month. We also hypothesized that some combination of simple variables could be used to distinguish between poles where an avian electrocution was known to have occurred (electrocution poles) from poles where an avian electrocution was not known to have occurred (comparison poles).

Methods

Study Area

Our study area was SCE's 129,500-km² service area, including all or parts of Fresno, Inyo, Kern, Kings, Los Angeles, Orange, Riverside, San Bernadino, Santa Barbara, Tulare, Tuolumne, and Ventura Counties in central, coastal, and southern California (Fig. 1). SCE's service area in Fresno and Tuolumne Counties was in mountainous conifer-forested portions of the Sierra bioregion (FRAP 2006). The service area in Inyo and San Bernadino Counties was in the Mojave Desert of the Mojave bioregion, and in Kern and Kings Counties the service area was primarily in agricultural, grassland, and desert shrubland. In Los Angeles and Orange Counties, the service area was dominated by urban landscapes and ringed by mountainous shrublands typical of the South Coast bioregion. Shrubby areas extended into the southwestern corner of San Bernadino County and the western half of Riverside County. Santa Barbara and Ventura Counties were composed largely of rolling hills supporting a mosaic of suburban areas interspersed with shrubby natural landscapes. The service area in Tulare County was in agricultural, herbaceous, and hardwood and coniferous forest (FRAP 2006). Thus, our study area incorporated diverse

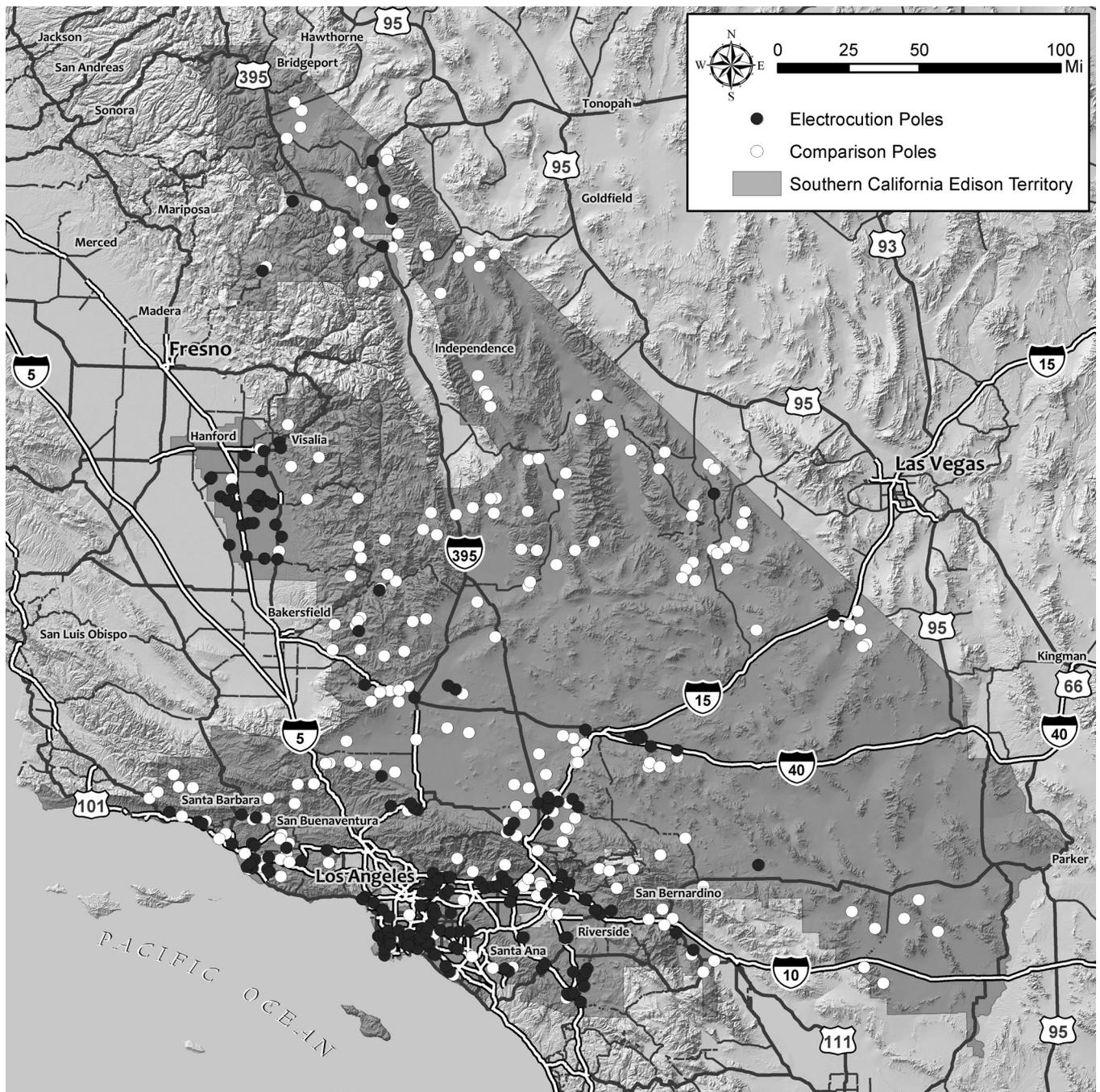


Figure 1. Locations of power poles in California (U.S.A.) where corvids or raptors were electrocuted and comparative data were collected from poles not known to have been involved in an avian electrocution.

environments reflective of numerous ecosystems where avian electrocutions have been reported worldwide (Lehman et al. 2007).

Electrocution Records

SCE personnel regularly assess the overhead electric lines within the SCE service area to verify all equipment is intact and functioning. During these assessments and in response to outages, avian carcasses resulting from

electrocution are sometimes encountered. As part of an APP, SCE documents these events. We identified 2098 avian electrocutions by consolidating electrocution records collected by SCE personnel from September 1981 through December 2009. We examined these records for patterns in avian electrocutions by voltage, year, and month and identified the species and species groups that were most often electrocuted. We used the chi square test command in program R (The R Foundation for Statistical Computing, Vienna, Austria) to test for

differences in the proportions of electrocutions on the basis of voltage, year, and month. The null hypothesis was electrocutions are proportional to exposure in voltage, year, and month. For example, we hypothesized that across years, 8.3% of electrocutions occur in each calendar month (because $12 \text{ months} * 8.3\% = 100\%$). We considered differences significant at $\alpha = 0.05$.

Predictive Modeling

Avian electrocution studies typically focus on raptor species (Lehman et al. 2007; Pérez-García et al. 2011). Corvids are not usually included as focal species, but their deaths are often noted when authors report all electrocutions (e.g., Dwyer & Mannan 2007; Harness et al. 2008; Ferrer 2012). Because corvids can be associated with outages and equipment damage just as raptors can, inclusion of corvids could be useful to electric utilities developing and implementing APPs. We thought inclusion of corvids might also substantially affect scientific conclusions and subsequently expand overall understanding of avian electrocution. Corvids can occupy more urban areas than some raptors. This fact affects interpretation of our results overall and our land cover variable in particular and is addressed in detail in the Discussion.

Of 2098 unique records of avian electrocution, 440 occurred on power poles that were still in service, and of these we randomly sampled 215 electrocution poles. We compared electrocution poles with 248 randomly sampled comparison poles. To select comparison poles, we generated random coordinates within SCE's service area and sampled the closest accessible pole to each random location. The possibility that some comparison poles may have caused an undocumented electrocution is addressed in the Discussion. We collected data on 14 independent variables (described below) at each electrocution and comparison pole we visited. Because we had no prior information on the likely importance of these variables, we decided a priori to model all possible combinations of potentially influential variables. When modeling all possible combinations, the number of candidate models increases exponentially with the number of variables. To reduce the number of candidate models, we used univariate χ^2 analyses to identify potentially influential variables (Hosmer & Lemeshow 1989; Dwyer et al. 2012). To minimize the risk of accidentally excluding influential variables, we used $P \leq 0.50$ from univariate analyses as a cutoff for inclusion in multivariate modeling (Hosmer & Lemeshow 1989).

Each of the variables included in candidate modeling were selected because they were independent of other variables, were indicated as influential in other studies (Platt 2005; APLIC 2006; BRC 2008), or were believed to be of potential importance on the basis of our experience developing APPs (Harness & Wilson 2001; Harness & Nielsen 2006; Dwyer & Mannan 2007).

We used multivariate logistic regression to evaluate the simultaneous effects of multiple variables on the probability that a pole would electrocute a corvid or raptor. Each candidate model represented a competing hypothesis regarding variables that affect avian electrocutions. We used the logit link in the *glm* package (Calcagno & de Mazancourt 2010) of program R to model all possible subsets of variables, to rank models with Akaike's information criterion corrected for small sample size (AIC_c) (Anderson 2008), and to calculate an averaged model, averaged estimates of model parameters ($\hat{\beta}$'s), and estimates of error for $\hat{\beta}$. We used the binary logistic-regression option in Minitab 16 (Minitab, State College, Pennsylvania) to conduct a Hosmer-Lemeshow goodness-of-fit test. We used AIC_c scores to rank and weight models (Burnham & Anderson 2004; Burnham et al. 2011). We report $\hat{\beta}$ estimates and standard error estimates for a weighted average model on the basis of values from all candidate models because weighted model averaging provides the optimal method of constructing a final model that accounts for uncertainty in model selection (Burnham & Anderson 2004).

We used data from 80% of sampled poles to create candidate models and our final averaged model and data from 20% of sampled poles to validate our final averaged model (out of sample cross-validation; Tintó et al. 2010). We randomly assigned poles to be used in either model building or validation. Because species did not contribute equally to our data set, we did not assume the final averaged model would necessarily predict electrocution risk with equal accuracy for each species. To identify species best fit and least fit by the final averaged model, we compared prediction probabilities by species from poles used for out of sample cross validation. We assumed species with average prediction values closer to the average prediction value for electrocution poles than comparison poles used in cross-validation fit the final model well. We assumed species with average prediction values closer to the average prediction for comparison poles than electrocution poles used in cross-validation fit the model less well.

In predictive modeling, we distinguished important variables as those with weights ≥ 0.99 . Four of 14 candidate variables were necessary to distinguish electrocution from comparison poles (see Results), and they are described in detail below: number of jumpers, number of primary conductors, presence of grounded equipment, and presence of unforested, unpaved areas as the dominant nearby land cover. The remaining 10 variables are described briefly below and in detail online (Supporting Information).

We counted the number of jumpers on each pole. Jumpers are the wires linking pieces of pole-mounted equipment to one another and to primary conductors running from pole to pole. Pole-mounted equipment including transformers, surge arresters, etc. are regularly

associated with avian electrocution (APLIC 2006; Dwyer & Mannan 2007; Harness et al. 2008). Counting jumpers allowed us to incorporate all pole-mounted equipment into a single variable. Incorporating highly correlated variables in modeling can lead to bias in estimation of parameter coefficients. Our approach avoided the lack of independence that would have occurred if we had recorded each type of energized equipment separately. Counting jumpers also minimized the background electrical knowledge required to describe a pole.

We also counted the number energized primary conductors on each pole. Typically there were 1–3, but some poles supported multiple sets of separate primary conductors (e.g., multicircuit distribution poles and under-build configurations where transmission and distribution circuits occurred one above the other). The number of primary conductors on a pole has been identified as contributing to electrocution risk (APLIC 2006), but does not appear to have been explicitly included in any existing models (Sergio et al. 2004; Guil et al. 2011).

We identified grounded equipment on each pole, including grounded metal brackets, grounded guy wires, pole-top grounds, overhead neutral wires, and metal and concrete poles. Presence of grounded equipment consolidated these pieces of equipment in one variable so personnel lacking expertise in overhead electric systems need only identify whether there is a wire that runs continuously from at least as high as the lowest energized part of the pole to the ground. This variable excluded grounding associated with energized equipment such as transformers because electrocution risks associated with equipment were reflected in the number of jumpers. The presence of grounding on a pole affects electrocution probability (Mañosa 2001; Harness et al. 2008; Gerdzhikov & Demerdzhiev 2009), but grounding has typically been modeled only as a function of pole type. To our knowledge, this concept has not been expanded to pole-top ground wires, uninsulated grounded guy wires, and overhead neutral wires, although each of these components is regularly considered in APPs and risk assessments (APLIC 2006; Harness & Nielsen 2006).

We used the presence of unforested unpaved area as the dominant nearby land cover to describe the general land cover within 200 m of each pole. We estimated presence of this land cover visually while standing at the base of the pole. If $\geq 50\%$ of the landcover within 200 m of the pole was covered by vegetation ≤ 1 m tall, we considered the land cover open and unpaved and recorded a value of 1. If vegetation was > 1 m tall or the land was paved, we recorded a value of 0. This variable was intended to facilitate rapid use by electric-utility personnel who may not have extensive ecology training. We selected this variable because some studies identify open environments as a risk factor (Schomburg 2003; Sergio et al. 2004; Tintó et al. 2010), whereas others show urban

areas have high electrocution rates (Dwyer & Mannan 2007; Guil et al. 2011).

The following variables were not significant in univariate analyses and so are described only briefly here. Count of canopy heights was the total number of canopy heights within 200 m of the pole. Presence or absence of deadends indicated whether a primary conductor terminated at the pole. Presence or absence of primary conductors on top of pole indicated whether an energized primary conductor occurred on the pole top or uppermost crossarm. Presence or absence of commanding view indicated whether a pole occurred on flat ground, the base of a topographic rise, or on the side or top of a topographic rise. Presence of public land indicated the base of a pole could be viewed without crossing a private fenceline. Presence of prey occurrence or raptor use consolidated observations of corvids and raptors and their sign or prey on or near poles. Effective height sum estimated the difference between the height of the pole being evaluated and the height of the adjacent poles. Arm orientation described the orientation of the crossarm relative to the assumed prevailing wind. Presence of guy wire indicated the presence of an ungrounded guy wire. Presence of metal crossarms indicated the presence of a metal crossarm.

Results

Electrocution Records

We identified 2098 avian electrocutions. Most occurred at distribution voltages (≤ 33 kV) rather than subtransmission (55–66 kV) or transmission (≥ 115 kV) voltages ($\chi^2 = 3269.93$, $df = 2$, $P < 0.001$). There was an 1880% increase in the average number of electrocutions recorded from 2000 through 2009 (94.3%, \bar{x} [SD] = 197.9 [31.841]) versus 1981 through 1999 (5.7%, $\bar{x} = 10$ [6.037]). Electrocutions were more likely during May through August (positive residuals for each month; Fig. 2) than during September through April (negative residuals for each month; $\chi^2 = 356.715$, $df = 11$, $P < 0.001$). Among records where a species was identified, Red-Tailed Hawks (*Buteo jamaicensis*) ($n = 265$) and American Crows (*Corvus brachyrhynchos*) ($n = 258$) were the most commonly identified species. Many records described the species only as “bird” ($n = 612$) or “bird nonraptor” ($n = 433$), and these 2 categories together accounted for 48.2% of records. Electrocutions involving corvids occurred at 44.6% of the electrocution poles visited, and most of those electrocutions (77.9%) occurred where unforested unpaved areas were not the dominant nearby land cover ($\chi^2 = 29.568$, $df = 1$, $P < 0.001$). Rather, these events tended to occur in areas dominated by pavement (i.e., urban areas). Electrocutions involving *Buteo* species ($n = 352$, primarily Red-Tailed Hawks) were not disproportionately associated with presence of unforested

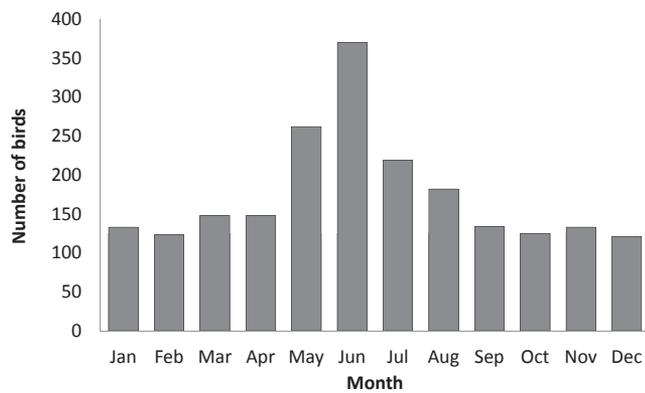


Figure 2. Electrocutations of corvids and raptors on overhead power lines in Southern California in 1981-2009.

unpaved area as the dominant nearby land cover, forested or paved land covers ($\chi^2 = 0.710$, $df = 1$, $P < 0.399$), or the presence of owls ($n = 147$, $\chi^2 = 2.286$, $df = 1$, $P < 0.399$). Electrocutations of Golden Eagles (*Aquila chrysaetos*) and Bald Eagles (*Haliaeetus leucocephalus*) tended to occur on poles where unforested unpaved areas were the dominant nearby land cover ($n = 47$, $\chi^2 = 17.191$, $df = 1$, $P < 0.001$).

Predictive Modeling

We visited 213 electrocution poles and 248 comparison poles from 10 through 22 May 2011 and from 1 through 6 November 2011. Univariate analyses indicated 10 of the 14 candidate variables had $P < 0.50$; thus, these

10 variables met the criteria for inclusion in multivariate modeling (Table 1). We subsequently constructed 1024 candidate models. The Hosmer-Lemeshow goodness-of-fit test for the full 10-variable model indicated QAIC (i.e., quasi AIC, used in analyses of overdispersed count data) was unnecessary ($\chi^2_8 = 2.603$, $n = 461$, $P = 0.957$), so we used AIC_c corrected for small sample size to rank models (Supporting Information). More complex models tended to have lower AIC_c scores. However, standard errors for many of the variables in the models overlapped zero, indicating these variables contributed minimally to the model as a predictor. Averaging over all models indicated only 4 variables were necessary to predict avian electrocution risk:

$$Y = -0.93167 + (0.09048 \times \text{number of jumpers}) + (0.14506 \times \text{number of primary conductors}) + (0.53203 \times \text{grounding present}) - (0.55151 \times \text{unforested unpaved area dominant}), \quad (1)$$

where Y is the model output to be transformed into probability of electrocution via Eq. 3 (below).

The revised model successfully distinguished electrocution from comparison poles. Specifically, the average probability of avian electrocution was higher for electrocution poles than for comparison poles ($F_{1,90} = 20.65$, $P < 0.001$; mean electrocution poles [SE] = 0.556 [0.021]; mean comparison poles = 0.418 [0.022]). The model also distributed poles relatively normally across risk values (Fig. 3). The average prediction probability for poles used in cross-validation where American Crows ($n = 19$), Great-horned Owls (*Bubo virginianus*) ($n = 2$), Red-shouldered hawks (*Buteo lineatus*) ($n = 1$), and Red-tailed Hawks ($n = 10$) were electrocuted was closer to

Table 1. Results of univariate analyses of environmental variables and variables specific to electrical poles^a and results of multivariate analyses indicating model-averaged parameter estimates^b ($\hat{\beta}$) and relevance of variables to avian electrocution risk in southern California.

Variable ^c	χ^2	P	Selected for multivariate modeling	$\hat{\beta}$	SE	Importance (sum of weights)
Intercept	NA	NA	NA	-0.932	0.354	1.000
Number of jumpers	91.930	<0.000	yes	0.091	0.020	1.000
Number of primary conductors	61.080	<0.000	yes	0.145	0.047	0.993
Presence of grounding	20.644	<0.000	yes	0.532	0.153	0.997
Presence of unforested unpaved areas	12.231	0.001	yes	-0.552	0.1634	0.996
Number of canopy heights	33.340	<0.000	yes	0.033	0.050	0.440
Primary conductor terminating on pole (deadend)	29.820	<0.000	yes	-0.121	0.177	0.465
Presence of primary conductors on top of pole	25.839	<0.000	yes	-0.172	0.202	0.574
Presence of commanding view	12.850	<0.000	yes	-0.229	0.192	0.728
Presence of public land	7.318	0.007	yes	-0.024	0.080	0.276
Presence of prey or raptor use	6.244	0.013	yes	0.234	0.217	0.687
Effective height of adjacent poles (sum)	0.390	0.532	no	NA	NA	NA
Arm orientation	0.380	0.536	no	NA	NA	NA
Presence of guy wire	0.335	0.563	no	NA	NA	NA
Presence of metal crossarms	0.157	0.692	no	NA	NA	NA

^aVariables with $P \leq 0.50$ were included in multivariate modeling.

^bFrom final averaged model.

^cJumpers are the wires linking pieces of pole-mounted equipment to one another and to primary conductors running from pole to pole. Number of canopy heights is the total number of canopy heights within 200 m of the pole as estimated visually from the base of the pole.

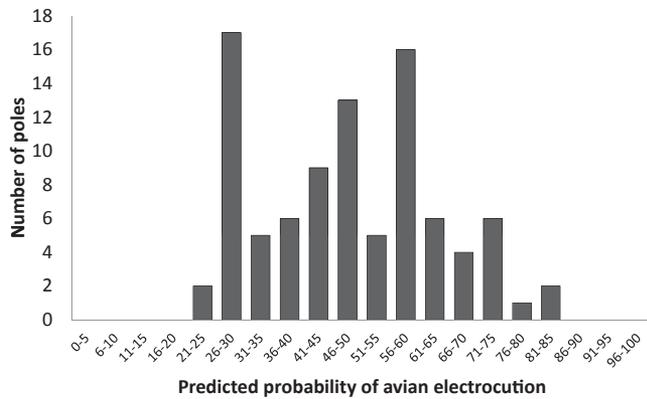


Figure 3. Probability of raptor and corvid electrocution by overhead powerlines relative to the number of poles present.

the average prediction probability for incident poles used in cross-validation than it was to the average prediction probability for comparison poles. The average prediction probability for poles used in cross-validation where Common Ravens (*Corvus corax*) ($n = 4$), Turkey Vultures (*Cathartes aura*) ($n = 2$), and Golden Eagles ($n = 3$) were electrocuted was closer to the overall electrocution probability for comparison poles than for electrocution poles.

Discussion

Electrocution Records

Distribution voltage poles were most commonly implicated in avian electrocutions here and in previous studies (Harness & Wilson 2001; APLIC 2006; Dwyer & Mannan 2007). This occurred because conductors were closer to one another and to paths to ground at lower voltages; thus the likelihood that a bird could simultaneously contact two points of different electric potential increased. Retrofitting should focus on these structures. When strategies are implemented to prevent avian electrocution, new awareness training and reporting mechanisms are typically used (APLIC & USFWS 2005). These mechanisms can lead to increases in the number of reported electrocutions even as the number of actual electrocutions declines (Dwyer & Mannan 2007). The increase in detection of electrocutions we found in 2000 through 2009 relative to 1981 through 1999 likely reflected this increased awareness. The relatively high number of electrocutions from May through August correlated with breeding and fledging seasons. Birds tend to have relatively low survival at fledging because individuals must adapt to a complex suite of risks not previously encountered (Kershner et al. 2004). Among this suite of risks is electrocution, and results of previous studies

show electrocution rates are higher during breeding seasons for both breeding birds and their young (Harness & Wilson 2001; Platt 2005; Dwyer & Mannan 2007). Thus, the difference in electrocutions by month reported here is consistent with results of previous studies.

Predictive Modeling

Our predictive model can be used to investigate the effects of model parameters on the probability that the electrocution of a corvid or raptor will occur. The probability of an avian electrocution increased 1.0–2.3% with each additional jumper and 2.0–3.5% with each additional primary conductor (Fig. 4a). The probability of an electrocution increased 4.0–13.0% with the addition of pole-top grounding and increased 4.5–13.7% when un-forested unpaved areas where not the dominant nearby land cover (Fig. 4b). Overall, poles in un-forested unpaved areas (i.e., urban areas) with many jumpers and primary conductors and the presence of grounding had relatively

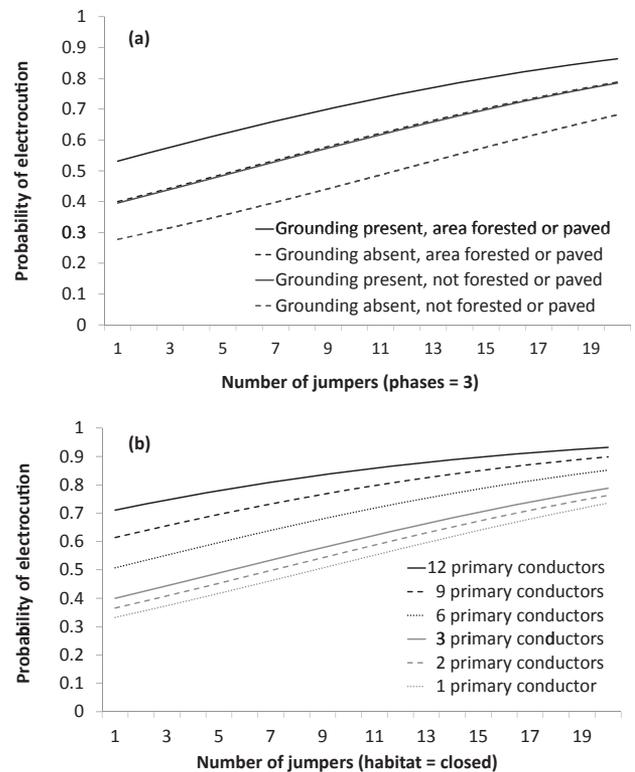


Figure 4. Probability that a power pole will electrocute a corvid or raptor in Southern California as a function of the number of jumpers (i.e., wires linking pieces of pole-mounted equipment to one another and to primary conductors running from pole to pole) and (a) the presence of grounding on a pole and the presence of un-forested unpaved areas as the dominant land cover within 200 m of a pole and (b) number of primary conductors on a pole.

high probabilities of being involved in an electrocution. Poles in undeveloped areas with few jumpers and primary conductors and no grounding had low probabilities of being involved in an avian electrocution. The role of unforested unpaved areas in our model was largely a function of the high proportion of American Crow and Red-tailed Hawk electrocutions contributing to the data set. These two species occur commonly in urban landscapes, and this result highlights the importance of including urban-adapted species in electrocution studies. Overall our model distinguished between electrocution and comparison poles well, but the model nevertheless identified some electrocution poles as relatively low risk and some comparison poles as relatively high risk. This apparent paradox likely occurred because even low-risk poles can electrocute birds (Harness & Wilson 2001; APLIC 2006; Dwyer & Mannan 2007) and because some comparison poles could have been involved in an undocumented avian electrocution.

Implications for APPs

All poles in an overhead electric system are not equally likely to electrocute a bird (Harness & Wilson 2001; APLIC 2006). Thus, to minimize avian electrocution it is important to identify high-risk poles so electric utilities can use their limited budgets to greatest effect when implementing APPs (Harness & Neilsen 2006; Dwyer & Mannan 2007). Our model achieves this with regard to predicting the electrocution of most corvids and raptors in the SCE service area by quantifying number of jumpers, number of primary conductors, presence of grounding, and presence of unforested unpaved areas as the dominant land cover within 200 m. These 4 factors can be used to predict the probability of electrocution on a pole. For example, if a pole supports 9 jumpers, 3 primary conductors, a pole-top ground, and occurs in an area dominated by pavement (i.e., a typical pole supporting 3 transformers in an urban area), the probability (P) of electrocution can be calculated with the following equations:

$$Y = -0.93167 + 0.09048(9) + 0.14506(3) + 0.53203(1) - 0.55151(0) = 0.8498 \quad (2)$$

and

$$P = 1/(1 + \text{EXP}(-0.8498)) = 0.700. \quad (3)$$

Equation 3 is the standard inverse logit link necessary to transform model outputs into probability on a 0 to 1 scale. Additional examples of important pole-top variables and an excel spreadsheet containing our final averaged model set up to return prediction probabilities based on user inputs are in Supporting Information.

Because our model is consistent with results from other regions and continents, but more explicit than expert-

based approaches, it may be useful beyond its original scope. For example, many electric distribution utility structures in Spain are composed of grounded towers of metal lattice (Mañosa 2001; Ferrer 2012), and in India they are composed of grounded metal arms attached to concrete poles (Harness et al. 2008). To adapt our model to these scenarios, users would simply indicate the presence of a pole-top ground in the model even though the particular type of pole-top ground differed from that in our study. The precise probability estimate produced by the model may not be strictly correct when applied outside our model's original scope, but likely it would correctly reflect relative differences in risk between poles and thus facilitate identification and prioritization of retrofitting for high-risk poles.

When implementing an APP, retrofitting decisions are often affected by fiscal obligations to shareholders and customers. Models such as ours can be used to explicitly link budgets to biology. To do so, an electric utility can identify the budget available for retrofitting and then divide that budget by the average cost to retrofit a pole (unique to each utility). This will generate an estimate of the number of poles that can be retrofitted. By dividing the number of poles that can be retrofitted by the number of poles in the system, a utility company can identify the proportion of poles that can be retrofitted. The utility can then model a sample of poles to identify a P value to act as a cutoff so that poles above the cutoff (the most dangerous) are retrofitted, whereas poles below the cutoff are not. Larger budgets would allow a lower P value to be used as a retrofitting threshold.

We modeled all jumpers as exposed and energized because jumper covers were not installed on the poles we studied prior to the occurrence of an avian electrocution. When using our model to predict electrocution risk, insulated jumpers should not be counted toward the total number of jumpers unless any portion of a jumper is exposed. Exposure of only 1 mm of energized jumper can lead to electrocution on an otherwise fully retrofitted pole (J.F.D. and R.E.H., personal observation). Low-voltage insulated conductors linking transformers to buildings also should not be counted. Users of our model should count all primary conductors supported by a pole of interest including transmission and distribution conductors. Distribution conductors linked via a jumper are counted only once because the jumper will be counted. Because any path to ground poses avian electrocution risk, users of our model must carefully study poles to identify whether any possible path to ground exists (see Supporting Information and APLIC [2006] for illustrations).

Our model indicated electrocution risk was lower in unforested unpaved areas than in forested or urban areas. This is consistent with results of previous studies of electrocution in urban raptors (Dwyer & Mannan 2007; Guil et al. 2011) but contrasts with results of exurban

studies in which unforested unpaved environments were identified as risk factors (Schomburg 2003; Sergio et al. 2004; Gerdzhikov & Demerdzhiev 2009). We included corvids in our study precisely because we believed the species might affect predictions of avian electrocution risk in surprising ways. Electric service areas for which APPs are developed should incorporate urban species in retrofitting. Notably, our model predicted electrocution risk well for American Crows but poorly for Common Ravens. This emphasizes that inferences drawn for one species in a taxonomic group do not necessarily apply well to all species in that group. Our model also predicted electrocution risk for Great-horned Owls, Red-shouldered Hawks, and Red-tailed Hawks well, but it predicted risk for Turkey Vultures and Golden Eagles poorly. The poorly predicted species tended to occupy unforested unpaved areas, where our model predicted lower risks. As a correction factor for exurban species, we suggest using the unforested unpaved area value (a value of 0) in our model in all locations where electrocution of raptors may be of concern.

One important weakness of our model is that it includes no information on nesting. A model incorporating information on nesting would be particularly informative because the proximity of nests to overhead electric poles affects electrocution risk (Dwyer & Mannan 2007) but is rarely investigated. Although our model can likely be used in other service areas to quantify relative risk among poles, comparison between models constructed from different types of data also would provide an important wider perspective on differences in important predictors between service areas. Our model also demonstrates the substantial effect of including corvids and urban areas in studies of avian electrocution.

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Supporting Information

Descriptors of variables not included in the final model (Appendix S1), multivariate AIC_c analysis results

(Appendix S2), example poles evaluated with the prediction calculator (Appendix S3), and a prediction calculator for use in spreadsheets (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of material) should be directed to the corresponding author.

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