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AVIAN ELECTROCUTIONS IN WESTERN RAJASTHAN, INDIA

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Abstract.—Avian electrocutions are regularly documented worldwide. Electrocutions are thought to affect avian populations in Asia, but regional research has not been widely disseminated. In this study, we sought to identify whether power lines in rural India were involved in avian electrocutions and, if so, to identify at-risk species and problematic configurations, and to develop a predictive model. To collect data, we visited power poles to search for avian carcasses. We recorded six variables at each pole: line voltage, insulator configuration, conductor separation, jumper count, surrounding habitat, and presence of an avian carcass. We used multivariate logistic regression to model the probability that an avian carcass was found. We surveyed 15 line segments supported by 675 poles, and found 162 carcasses. We found carcasses of five raptor species, including Eurasian Kestrel (n = 5; *Falco tinnunculus*) and White-eyed Buzzard (n = 4; *Butastur teesa*), though passerine carcasses were more numerous. All modeled variables contributed to the probability of finding a carcass; however, only pin height and jumper count were important contributors to the averaged model. Specifically, carcasses were most common beneath poles supporting jumpers and beneath tangent poles with low center pins. This is similar to another recently completed electrocution model from California, U.S.A., where jumpers and grounding were key predictive variables. There is an ongoing effort to provide electric power to all rural areas in India. Unless poles are retrofitted to minimize electrocution risk, avian electrocutions are likely to increase as power delivery expands. With the simple model we provide, personnel with minimal training can report the results of surveys quantifying electrocution risk, and help utilities prioritize retrofitting dangerous poles.

Key Words: *Eurasian Kestrel*; Falco tinnunculus; *White-eyed Buzzard*; Butastur teesa; *avian*; *electrocution*; *India*; *predictive model*; *raptor*.

ELECTROCUCIONES DE AVES EN EL OESTE DE RAJASTHAN, INDIA

Resumen.—Las electrocuciones de aves son documentadas regularmente a lo largo del mundo. Se piensa que las electrocuciones afectan a las poblaciones de aves en Asia, pero las investigaciones a nivel regional no han sido difundidas ampliamente. En este estudio, buscamos identificar si las líneas de electricidad en la India rural estuvieron involucradas en electrocuciones de aves y, de ser así, identificar las especies en riesgo y las configuraciones problemáticas, y desarrollar un modelo predictivo. Para colectar datos, visitamos postes de electricidad en busca de cadáveres de aves. Registramos seis variables en cada poste de electricidad: voltaje de la línea, configuración del aislante, separación de los conductores, número de puentes eléctricos, hábitat circundante y presencia de un cadáver de ave. Utilizamos regresiones logísticas multivariadas para modelar la probabilidad de encontrar un cadáver de ave. Muestreamos 15 segmentos de cable sostenidos por 675 postes y encontramos 162 cadáveres. Encontramos cadáveres de cinco especies de rapaces, incluyendo a *Falco tinnunculus* (n = 5) y *Butastur teesa* (n = 4), aunque los paseriformes fueron más numerosos. Todas las variables modeladas contribuyeron a la probabilidad de encontrar un cadáver; sin embargo, sólo la altura del pasador y el número de puentes eléctricos contribuyeron de modo importante al modelo promediado. Específicamente, los cadáveres fueron más comunes debajo de postes que soportaban puentes y debajo de postes tangentes con pasadores centrales bajos. Esto es similar a otro

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modelo de electrocución recientemente realizado en California, EE.UU., en el cual los puentes y la toma a tierra fueron las variables predictivas clave. Está en marcha un esfuerzo para proveer de electricidad a todas las áreas rurales de India. A menos que los postes sean modernizados para minimizar el riesgo de electrocución, es muy probable que el número de electrocuciones de aves aumente a medida que la provisión de electricidad se expanda. Con el modelo simple que proveemos, personal con un mínimo de entrenamiento puede reportar los resultados de censos que cuantifiquen el riesgo de electrocución y ayudar a priorizar la modernización de los postes de electricidad peligrosos.

[Traducción del equipo editorial]

Despite a wealth of information on avian interactions with power lines, problems persist throughout the world (Lehman 2001, Jenkins et al. 2010). Avian electrocutions are widely documented in North America (e.g., Platt 2005, Dwyer and Mannan 2007, Harness 2007), as are avian electric-shock injuries (Morrow and Morrow 2003, Dwyer 2006). Avian electrocutions are also widely reported from Europe (Tintó et al. 2010, Guil et al. 2011, López-López et al. 2011) and Africa (Kruger and Van Rooyen 2000, Van Rooyen et al. 2003, Boshoff et al. 2011), where persistent electrocution mortality has been implicated in Egyptian Vulture (*Neophron percnopterus*) declines (Angelov et al. 2012). Electrocutions are also suspected to affect some avian populations in Asia (Harness et al. 2008, Karyakin et al. 2009, Goroshko 2011), but detailed, quantitative, regional information is not widely available, particularly in English-language journals.

India's government is working to provide electric power to all households and, although this goal has not yet been achieved, power is currently being provided to many rural centers (Modi 2005) and new power-generation facilities are being developed (Pande et al. 2013). The poles used to deliver this power typically operate at 11 or 33 kilovolts (kV) of alternating current and the power lines cross undeveloped landscapes occupied by numerous avian species. Birds may safely contact energized equipment as long as all points of contact are at the same electric potential. Death (electrocution) or injury (shock) occurs only when birds become a pathway through which electric current flows from a higher potential (or voltage) to a lower potential (often a path to ground). This can occur if a bird simultaneously contacts two differently energized wires (phase wires) or simultaneously contacts an energized wire and any grounded, conductive material (Avian Power Line Interaction Committee [APLIC] 2006).

Avian electrocution risk has not been evaluated in rural India, where many poles are constructed of concrete, supported by an internal lattice of grounded metal rebar, and affixed with metal cross-arms and pole-top insulator supports (Fig. 1). Because the rebar lattice within the concrete is conductive and grounded, the metal cross-arms attached to the pole are indirectly grounded. This creates pole configurations that are functionally similar to metal poles, where electrocution risk is substantially higher than on wooden poles (e.g., Harness 1998, Janss and Ferrer 1999, Garrido and Fernández-Cruz 2003).

In this study, we sought to identify whether distribution power lines in rural India were involved in avian electrocutions, to identify at-risk species and problematic configurations, and to provide retrofitting strategies to minimize electrocution risks. A secondary objective was to develop a simple but accurate model to predict electrocutions, so personnel with minimal training could undertake effective surveys to identify poles most in need of retrofitting (applying corrective measures; APLIC 2006).

METHODS

Study Area. We conducted our study in the state of Rajasthan, India (Fig. 2), between the cities of Bikaner (28°1.2′N, 73°19.08′E) and Jaisalmer (26°54.9′N, 70°54.5′E). Bikaner and Jaisalmer are located in the Thar Desert, where the average annual rainfall is 10–40 cm and temperatures range from a minimum of -2°C in winter to a maximum of 51°C in summer (Sharma and Mehra 2009). Vegetation is mainly dry, open grassland or grassland interspersed with thorny, drought-resistant bushes growing in sandy soils (Gupta 1975). In arid areas where tall trees are largely absent, anthropogenic structures such as utility poles provide tall perches used by a variety of birds, including raptors (Benson 1981, Dhindsa et al. 1988).

We selected this area because 98% of rural villages were electrified as of 2004 (Modi 2005). Rajasthan also contains sites identified as high-priority areas for avifaunal conservation, and is recognized by the Bombay Natural History Society of Mumbai as an International Birdlife Area (Islam and

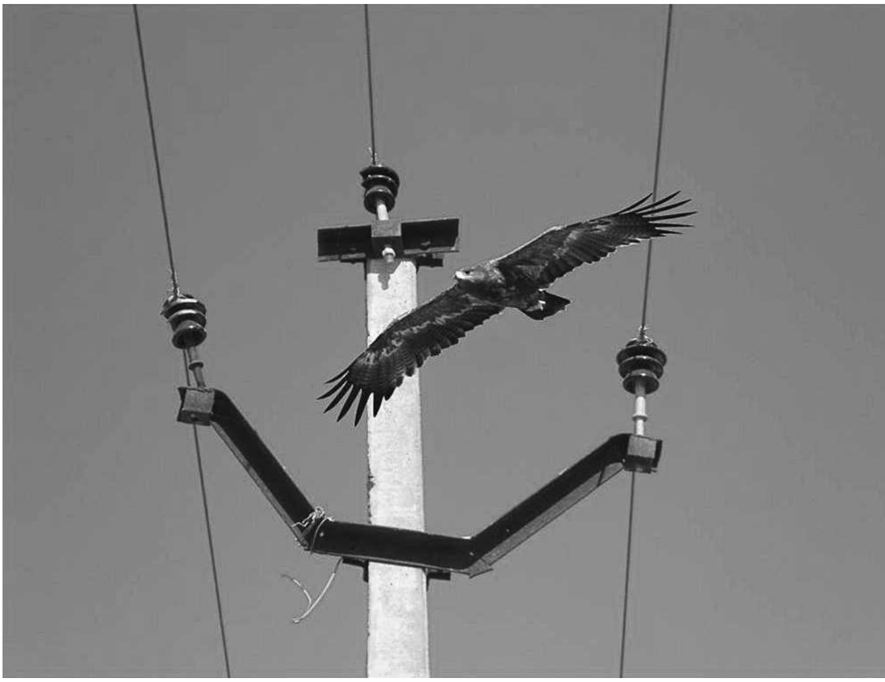

Figure 1. Typical 11-kV concrete pole with a grounded metal cross-arm. A Steppe Eagle (*Aquila nipalensis*), a common raptor in Rajasthan, India, with a wingspan of 165–190 cm, provides a reference for relative size.

Rahmani 2004). The area supports an estimated 250 avian species (Rahmani 1997) and includes the rural village of Jorbeer, where a regional disposal location for cattle carcasses exists. Religious practices preclude human consumption of cattle in the study area. As a result, cattle carcasses are skinned for leather and otherwise discarded intact near Jorbeer. The carcass disposal site attracts numerous wintering raptors (Sharma and Sundar 2009), including four eagle species (Eastern Imperial Eagle [*Aquila heliaca*], Indian Spotted Eagle [*A. hastata*], Steppe Eagle [*A. nipalensis*], and Tawny Eagle [*A. rapax*]) and six vulture species (Cinereous Vulture [*Aegypius monachus*], Egyptian Vulture [*Neophron percnopterus*], Eurasian Griffon Vulture [*Gyps fulvus*], Long-billed Vulture [*G. indicus*], Red-headed Vulture [*Sarcogyps calvus*], and White-rumped Vulture [*G. bengalensis*]). Three of the six vulture species noted in our study area are of conservation concern, with the Egyptian Vulture listed as endangered, the Red-headed Vulture listed as critical, and the Cinereous Vulture listed as near threatened (Thakur and Narang 2012). Vulture numbers have been declining in India (Prakash et al. 2005, Sharma 2012) and vulture electrocutions are a persistent problem globally (Anderson 2000). Thus, information on compounding factors such as electrocution, is critical to the effective management and conservation of this taxonomic group.

Survey Methods. From 31 November through 6 December 2011, we drove Highway 15 from Jaisalmer to Bikaner in search of rural power lines with public access. Restricted by the terrain, we visited 13 energized line sections and two nonenergized line segments in rural habitat parallel to public roads, but away from towns and villages. In the Discussion, we address the potential consequences of using convenience sampling focused on areas of public access rather than randomized sampling regardless of ownership. To conduct surveys, two of us walked the entirety of each sampled line segment, inspected each pole-top, and searched the ground within a radius of 7.6 m around the base of each pole for the presence of avian remains (Harness 2001, Dwyer and Mannan 2007). We also walked beneath the wires to record mid-span fatalities that may have resulted from power-line collisions.

We recorded six variables at each pole: conductor separation, insulator configuration, jumper count, line voltage, surrounding habitat, and whether or

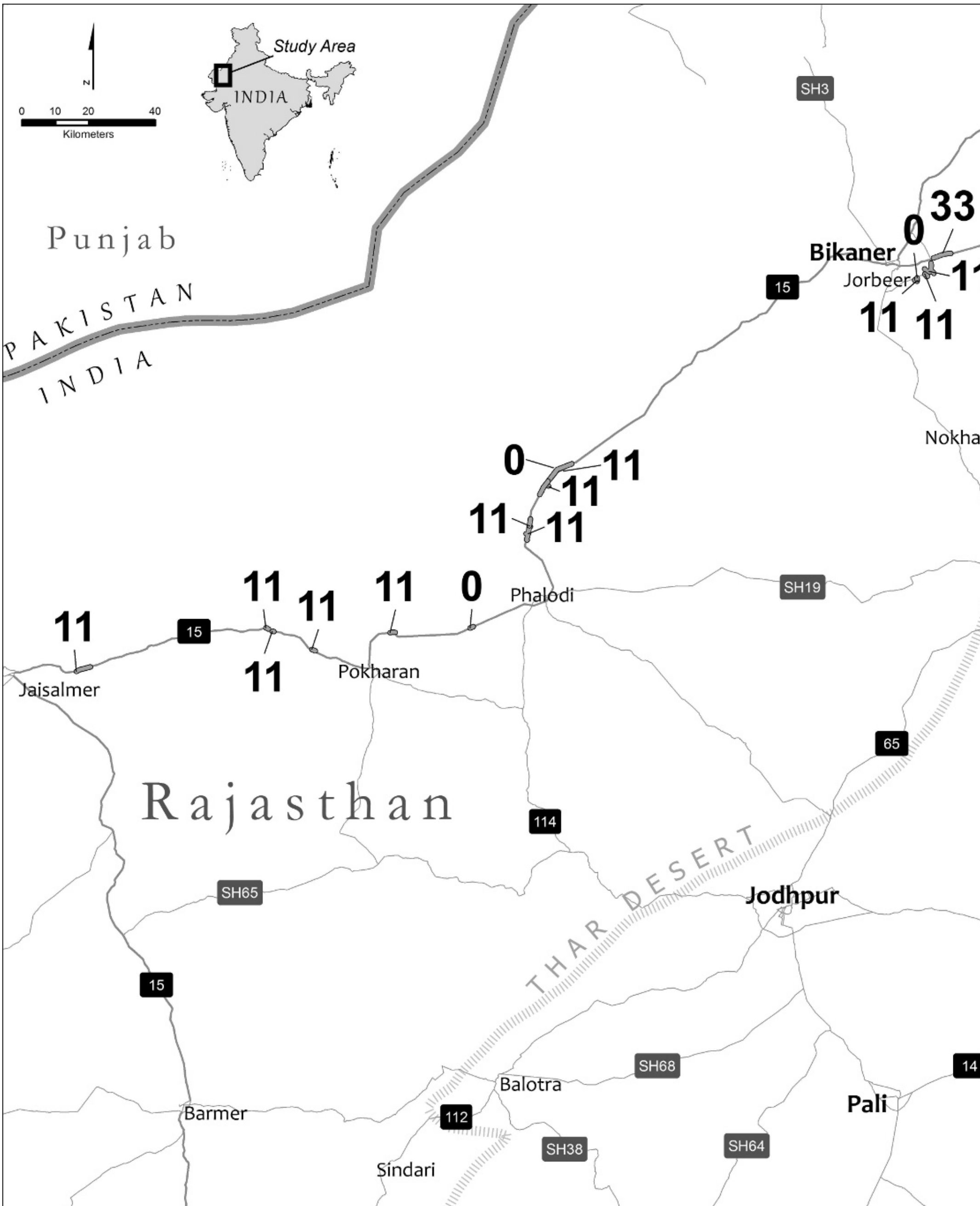

Figure 2. Locations of line segments surveyed from 31 November through 6 December 2011 in Rajasthan, India. Numbers in the figure indicate voltage (kV) of the line segments.

not an avian carcass was present. We identified the presence of an avian carcass *a priori* as our response variable for both univariate analyses and multivariate modeling.

We classified conductor separation as either sufficient or insufficient, following APLIC (2006) guidelines. APLIC (2006) suggests that to prevent avian electrocution, conductors should be separated from one another by at least 152 cm horizontally and 102 cm vertically (Fig. 3). If phase-to-phase and phase-to-ground separation equaled or exceeded APLIC recommendations, we recorded the pole as having sufficient separation. If not, we recorded insufficient separation. This level of separation is designed to prevent the electrocution of large eagle species in North America (e.g., Golden Eagle [*Aquila chrysaetos*]), because meeting separation requirements for eagles acts as an umbrella to minimize risk for smaller species. We address extrapolation to Indian species in the Discussion.

We classified the insulator configuration on each pole as low, high, or absent (Fig. 5). Each pole carried three phase wires, with the center phase typically supported on top of the pole by a pin insulator. If the top of the center-phase insulator was ≤30 cm above the grounded bracket, we recorded a low configuration. If the top of the center-phase insulator was >50 cm above the grounded bracket, we recorded a high configuration. We estimated insulator heights based on known pole-top dimensions. If the phase wires were suspended rather than supported by pin insulators, we recorded absent as the configuration.

The jumper count equaled the number of jumpers on each pole (Fig. 4). Jumpers are short wires that connect energized devices such as switches and transformers to the primary circuit wires running between poles. Jumpers are also used to connect primary wires at poles where lines diverge or change direction. Counting the number of jumpers allowed us to incorporate all energized equipment in a single modeled variable. This avoided problems with lack of independence among variables, which otherwise would have arisen if we quantified each type of pole-mounted equipment separately (Dwyer et al. 2013).

We classified line voltage as 0 kV (nonenergized), 11 kV, or 33 kV. Because larger insulators are required for higher voltages, we used insulator size to distinguish between voltage levels. Nonenergized sections included either poles with no wires or poles with wires that were not energized. Nonenergized

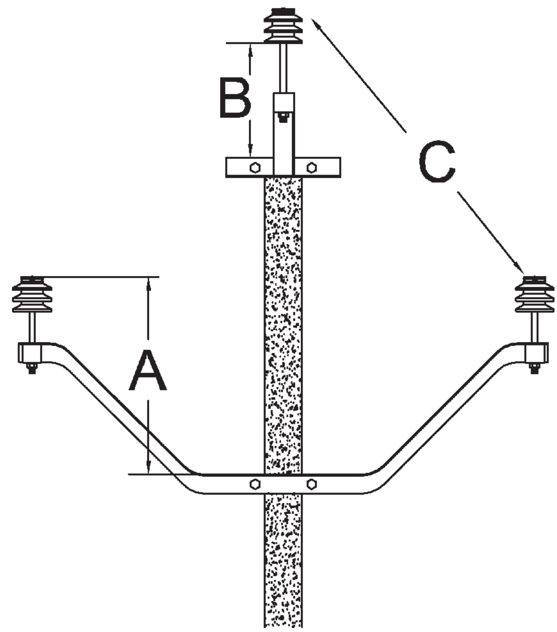

Figure 3. Examples of risk points where sufficient conductor separation is required to minimize avian electrocution risk on an energized utility pole: (A) phase to grounded crossarm, (B) phase to grounded pole top, and (C) center phase to outer phase.

and energized poles were configured identically, and we surveyed both types in the same manner. We visited nonenergized poles, where birds could not possibly have been electrocuted, because an avian carcass found dead beneath a power line is not necessarily the result of electrocution (Dwyer 2004). This is particularly true in India, where diclofenac poisoning of vultures has been a persistent concern (Oaks et al. 2004, Schultz et al. 2004, Prakash et al. 2005). Consequently, identifying electrocution as the cause of death may reflect researcher bias, unless assumptions of electrocution are verified. We used the number of carcasses found (n = 1) beneath nonenergized poles (n = 78) to estimate the proportion of carcasses beneath energized poles not attributable to electrocution.

We classified habitat as disturbed or undisturbed. We defined disturbed habitats as those with anthropogenic features such as buildings or roads within 50 m of the pole, and undisturbed habitats as lacking those features within 50 m.

For each surveyed pole, we recorded whether one or more carcasses was present, and if present, the number of carcasses, the species of each carcass,

Figure 4. Indian Roller (*Coracias benghalensis*) perched on a typical 11-kV utility pole with six jumpers in Rajasthan, India.

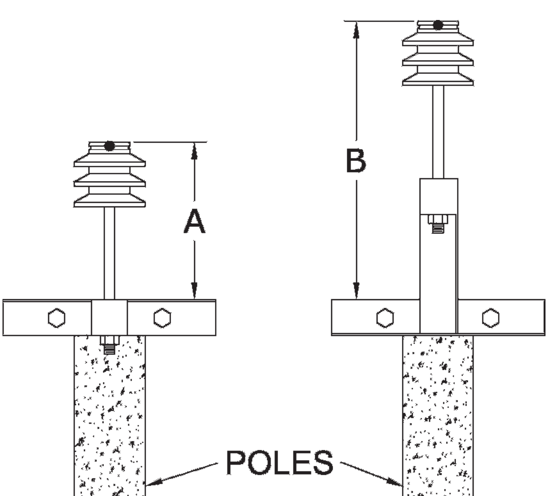

Figure 5. Illustration of low (A; ~30 cm) and high (B; ~50 cm) insulator configurations on a utility pole.

and whether there was evidence of electric-shock injury. We used presence-absence data as the response variable in logistic regression models. Many carcasses were decomposed or desiccated, thus precluding formal necropsy. Instead of necropsies, we followed Dwyer (2004, 2006) and Harness and Hurmence (2004) in identifying external damage (burns) to carcasses consistent with electrocution (Fig. 6). We left all carcasses where we found them and used a GPSmap 62s (Garmin, Olathe, Kansas, U.S.A.) to record carcass locations. Carcass locations are available upon request so future researchers can avoid identifying known carcasses as new records.

Statistical Methods. Because we surveyed every accessible pole, we treated poles as independent samples, even though they occurred in distinct line segments. A very low number of carcasses found under nonenergized poles (n = 1) obviated the need for statistical analysis to discern differences in the probability of finding a carcass under energized versus nonenergized poles (see Results). This fact and burns observed on carcasses supported the assumption that electrocution was the cause of death for

Figure 6. Eurasian Kestrel (*Falco tinnunculus*) with electric burn marks visible on the left scapulars, found beneath an energized utility pole in Rajasthan, India.

most individuals found under energized poles. We used multivariate logistic regression to model the probability that at least one avian carcass was found at the base of an energized pole, with electrocution the presumed cause of death. We used a logit link in the gmulti package (Calcagno and de Mazancourt 2010) for program R (The R Foundation for Statistical Computing, Vienna, Austria) to model all possible subsets of the five candidate predictor variables (n = 32 candidate models), to rank models using Akaike's Information Criterion (AIC), and to calculate an averaged model, averaged model parameters, and standard errors for averaged model parameters based on the response variable (presence-absence of a carcass). We also used the binary logistic regression option in Minitab 16 (Minitab, State College, Pennsylvania, U.S.A.) to conduct the Hosmer-Lemeshow (Hosmer et al. 2013) goodness-of-fit test on the global model with no interactions. The goodness-of-fit test supported use of AIC corrected for small sample size (AICc; Anderson 2008) to rank models (χ^2 = 0.778, df = 3, P = 0.855).

Out-of-sample cross validation uses individuals of interest (power poles in this case) not used in model building to test the predictive ability of a model (as in Tintó et al. 2010). We used 80% of the data from energized poles (478 poles) to create the model and the remainder (119 poles) to compose an out-of-sample cross validation test. Parameters with standard errors (SE) overlapping zero did not contribute substantially to the overall fit of the final model. We do not report these parameters as part of the final model and excluded them during model validation.

Table 1. Bird species found dead beneath energized utility poles from 31 November through 6 December 2011 in Rajasthan, India.

SPECIES	COUNT
House Crow[a] (*Corvus splendens*)	59
Indian Roller (*Coracias benghalensis*)	47
Eurasian Collared-Dove (*Streptopelia decaocto*)	18
Rock Pigeon (*Columba livia*)	7
Common Myna (*Acridotheres tristis*)	7
Unidentified bird (non-raptor)	6
Eurasian Kestrel (*Falco tinnunculus*)	5
White-eyed Buzzard (*Butastur teesa*)	4
Tawny Eagle (*Aquila rapax*)	2
Indian Peafowl (*Pavo cristatus*)	1
Rose-ringed Parakeet (*Psittacula krameri*)	1
Rock Eagle-Owl (*Bubo bengalensis*)	1
Unidentified owl (*Strigiformes* species)	1
Spotted Owlet (*Athena brama*)	1
Unidentified Lapwing (*Vanellus* species)	1
Total	161

[a] One additional House Crow was found dead beneath a nonenergized pole, for a total of 162 birds used in modeling.

RESULTS

We surveyed 15 line segments (length: $\bar{x}$ = 3.5 km, range 0.5–14.0 km) supported by 675 poles, including 597 energized poles and 78 nonenergized poles. We found 161 carcasses of 13 bird species at the bases of 27% of the energized poles (Table 1), and one carcass (House Crow [*Corvus splendens*]) at the base of a nonenergized pole (1% of the total nonenergized poles), unequivocally confirming a higher probability of finding a carcass under energized versus nonenergized poles. One carcass found beneath 78 nonenergized poles suggests that 7–8 of the 161 carcasses found beneath energized poles may not have resulted from electrocution. We also found two carcasses mid-span, which we did not include in electrocution modeling: a Greater Short-toed Lark (*Calandrella brachydactyla*) and a Rock Pigeon (*Columba livia*).

Our overall discovery rate was 0.27 carcasses per energized pole. We found multiple carcasses (2–10) at the bases of 6% (30) of the energized poles. Poles supporting energized transformers (n = 19) averaged 1.0 carcass per pole. We found three carcasses hanging from energized poles: a Rock Eagle-Owl (*Bubo bengalensis*), an Indian Peafowl (*Pavo cristatus*), and a House Crow.

The most common configuration was a pole supporting three phases and lacking any pole-mounted

Table 2. Models predicting the probability of finding an avian carcass at the base of an energized utility pole from 31 November through 6 December 2011 in Rajasthan, India.

MODELS[a]	K[b]	$-\ln(L)$[c]	ΔAICc[d]	ω_i[e]
Jumpers + voltage + pins	4	189.918	0.000	0.066
Jumpers + pins	3	189.001	0.133	0.066
Jumpers + voltage + pins + habitat	5	191.392	0.991	0.063
Jumpers + pins + habitat	4	190.732	1.628	0.061
Jumpers + phases + pins	4	190.798	1.761	0.061
Jumpers + voltage + phases + pins	5	191.784	1.775	0.061
Jumpers + voltage + phases + pins + habitat	6	193.201	2.659	0.058
Jumpers + phases + pins + habitat	4	191.471	3.107	0.057
Voltage + pins	3	192.262	6.654	0.047
Pins	2	191.629	7.364	0.046
Voltage + pins + habitat	4	193.616	7.396	0.046
Voltage + phases + pins	4	194.217	8.598	0.043
Pins + habitat	3	193.296	8.722	0.043
Phases + pins	3	193.536	9.202	0.042
Voltage + phases + pins + habitat	5	195.530	9.267	0.042
Phases + pins + habitat	4	195.158	10.480	0.039
Jumpers + voltage + habitat	4	201.816	23.796	0.020
Jumpers + voltage	3	200.946	24.022	0.020
Jumpers + voltage + phases + habitat	5	202.966	24.139	0.020
Jumpers + voltage + phases	4	202.258	24.681	0.019
Jumpers	2	203.265	30.636	0.014
Jumpers + phases	3	204.359	30.849	0.014
Jumpers + habitat	3	205.023	32.177	0.013
Jumpers + phases + habitat	4	206.011	32.186	0.013
Voltage + phases + habitat	4	216.425	53.015	0.005
Voltage + phases	3	216.262	54.655	0.004
Voltage + habitat	3	216.809	55.749	0.004
Voltage	2	216.361	56.827	0.004
Phases	2	218.976	62.058	0.003
Phases + habitat	3	220.407	62.945	0.003
Intercept only	1	219.501	65.090	0.003
Habitat	2	221.133	66.370	0.002

[a] See text for descriptions of the five model variables.
[b] Number of parameters.
[c] Log likelihood.
[d] Change in Akaike's Information Criterion value corrected for small sample size compared to the lowest value in the model set.
[e] Model weights.

equipment (i.e., a tangent pole with no jumpers). This configuration (n = 507 poles) applied to 85% of the energized poles and was associated with 93 bird carcasses (57% of all carcasses found). Approximately 55% of the tangent poles had low insulator configurations and 45% had high insulator configurations; however, a disproportionate share (96%) of the carcasses documented at tangent poles occurred at those with a low configuration. The remaining 15% of the energized poles (n = 90) were associated with 68 bird carcasses (42% of all carcasses found).

Because the global logistic-regression model was within 7 ΔAIC of our best model, all variables contributed to the probability of finding an avian carcass beneath an energized pole (Table 2). Following model averaging, however, only the jumper-count and insulator-configuration variables had confidence intervals that did not overlap zero and remained as important predictors of avian electrocution for the poles we evaluated (Table 3). The probability of detecting an avian carcass increased with an increasing jumper count, and decreased with the presence of a high center-phase pin configuration (Fig. 7).

Table 3. Model-averaged parameter estimates[a], unconditional standard errors, and relative importance values (sum of model weights) for variables predicting detection of an avian carcass beneath an energized utility pole from 31 November through 6 December 2011 in Rajasthan, India.

VARIABLE	$\hat{\beta}$	SE	IMPORTANCE
Intercept	−2.361	0.533	1.000
Pin low	1.089	0.237	1.000
Pin absent	1.208	0.333	1.000
Number of jumpers	0.125	0.047	0.969

[a] Users of these estimates must perform an inverse logit link transformation on the Y (output) value to transform values to a 0 to 1 probability scale: $P = 1/(1 + e^{-Y})$.

For each pole among the model validation group where we found an avian carcass, all characterized by having at least one jumper and a low insulator configuration, the model predicted that the probability of finding a carcass was ≥0.20. Conversely, the model predicted that the probability of electrocution was <0.20 for poles where we did not find any carcasses, all of which had no jumpers and high insulator configurations.

DISCUSSION

Our model accurately predicted the likelihood that an 11-kV or 33-kV pole would electrocute a bird in rural Rajasthan, India. Specifically, we found that the jumper count and insulator configuration were sufficient to predict the probability of an avian electrocution, and that a 20% probability of finding a carcass was a reasonable cutoff for identifying poles requiring retrofitting. Jumpers and grounding were also identified as predictive factors in a model of avian electrocution in California, U.S.A. (Dwyer et al. 2013). In California, historical data on avian electrocution, from an overhead electric system composed primarily of wood poles and wood cross-arms in urban and rural areas, indicated electrocution risk could be modeled with 4 of 14 candidate variables: jumper count, presence of grounding, number of phase wires, and presence of unforested, unpaved areas as the dominant nearby land cover. Notably, the jumper count and a measure of grounding were important in both the California model and the model reported here. Number of phase wires was important in California where up to 12 phase wires occurred on a single pole, but was not predictive in this study where every pole had 3 phase wires. A qualitative measure of habitat was predictive in California, but was not predictive in this study, where all evaluated poles occurred in rural areas. We predict that as variation in habitat increases within a study, the habitat variable will become more important in predicting electrocution risk. The striking similarity of the most

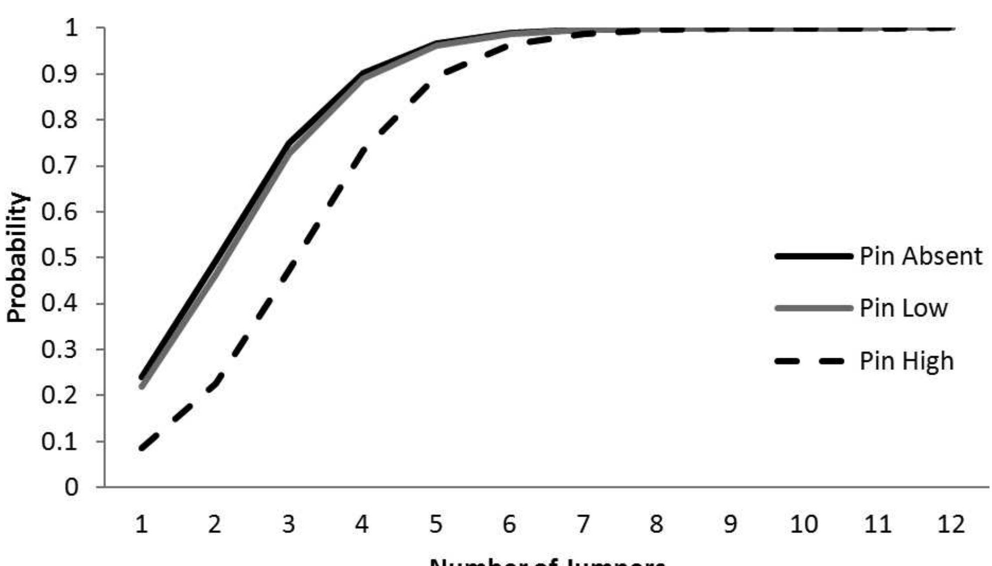

Figure 7. Probability of detecting an avian carcass beneath an energized utility pole in Rajasthan, India, between 31 November and 6 December 2011 as a function of the jumper count and insulator configuration.

important predictive factors in the two models, based on very different data sources, variables quantified, and electric systems evaluated, suggests the predictive factors described herein should be carefully considered when evaluating electrocution risk beyond the scope of these two studies.

Insulator configuration as a measure of phase-to-ground avian electrocution risk has not previously been quantified, likely because this is the first study of the kinds of poles we surveyed. Pole-top grounding has, however, been previously identified as influential to electrocution risk (Harness and Wilson 2001, Harness et al. 2008, Dwyer et al. 2013), particularly in Spain where much of the electric distribution system is composed of steel-lattice structures (Janss and Ferrer 1999, Garrido and Fernández-Cruz 2003, Ferrer 2012). Because every pole we evaluated was grounded, our insulator-configuration variable essentially measured subtle differences in pole-top grounding. These subtle differences will be influential in electrocution risk for relatively small species, such as Eurasian Kestrel (*Falco tinnunculus*), but will be less important for large species that can make phase-to-ground contact regardless of differences we observed in insulator pin heights. Insulator pin heights may be less effective predictors of avian electrocution risk near regular vulture feeding areas where very large species would perch regularly. Thus, the high configuration must not be regarded by utilities in India, or other utilities using steel or concrete poles and grounded cross-arms, as safe poles for all species.

House Crow was the most prevalent species found electrocuted in this study, and American Crow (*Corvus brachyrhynchos*) was one of the two (along with Red-tailed Hawk [*Buteo jamaicensis*]) most prevalent species found by Dwyer et al. (2013). Avian electrocution studies typically focus on raptors (e.g., Lehman et al. 2007, 2010). Corvids are not typically included as focal species, but their electrocutions are often noted when authors report all electrocutions found (e.g., Harness et al. 2008, Tintó et al. 2010, Dwyer et al. 2013). Because corvids, like raptors, can be species of conservation concern and be involved in electrocutions causing outages and equipment damage, future research of avian electrocution should include dual foci on corvids and raptors.

Our model included the surprising result that habitat was not important in predicting electrocution risk. Previous studies identified open habitat as a risk factor for electrocution (APLIC 2006, Harness and Wilson 2001, Tintó et al. 2010). We hypothesize that, because the habitat in our study area was relatively homogeneous and persecution of raptors in India is minimal, the influence of small dwellings and roads was minimized. Voltage has been identified as important in other studies, but mostly in comparing risk on poles with ≥66 kV (transmission voltages) to poles with ≤33 kV (sub-transmission and distribution voltages). Voltages ≥66 kV typically pose little avian electrocution risk, because the phase-to-phase and phase-to-ground separations required from an engineering perspective are usually sufficient to prevent simultaneous avian contact (APLIC 2006). This was supported in our study, where ≥66-kV poles were less problematic than ≤33-kV poles.

We did not select surveyed poles randomly. Instead, we opportunistically surveyed only poles and line segments on publicly accessible land. Consequently, our scope of inference applies only to these types of poles, and our tally of carcasses may be biased toward human-tolerant species. Species at risk of electrocution in less accessible areas of Rajasthan, India, remain unknown and may be biased toward species less tolerant of human activities.

Management Implications. There is an ongoing, concerted effort to provide power to all rural areas in India (Modi 2005). Power lines can play a positive role for raptors by providing nest substrates and perches used for hunting and roosting (APLIC 2006, Puzović 2008, Ellis et al. 2009). As demonstrated here, however, the trend to use concrete poles with metal cross-arms counters at least some of the potential benefits for birds. Existing poles, particularly those with a modeled electrocution risk of ≥20%, should be retrofitted and new poles should be constructed to standards explicitly designed to minimize avian electrocution risk. This is particularly important near the Jorbeer carcass disposal site, where we noted numerous vultures around recently constructed and presently nonenergized power lines. If these lines are energized without first installing conductor covers, substantial numbers of avian electrocutions are likely.

To prevent avian electrocutions, APLIC (2006) recommends 152 cm of horizontal and 102 cm of vertical separation between different phases and between phases and grounded equipment, including concrete poles and grounded metal cross-arms. These parameters are useful to electric utility personnel trained in the technical details of power poles, but untrained observers may have difficulty discerning such characteristics. Critical dimensions defined by APLIC (2006) also may fail to protect the Cinereous Vultures and Eurasian Griffon Vultures occurring in our study area, which can exceed the size of Golden Eagles in North America by 4–22% (Ferguson-Lees and Christie 2001). Using jumper counts and insulator configurations as predictive variables facilitates quantification of avian electrocution risk without requiring detailed understanding or specialized training to distinguish different types of pole-mounted equipment, and without relying on separation standards developed outside India. With the simple model we provide, personnel with minimal training in electric utilities can report the results of surveys quantifying the jumper count and pin height on poles, and utilities can subsequently prioritize retrofitting the most dangerous poles. To do so, utilities only need to use the following two equations, entering field data into Equation 1 and the output from Equation 1 into Equation 2.

$$\begin{aligned} Y = -2.3608 + 0.1254 * \text{ jumper count} \\ + 1.2082 * \text{ pin insulator} \\ + 1.0893 * \text{ insulator height} \end{aligned} \quad (1)$$

$$\text{Probability (avian electrocution)} = 1/\left(1 + e^{-Y}\right) \quad (2)$$

In Equation 1, the jumper count is entered as a numerical value from 1 to *n*. For the other two variables (pin insulator and insulator height) only categorical values of 0 or 1 are allowed in the equation. If phase wires are suspended such that no pin insulator exists, then pin insulator = 0 and insulator height = 0. If a pin insulator exists, then pin insulator = 1 and the insulator height value depends on the configuration. If a high pin insulator exists, then insulator height = 0. If a low pin insulator exists, then insulator height = 1. If primarily large species are being considered, such as near the Jorbeer carcass disposal site, then use of a value of 1 for the insulator height variable will likely yield the greatest benefit, regardless of actual pin insulator heights.

The least expensive strategy to minimize avian electrocution risk on new construction is to frame poles with sufficient spacing between conductors or conductors and grounds to prevent simultaneous contact (APLIC 2006). When using concrete poles, alternative construction methods must be used and framing changed to prevent electrocutions (Harness 1998, Cartron et al. 2004). In Russia, new steel-pole lines are being constructed using suspension insulators, which apparently is a reliable configuration that allows for increased span lengths (Hunger et al. 2006) and safely accommodates perching by both small and large birds. Retrofitting existing electric poles is more expensive, but can be accomplished by insulating or isolating energized equipment. Specific to the poles evaluated here, insulation should be added to all jumpers, all equipment serviced by those jumpers, and all conductors on metal or concrete substrates. If even a small gap remains on a jumper, electrocution risk can remain high and avian electrocutions can persist (Dwyer and Mannan 2007).

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