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Management and Conservation Article

Predicting and Correcting Electrocution of Birds in Mediterranean Areas

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ABSTRACT Bird electrocution on power lines is an important conservation problem that affects many endangered species. We surveyed 3,869 pylons in the Barcelona Pre-littoral Mountains (Catalonia, NE Spain) and collected 141 carcasses of electrocuted birds, mainly raptors and corvids. Univariate analysis indicated that metal pylons with pin-type insulators or exposed jumpers, with connector wires, located on ridges, overhanging other landscape elements, and in open habitats with low vegetation cover were the most dangerous. A logistic regression model indicated that the probability of a pylon electrocuting a bird was mainly related to pylon conductivity, distribution of the conductive elements on the cross-arms, cross-arm configuration, habitat, topography, whether the pylon was overhanging other landscape elements, and presence of rabbits (*Oryctolagus cuniculus*). We validated the predictive power of this model by using a random sample of 20% of all pylons surveyed. We found that bird mortality was aggregated mainly on pylons assigned a high probability risk by the model. Pylons included in the very high electrocution risk category (9.2%) accounted for 53.2% of carcasses, whereas pylons classified in the low electrocution risk category (54.5%) only accounted for 3.5% of mortality. Power companies employed this classification to prioritize the correction of 222 pylons by installing alternate cross-arms and suspended jumpers and isolating wires and jumpers. We evaluated the effectiveness of this mitigation strategy. A significant fall in the mortality rate on corrected pylons combined with the lack of any reduction in the mortality rate in a sample of 350 noncorrected pylons indicated that the model selected adequately the most dangerous pylons and that the applied correction measures were effective. Consequently, our strategy may be a useful tool for optimizing efforts and resources invested in solving the problem of bird electrocution.

KEY WORDS Catalonia, conservation, electrocution of birds, endangered species, Mediterranean ecosystems, mitigation measures, power lines, predictive models, raptors, Spain.

Electrocution on power lines is an important human-induced mortality factor in birds and kills several thousand birds every year (Bevanger 1994, Bayle 1999, Janss and Ferrer 1999*b*, Avian Power Line Interaction Committee [APLIC] 2006, Lehman et al. 2007). In North America, raptors are the main group of birds affected by electrocution mortality, especially eagles, hawks, and owls (Lehman 2001, APLIC 2006). In the United States electrocution is the second and fourth most important cause of death in the golden eagle (*Aquila chrysaetos*) and bald eagle (*Haliaeetus leucocephalus*), respectively (Harness and Wilson 2001). Raptors with large wingspans such as the Cape vulture (*Gyps coprotheres*) are the main victims of electrocution in South Africa (Ledger and Annegarn 1981, Ledger and Hobbs 1999). In Europe a wide variety of raptors, storks, owls, corvids, and other passerines of all sizes are reported to suffer electrocution on power lines (Bevanger 1998, Negro 1999, Janss 2000, Moleón et al. 2007), and electrocution may pose a serious threat to certain endangered species such as the Spanish imperial eagle (*A. adalberti*, Ferrer et al. 1991, Ferrer and Hiraldo 1992, González et al. 2007) and Bonelli's eagle (*Aquila fasciata*; Real et al. 1997, 2001).

Bird electrocution on power lines has been the focus of extensive research worldwide (Olendorff et al. 1981, Olendorff 1993, Janss and Ferrer 1999*b*, APLIC 2006, Lehman et al. 2007). Many studies have tried to understand which variables determine the risk of electrocution in birds. Pylon design and location, bird abundance, species characteristics (e.g., size, wingspan, gender, age, and behavior), prey availability, season, and weather conditions have all been suggested as causes (Bevanger 1998, Janss and Ferrer 2001, Mañosa 2001, Rubolini et al. 2001, APLIC 2006).

On the other hand, important efforts have been made to mitigate the risk of electrocution on dangerous pylons (Negro 1999). A wide range of mitigation techniques have been developed, although as yet their effectiveness has rarely been tested (Miller et al. 1975, Janss and Ferrer 1999*b*, APLIC 2006, Lehman et al. 2007). In the United States some studies conducted on wooden (nonconductive) pylons indicated that the use of perch guards and alternative perches does not eliminate the electrocution risk (Garret 1993, Harness and Garret 1999, Harness 2000). On the other hand, cross-arm modification and the use of isolating materials have achieved a significant reduction in bird mortality (Garret 1993, Dwyer 2004). Nevertheless, most mitigation measures used on wooden pylons are not effective on metal pylons (Janss and Ferrer 1999*a*). Some studies conducted in southern Spain indicated that perches and perch guard devices do not significantly reduce the risk of bird electrocution, although the isolation of conductive wires and jumpers does lower bird mortality (Regidor et al. 1988, Negro et al. 1989, Janss and Ferrer 1999*a*, Moleón et al. 2007).

Bird electrocutions tend to be aggregated, so implementation of mitigation actions can be made more cost-effective by the use of multivariate models to identify the most dangerous pylons where corrective actions should be carried

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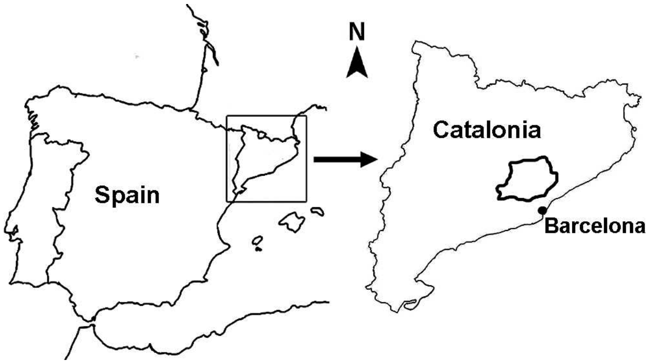

Figure 1. Study area in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–December 2008.

out (Benson 1982, Janss and Ferrer 1999*b*, Mañosa 2001, Sergio et al. 2004, Lehman et al. 2007). However, to date no multivariate model has ever been properly validated. Moreover, after correcting power lines the success of the mitigating actions in reducing electrocution is not usually tested (Lehman et al. 2007).

In this study, we aimed to 1) assess the impact of electrocution on birds in a Mediterranean area in which electrocution is one of the main causes of death of some bird species, 2) identify technical and environmental factors that determine the risk of electrocution on pylons, 3) develop predictive models for assessing the risk of electrocution on pylons and to validate the best model, 4) provide a tool for prioritizing correction of the most dangerous pylons, and 5) evaluate the reduction in bird mortality achieved by the application of corrective measures.

STUDY AREA

We conducted our study within 2,100 km^2 in the Barcelona Pre-littoral Mountains (Catalonia, NE Spain) and surrounding plains (Fig. 1). Our study area was an Important Bird Area (Viada 1998) that included 4 Special Protection Areas (SPAs) for birds and 3 natural parks, all part of the European Natura 2000 network (Directives 79/409/CE and 97/49/CEE). The diversity of habitats supported a variety of bird species of different morphological and behavioral characteristics. Of special significance were breeding populations of endangered species such as Bonelli's eagle, as well as other raptors such as short-toed eagle (*Circaetus gallicus*), European buzzard (*Buteo buteo*), European honey buzzard (*Pernis apivorus*), northern goshawk (*Accipiter gentilis*), Eurasian sparrowhawk (*Accipiter nisus*), peregrine falcon (*Falco peregrinus*), Eurasian hobby (*F. subbuteo*), common kestrel (*F. tinnunculus*), tawny owl (*Strix aluco*), Eurasian eagle-owl (*Bubo bubo*), little owl (*Athene noctua*), Eurasian scops owl (*Otus scops*), and long-eared owl (*Asio otus*). The nonbreeding population of white stork (*Ciconia ciconia*) was increasing, especially during migratory periods, and wintering colonies of great cormorant (*Phalacrocorax carbo*) were present in riparian habitats (Ribas 2000, Estrada et al. 2004, Estrada and Anton 2007). Previous research in the area identified electrocution as the main mortality cause for Bonelli's eagle (Real and Mañosa 1997).

Relief was variable and the landscape was dominated by Mediterranean ecosystems exhibiting heterogeneity of habitats (Pino et al. 2000). Plains (<400 m above sea level) were mainly occupied by scattered medium-sized cities (100,000–200,000 inhabitants) interspersed with woodland and agricultural areas. Human activity was scarce in upland areas (400–1,200 m above sea level) where the dominant vegetative cover was Mediterranean holm oak (*Quercus ilex*) and Aleppo pine (*Pinus halepensis*) forests. The network of power lines was dense (17,804 pylons) but irregularly distributed, and pylon designs differed.

METHODS

Model Development

During January 1999 to November 2006 we surveyed a random sample of 3,869 pylons (22% of pylons in the study area) in search of carcasses of electrocuted birds (first survey). We visited each pylon once, removed the carcasses, and checked them for signs of electrocution. A detailed examination of the remains enabled us to identify the species concerned and the antiquity of the remains: fresh carcasses (<1 month) or dry carcasses and bone remains (>1 month). To identify principal factors determining the risk of electrocution, we classified pylons in terms of 12 technical and environmental variables (Tables 1, 2) and determined the specific design of each pylon (Fig. 2).

We quantified the frequency with which we found bird species electrocuted and calculated electrocution rates (carcasses/pylon) for every category of each variable and for all surveyed pylons. We then performed univariate statistical analyses to identify the importance of each of the 12 electrocution risk variables, and we analyzed interactions between each variable and presence or absence of carcasses below pylons using contingency tables and chi-square tests. We considered observed frequencies of each category significantly different from expected frequencies when the absolute value of the standardized residual was $>Z_{\alpha/2}$ ($\alpha = 0.05$). We tested the correlation between categories of different variables using the Spearman correlation coefficient (r_s; $P \leq 0.05$; Zar 1984). We also tested for the influence of rabbit (*Oryctolagus cuniculus*) presence on the frequency of pylons with carcasses of rabbit predator species (i.e., common buzzard, Eurasian eagle-owl, northern goshawk, and Bonelli's eagle).

We built logistic multiple regression models using presence or absence of carcasses below the pylons, as a dichotomous dependent variable, and several combinations of categorical independent variables (Tables 1, 2) to determine probability of electrocution risk for each pylon and the relative contribution of each variable. Using a logistic regression model, probability of electrocution risk can be expressed as: $P = e^z / (1 + e^z)$, where $z = b_0 + b_1x_1 + b_2x_2 + \ldots b_nx_n$, b_0 is an intercept constant, and b_n are coefficients indicating the relative importance of each variable in the model. We transformed variables with >2 categories into $a - 1$ dummy dichotomous variables (where a is the no. of categories of the original variable). We constructed models by a forward iteration process, testing

Table 1. Technical variables we used to classify pylon designs and codes of the dichotomous variables we used in logistic regression models. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, January 1999–November 2006.

Variables and categories	Description	Model variables
CONDUCTIVITY	Pylon conductivity related to material characteristics of pole and cross arms, and presence of a grounded conductor.	
Unearthed	Wood or concrete unearthed pylons. Not conductive.	[a]
Earthed	Wood or concrete earthed pylons. Conductive.	EARTH
Metal	Metal pylon. Conductive.	METAL
CONDUCTORS	Distribution of conductive elements (conductors and jumpers) on the cross-arm, related to the electrocution risk of possible perching places on the cross-arm.	
Suspended	All conductors situated under the corresponding cross-arm braces. All insulators or jumpers suspended.	[a]
Partially exposed	Pin-type insulators or exposed jumpers only on the lower cross-arm braces (used as secondary perching places).	PAREX
Principal exposed	Pin-type insulators or exposed jumpers on the top of the pylon (principal perching places on the cross-arm) or on all cross-arm braces.	PRIEX
All exposed	All conductors situated at the same level above the cross-arm (electrocution is possible because birds can simultaneously touch the different phases).	ALLEX
TECHNICAL ELEMENTS	Presence of different technical accessories on the cross-arm related to the pylon's function.	
Only insulators	Pylons with only pin-type suspended or strained insulators or jumper wires.	[a]
Connector wires	Pylons with wires connecting conductors placed on cross-arm braces without electrical devices.	CONNE
Devices	Pylons with switches, fuses, or transformers.	DEVIC
CONFIGURATION	No. and distribution of cross-arm braces, related to the possible no. and characteristics of perching points.	
Flat or cross	Pylons with a single cross-arm or with ≥2 vertically arranged cross-arms in the same plane.	[a]
Vault	Pylons with a possible perching point under the central part of one cross-arm.	VAULT
Vertical	Single-circuit (3 phases) arranged vertically on pylons, or multiple-circuits (6, 9, or 12 phases) arranged vertically in pairs on opposite sides of pylons.	VERTI
Alternate	Single-circuit (3 phases) arranged vertically and alternately on pylons.	ALTER
Perpendicular	Pylons with ≥2 vertically arranged cross-arms in a perpendicular plane.	PERPE

[a] Reference categories for dummy variables used in the models.

one variable at each step. When a variable had many dummy variables, we included all of them in the same step. We used the likelihood-ratio chi-square test to retain or discard variables (Hosmer and Lemeshow 2000) and we evaluated performance of the models using Receiver Operator Characteristic (ROC) plots and by calculating corresponding Area Under the Curve (AUC) values (Fielding and Bell 1997). The AUC values indicate the relationship between sensitivity (positive cases classified correctly) and specificity (negative cases classified correctly).

Model performance varied from 0.5 (random classification) to 1 (excellent). We also used the Hosmer–Lemeshow test to select the most suitable models, because it indicated the residual chi-square and deviance of the models (Hosmer et al. 1991). Low significant values corresponded to the best adjusted models, indicating that the remaining unused variables had no significant effect on improving the model. We used the chi-square of the Wald test as a complementary parameter to determine the individual significance of *b* coefficients for each variable (Carrasco and Hernán 1993). The models we obtained enabled us to assign a probability of electrocution risk (P_{ER}) to every pylon, and we subsequently arranged P_{ER} values into 10 percentiles with an equal number of cases (deciles). We also used the aggregation of P_{ER} values we obtained for each pylon with a carcass (positive cases) to select the best model. We considered models with positive cases that aggregated in the highest deciles better than those with a more scattered distribution of P_{ER} values.

Validating the Models

We used 3,094 pylons from the first survey (80%) to generate models (generation sample) and the remaining 20% (775 pylons), which we randomly segregated, to validate the models a posteriori. We calculated P_{ER} values for pylons in the validation sample using model equations we generated with the generation sample. To validate the models, we grouped pylons in the generation sample into 4 categories according to their P_{ER} value: LOW, comprising the lowest P_{ER} values that aggregated up to 5% of pylons with carcasses; MODERATE, which contained the next 15% of pylons with carcasses; HIGH, aggregating the next 30%; and VERY HIGH, aggregating the remaining 50% of pylons with carcasses. Then, we used the cut-off P_{ER} values between these categories to establish the same categories in the validation sample. We then compared (χ^2 test) the actual distribution of positive cases in each category (no. of pylons under which we found carcasses) in the validation sample with the expected distribution (5%, 15%, 30%, 50%) derived from the model. To have suitable values of expected frequencies for the analysis, we pooled the LOW and MODERATE categories.

Model Implementation

After November 2006, the various concerned power companies corrected 222 pylons classified in the 2 most dangerous categories of risk of electrocution: 136 VERY HIGH pylons (61.3%) and 86 HIGH pylons (38.7%).

Table 2. Environmental variables we used to describe pylon position and the codes of the dichotomous variables used in logistic regression models. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, January 1999–November 2006.

Variables and categories	Description	Model variables
HABITAT	Dominant habitat typology in a radius of 100 m around the pylon.	
Urban	Urban areas with a dense or disperse presence of buildings (towns, housing developments, or industrial estates).	[a]
Mosaic	Landscape with an extensive agricultural matrix and small patches of forest.	MOSAI
Scrubland	Homogeneous areas without trees or areas affected by forest fires: Mediterranean scrubland (maquis or garrigues) or dry grasslands.	SCRUB
Forest	Homogeneous areas with trees (oak forests or pine plantations).	FORES
VEGETATION COVER	Typology and density of the predominant vegetation cover in a radius of 50 m around the pylon.	
Dense	Woodland, tree plantations, or garrigues with thick impassable understory.	DENVC
Open woodland	Woodlands with low vegetation cover (ground is visible). Also included are plantations and dry or irrigated tree croplands.	OWOVC
Low	Mediterranean scrublands with low vegetation cover including maquis, shrubs, or dry grassland.	LOWVC
Cropland	Dry or irrigated herbaceous croplands (cereals or vegetables) and vineyards.	CROVC
Bare ground	Paved or human-modified areas without vegetation.	[a]
TOPOGRAPHY	Site of pylons in relation to their function as perches for birds.	
Ridge	Hill or mountain ridge or peak.	RIDGE
No ridge	Slopes of hills, flat areas, or valley bottoms.	
OVERHANGING	Pylons overhanging other landscape elements (trees, buildings) in a radius of 50 m around the pylon (importance as perches for birds).	
No	Pylons not overhanging.	
Yes	Pylons overhanging.	OVHAN
WATER POINTS	Presence of natural watercourses or infrastructures used for water storage in a radius of 100 m around the pylon.	
No	Absence of water points.	
Yes	Presence of rivers, reservoirs, or agricultural ponds.	WATER
INFRASTRUCTURES	Presence of buildings or other infrastructures regularly frequented by humans in a radius of 100 m around the pylon.	
No	Absence of frequented infrastructures (isolated chapels or ruins are included).	
Yes	Presence of frequented infrastructures (houses, farms, factories, rubbish dumps, quarries, or sports complexes).	INFRA
PAVED ROADS	Presence of paved roads in a radius of 100 m around the pylon.	
No	Absence of roads or only presence of unpaved forest tracks.	
Yes	Presence of paved roads (principal or secondary road network).	PROAD
PRESENCE OF RABBIT	Signs of rabbit presence in a radius of 50 m around the pylon, a factor directly related to the prey abundance for many raptor species present in the study area.	
No	No signs of rabbits detected.	
Yes	Signs of rabbits detected (direct observations, excrements, or tracks).	RABBI

[a] Reference categories for dummy variables used in the models.

Corrective measures implemented by the companies involved 1) substitution of the pylon with a new one based on alternate cross-arms designs (27 pylons, 12.2%; Figs. 2.1, 3.4); 2) substitution of exposed jumpers and pin-type insulators with suspended jumpers and insulators (25 pylons, 11.3%; Fig. 3.1); 3) isolation of the conductive parts of the cross-arms, principally in vault cross-arm pylons (60 pylons, 27.0%; Fig. 3.2); and 4) substitution of the central exposed jumper and pin-type insulator with a suspended insulator, along with isolation of the jumper and conductor wires as a supplementary measure (110 pylons, 49.5%; Fig. 3.3). Isolating materials consisted of silicone cases (3M Company, St. Paul, MN) to cover conductor wires and jumpers (Fig. 3.2, 3.3), silicone insulating tape (3M Company) to cover steel hook-ends on suspended insulators (Fig. 3.2), and BCIC cover packs (Raychem Company, Dorcan, Swindon, United Kingdom) to cover steel hook-ends on strained and suspended insulators (Fig. 3.3).

To evaluate the reduction in mortality rates after application of corrective measures, we conducted a second survey from December 2007 to December 2008. We visited the 222 corrected pylons (experimental sample) and 350 noncorrected pylons (control sample) to search for carcasses of electrocuted birds. The control sample included 200 VERY HIGH risk pylons (57.3%) and 150 HIGH risk pylons (42.9%), which we randomly selected from among pylons with comparable technical and environmental features to those of the experimental sample. We visited the experimental and the control samples before May 2004 during the first survey, and we conducted visits during the second survey ≥1 year after application of corrective measures.

We used the Wilcoxon test to evaluate variation in mortality rates on the experimental sample before and after application of corrective measures. To compare variation in mortality rates in the study area between the 2 prospecting

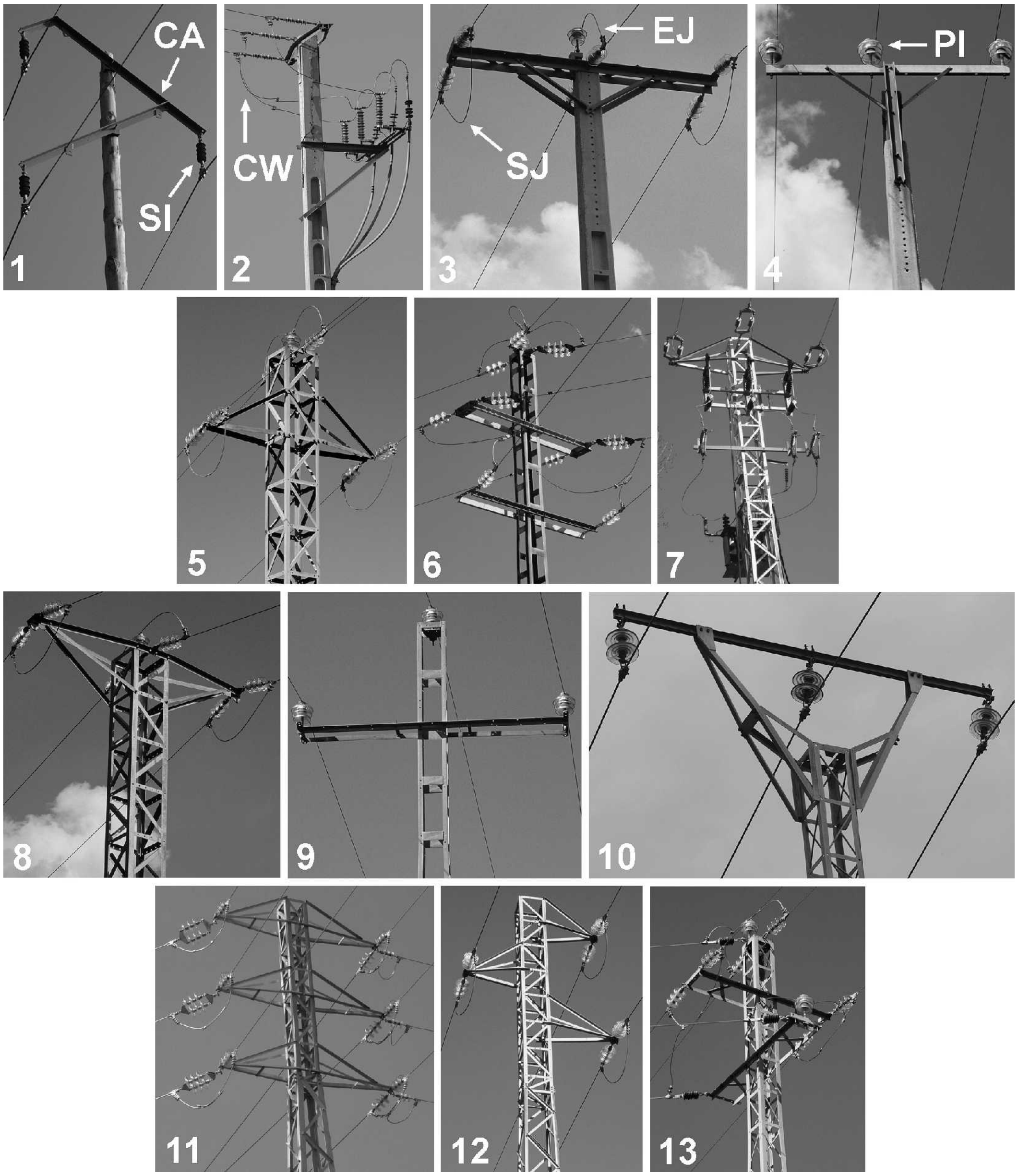

Figure 2. Illustrations of the different categories of technical variables examined in study of pylons in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, January 1999–November 2006. CONDUCTORS: (1) suspended, (2) partially exposed, (3) principal exposed, (4) all exposed; TECHNICAL ELEMENTS: (5) only insulators, (6) connector wires, (7) devices; and CONFIGURATION: (8) flat, (9) cross, (10) vault, (11) vertical, (12) alternate, (13) perpendicular. Parts of pylons indicated: CA, cross-arm; CW, connector wires; EJ, exposed jumper; PI, pin-type insulator; SI, suspended insulator; and SJ, suspended jumper.

periods, we conducted the same analysis using the control sample. During this second survey, we only used carcasses estimated <1 month old for this analysis. We conducted statistical analyses using the SPSS 15.0 statistical package (SPSS Inc., Chicago, IL).

RESULTS

During the first survey (Jan 1999–Nov 2006) we found 141 carcasses below 98 (2.5%) of 3,869 pylons prospected. Average electrocution rate was 0.036 carcasses/pylon prospected and average electrocution aggregation rate was 1.44 carcasses/pylon. Maximum number of carcasses we found below any one pylon was 6 ($n = 2$), although for most pylons ($n = 66$) we found only one carcass. We found 21 bird species, of which 5 are included in Annex I of the European Bird Directive for endangered species (79/409/CE; Table 3). The species most affected by electrocution were common buzzard and common raven; diurnal raptors (33.3%), corvids (31.2%), and owls (12.1%) were the principal groups affected. The remaining 23.4% of carcasses were doves, pigeons, small passerines, storks, cormorants, gulls, and woodpeckers. From a conservation point of view, the most significant species we found electrocuted was Bonelli's eagle (European Threat Status: Endangered, SPEC 3); other species we found electrocuted included white stork (SPEC 2), short-toed eagle (SPEC 3), common

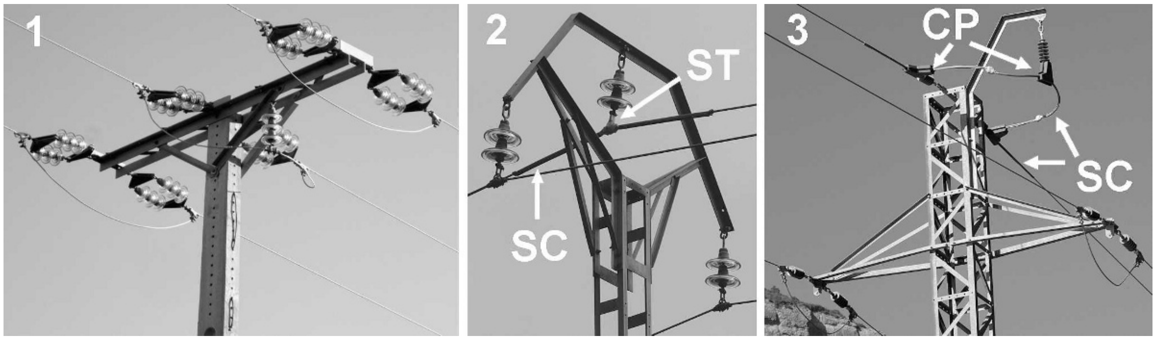

Figure 3. Illustration of examples of the corrective measures implemented in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in December 2006–December 2007: (1) concrete pylon in which the pin-type insulator and the central exposed jumper were substituted for one suspended insulator and jumper; (2) vault pylon in which the central conductor wire was isolated using 3M silicone covers (3M Company, St. Paul, MN; SC) and the metal hook-end of the suspended insulator isolated using 3M silicone insulating tape (ST); (3) metal pylon in which the pin-type insulator and the central exposed jumper were substituted with one suspended insulator. The new suspended jumper was isolated using 3M silicone covers and the metal hook-end of the 2 central strained insulators covered using Raychem BCIC cover packs (Raychem Company, Dorcan, Swindon, United Kingdom; CP).

kestrel (European Threat Status: Declining, SPEC 3) and Eurasian eagle-owl (SPEC 3; BirdLife International 2004). In all, 62% of age-identified carcasses found were adult birds ($n = 53$).

All the technical characteristics of the pylons and 5 of the environmental variables we considered had a significant effect on frequency distribution of carcasses below pylons (Table 4). Metal pylons, presence of connector wires, exposed conductors in dominant places, vault or perpendicular designs, presence of rabbits, overhanging pylons, ridge topography, low vegetation cover, and scrubland or mosaic habitats increased frequency of carcass occurrence. On the other hand, unearthed pylons, suspended conductors, alternate cross-arms, urban and forest habitats, and open woodland vegetation cover had significantly less risk of electrocution. We found a strong correlation between presence of connector wires and a perpendicular configuration ($r_s = 0.867$, $P \leq 0.001$) and between all exposed conductors and presence of devices ($r_s = 0.694$, $P \leq 0.001$). The rest of the combinations between categories had low or nonsignificant correlations ($P > 0.05$). The categories that had the lowest electrocution rates (carcasses/pylon) were unearthed pylons, designs with alternate cross-arms, suspended conductors, nonoverhanging pylons, and urban habitats, whereas the categories with the highest values were presence of rabbits, vault configuration, and presence of only connector wires (Table 4). Occurrence of carcasses of rabbit predators was higher in areas with rabbits (74.2% of pylons) than in areas with no detectable rabbits (28.3% of pylons; $n = 98$, $\chi^2_1 = 16.36$, $P \leq 0.001$).

Table 3. Species and number of birds found electrocuted in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

Family	Species	Carcasses
Phalacrocoracidae	Great cormorant (*Phalacrocorax carbo*)[a]	2
Ciconidae	White stork (*Ciconia ciconia*)[a]	3
Accipitridae	Short-toed eagle (*Circaetus gallicus*)[a]	4
	Northern goshawk (*Accipiter gentilis*)	10
	Eurasian sparrowhawk (*Accipiter nisus*)	1
	Common buzzard (*Buteo buteo*)	24
	Bonelli's eagle (*Aquila fasciata*)[a]	4
Falconidae	Common kestrel (*Falco tinnunculus*)	4
Laridae	Yellow-legged gull (*Larus michahellis*)	1
Columbidae	Wood pigeon (*Columba palumbus*)	3
	Collared dove (*Streptopelia decaocto*)	10
Strigidae	Eurasian eagle owl (*Bubo bubo*)[a]	11
	Tawny owl (*Strix aluco*)	6
Picidae	Great spotted woodpecker (*Dendrocopos major*)	1
Turdidae	Common blackbird (*Turdus merula*)	2
Corvidae	Eurasian jay (*Garrulus glandarius*)	2
	Common magpie (*Pica pica*)	14
	Western jackdaw (*Corvus monedula*)	1
	Carrion crow (*Corvus corone*)	13
	Common raven (*Corvus corax*)	20
Sturnidae	Common starling (*Sturnus vulgaris*)	5
Total		141

[a] Species included in Annex I of the Wild Bird European Directive (79/409/CE).

We selected the model that best fit the data ($\chi^2_{15} = 159.90$, $P \leq 0.001$) and that also had the highest AUC value for the ROC analysis (AUC = 0.871, 95% CI = 0.837–0.906, $P \leq 0.001$) and the highest residual probability value for the Hosmer–Lemeshow test ($\chi^2_8 = 3.37$, $P = 0.909$; Table 5). The best fitting model incorporated 15 dummy variables corresponding to the original variables: conductivity, conductors, configuration, habitat, topography, overhanging pylons, and presence of rabbits. Significance of chi-square in the Wald test for each *b* coefficient included in the logistic equation indicated that technical variables related to conductivity (EARTH, METAL) and distribution of the conductive parts of pylon (PAREX, PRIEX, ALLEX) most influenced the risk of electrocution. The VAULT variable was also significant. Environmental variables included in the model relating to habitat (MOSAI, SCRUB, FORES), topography (RIDGE), pylons overhanging other landscape elements (OVHAN), and presence of rabbits (RABBI) were relevant in differentiating safe from dangerous pylons of the same technical design.

Predicted values of the probability of electrocution risk (P_{ER}) were largely aggregated. More than 60% of pylons had P_{ER} values of <0.01, whereas <4% had values >0.1. Maximum P_{ER} was 0.370. Considering only pylons with

Table 4. Univariate analysis we conducted to determine technical and environmental variables and categories that influence the electrocution of birds in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

Variables and categories	Pylons	Pylons with carcasses	Carcasses	Electrocution rate (carcasses/pylon)	χ^2 (variables) and residuals[a] (categories)
CONDUCTIVITY					$\chi^2 = 63.09$, df = 2, $P < 0.001$
Unearthed	1,216	1	1	0.001	−6.6[b]
Earthed	811	13	16	0.020	−1.9
Metal	1,842	84	124	0.067	7.7[b]
CONDUCTORS					$\chi^2 = 9.51$, df = 3, $P < 0.05$
Suspended	732	9	10	0.014	−2.5[b]
Partially exposed	254	3	4	0.016	−1.4
Principal exposed	2,258	69	100	0.044	2.5[b]
All exposed	625	17	27	0.043	0.3
TECHNICAL ELEMENTS					$\chi^2 = 9.29$, df = 2, $P < 0.01$
Only insulators	2,628	63	85	0.032	−0.8
Connector wires	344	17	27	0.078	3.0[b]
Devices	897	18	29	0.032	−1.1
CONFIGURATION					$\chi^2 = 21.17$, df = 4, $P < 0.001$
Flat or cross	2,786	69	99	0.036	−0.5
Vault	100	7	8	0.080	2.5[b]
Vertical	392	4	6	0.015	−2.0
Alternate	210	1	1	0.005	−2.1[b]
Perpendicular	380	17	27	0.071	2.5[b]
HABITAT					$\chi^2 = 35.32$, df = 3, $P < 0.001$
Urban	1,166	12	18	0.015	−3.9[b]
Mosaic	1,754	61	91	0.052	3.4[b]
Scrub land	232	15	18	0.078	3.9[b]
Forest	717	10	14	0.020	−2.1[b]
VEGETATION COVER					$\chi^2 = 21.22$, df = 4, $P < 0.001$
Dense	822	15	19	0.023	−1.5
Open woodland	839	10	16	0.019	−2.8[b]
Low vegetation cover	989	43	59	0.060	4.2[b]
Cropland	1,108	28	45	0.041	−0.1
Bare ground	111	2	2	0.018	−0.5
TOPOGRAPHY					$\chi^2 = 16.22$, df = 1, $P < 0.001$
No ridge	3,459	75	111	0.032	−4.2[b]
Ridge	410	23	30	0.073	4.2[b]
OVERHANGING					$\chi^2 = 23.90$, df = 1, $P < 0.001$
Nonoverhanging	1,989	26	30	0.015	−5.0[b]
Overhanging	1,880	72	111	0.059	5.0[b]
WATER POINTS					$\chi^2 = 1.81$, df = 1, $P = 0.179$
Without water points	3,621	88	125	0.035	−1.6
With water points	248	10	16	0.065	1.6
INFRASTRUCTURES					$\chi^2 = 3.11$, df = 1, $P = 0.078$
Without infrastructures	2,373	69	90	0.038	1.9
With infrastructures	1,496	29	51	0.034	−1.9
ROADS					$\chi^2 = 1.11$, df = 1, $P = 0.293$
Without paved roads	3,248	78	112	0.034	−1.2
With paved roads	621	20	29	0.047	1.2
PRESENCE OF RABBITS					$\chi^2 = 25.24$, df = 1, $P < 0.001$
Rabbits absent	3,334	67	98	0.029	−5.2[b]
Rabbits present	535	31	43	0.080	5.2[b]
Total	3,869	98	141	0.036	

[a] Corrected standardized residuals.

[b] Significant corrected standardized residuals $<Z_{\alpha/2}$ ($\alpha = 0.05$).

carcasses (Fig. 4), >50% of pylons fell within the decile 10 with the highest P_{ER} (90–100%), and >75% fell in deciles 9 and 10. On the other hand, <5% of cases were in the lowest 50% of P_{ER} values (deciles 1–5) and the lowest P_{ER} for a pylon with a carcass was in decile 3 (20–30%). All pylons with >1 carcass were in decile 5 or above and 65% were in decile 10.

For model validation we established P_{ER} cut-off values for the 4 categories of risk of electrocution we used to classify the pylons: LOW to MODERATE: 0.006, MODERATE

Table 5. Variables included in the selected model, *b* coefficient, standard error, and Wald test results for each variable. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

Variables	*b* coeff.	SE	Wald
INTERCEPT	−12.67	1.71	54.68, $P < 0.001$
EARTH	2.77	1.07	6.82, $P = 0.009$
METAL	4.08	1.01	16.14, $P < 0.001$
PAREX	3.11	1.40	4.93, $P = 0.026$
PRIEX	4.33	1.32	10.77, $P = 0.001$
ALLEX	4.19	1.36	9.50, $P = 0.002$
VAULT	3.78	1.40	7.28, $P = 0.007$
VERTI	−0.10	0.56	0.03, $P = 0.864$
ALTER	1.15	1.35	0.73, $P = 0.394$
PERPE	0.09	0.34	0.07, $P = 0.787$
MOSAI	1.06	0.36	8.61, $P = 0.003$
SCRUB	1.31	0.49	7.10, $P = 0.008$
FORES	0.54	0.57	0.91, $P = 0.340$
RIDGE	0.78	0.30	6.72, $P = 0.010$
OVHAN	0.74	0.30	6.08, $P = 0.014$
RABBI	0.98	0.27	12.95, $P < 0.001$

to HIGH: 0.023, and HIGH to VERY HIGH: 0.064 (Fig. 5). We found no difference between observed distribution of positive pylons within the LOW–MODERATE, HIGH, and VERY HIGH categories in the validation sample with the expected distribution (20%, 30%, 50%; $\chi^2_2 = 1.145$, $P = 0.564$; Table 6). Hence, the model classified the validation sample according to the actual risk of electrocution. To calculate the electrocution rate associated with each category of risk of electrocution we pooled the generation and validation samples (Table 7). In total, 9.2% of pylons in the VERY HIGH category accounted for 53.2% of carcasses, whereas 54.5% of pylons included in the lowest category accounted for only 3.5% of mortality. Results also indicated that VERY HIGH pylons were approximately 2.6 times more dangerous than HIGH pylons, 9.2 times more so than MODERATE pylons, and 100 times more so than LOW pylons.

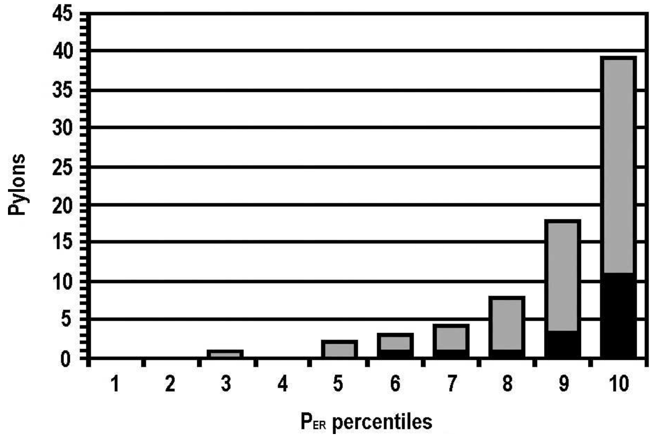

Figure 4. Distribution of the 75 pylons with carcasses included in the generation sample according to probability of electrocution risk (P_{ER}). We grouped P_{ER} values into 10 deciles. Decile 1 included the 10% of lowest P_{ER} values and decile 10 the highest 10%. Black color indicates the number of pylons below which we found >1 carcass. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

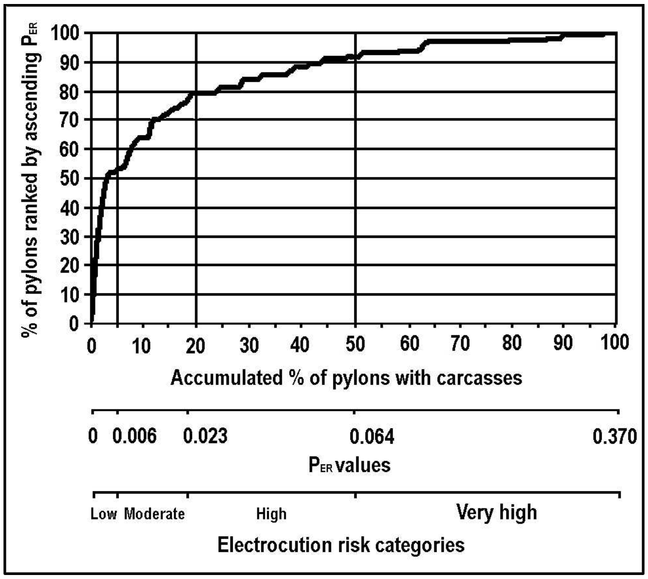

Figure 5. Accumulated percentage of pylons with carcasses in relation to the total percentage of pylons arranged in ascending order of probability of electrocution risk (P_{ER}) values. We indicated P_{ER} cut-off values selected for categories of the electrocution risk: LOW, MODERATE, HIGH and VERY HIGH. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

We found 29 carcasses below the pylons of the experimental sample before the implementation of the corrective measures (0.131 carcasses/pylon), and none after, thereby indicating a significant reduction in mortality rates (Wilcoxon test, $Z = -4.77$, $P \leq 0.001$). In the control sample, we found 25 carcasses (0.071 carcasses/pylon) during the first survey and 29 carcasses (0.083 carcasses/pylon) during the second (Wilcoxon test, $Z = -0.02$, $P = 0.984$). The proportion of carcasses of raptors (Accipitidae, Falconidae, and Strigidae) as opposed to other birds (Corvidae, Columbidae and Sturnidae) did not differ between the 2 surveys ($\chi^2_1 = 0.09$, $P = 0.759$; Table 8).

DISCUSSION

The frequency and number of carcasses found per pylon were lower in our study area than in other Mediterranean areas in Spain where similar searches have been conducted (Ferrer et al. 1991, Guzmán and Castaño 1998, Janss and Ferrer 2001, Mañosa 2001, Moleón et al. 2007). Still, we reported a high occurrence of electrocution in many raptor species, particularly the common buzzard, the Eurasian

Table 6. Frequency distribution of the number of pylons and pylons with carcasses included in each risk category in the generation and the validation samples. We pooled low and moderate categories for the risk of electrocution. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

	Generation sample		Validation sample	
Electrocution risk categories	Total pylons	Pylons with carcass	Total pylons	Pylons with carcass
Low–moderate	2,400	15	612	6
High	397	22	104	8
Very high	297	38	59	9

Table 7. Distribution of bird mortality for each category of risk of electrocution. We pooled generation and validation samples. Data collected in the Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in January 1999–November 2006.

Electrocution risk categories	Pylons		Pylons with carcass		Carcasses		Electrocution rate (carcasses/pylon)
	no.	%	no.	%	no.	%	
Low	2,105	54.5	5	5.1	5	3.5	0.002
Moderate	907	23.4	16	16.3	21	14.9	0.023
High	501	12.9	30	30.6	40	28.4	0.080
Very high	356	9.2	47	48.0	75	53.2	0.211
Total	3,869		98		141		0.036

eagle owl, the northern goshawk, and the short-toed eagle, as has been found in other areas in Catalonia (Mañosa 2001). If electrocution rates are similar throughout country, electrocution may be limiting populations of these species of raptors, as has been found elsewhere for the eagle owl (Sergio et al. 2004).

The lower occurrence of electrocution in our area compared to other studies in Spain may be because the latter were conducted in settlement areas where juvenile raptors concentrate (Real and Mañosa 2001, Martí and Del Moral 2003, Estrada et al. 2004). However, the demographic impact of electrocutions in our study area should not be underestimated, because most birds we found electrocuted were adult and were probably breeding birds (Ribas 2000, Estrada et al. 2004, Estrada and Anton 2007). The decrease in adult survival may have a severe direct negative effect on population viability of long lived birds of prey (Newton 1979, Real and Mañosa 1997, Ortega et al. 2008) and also may have negative indirect effects by inducing breeding failure or the recruitment of nonexperienced birds (Carrete et al. 2006, Martínez et al. 2008, Hernández-Matías et al. 2010). On the other hand, electrocution in our study area may have important consequences for the viability of some endangered species not found in other areas, particularly Bonelli's eagle, which declined from 6 pairs to 3 pairs during the 1990s (Real and Mañosa 1997, Real et al. 2001, Bosch et al. 2010). We found 4 adult eagles in the 1999–2006 survey and identified electrocution as the main cause of mortality in this eagle (Real et al. 2004). Thus, it is vital for the conservation of this species to detect dangerous pylons and to implement appropriate corrective measures as soon as possible. Paradoxically, although 75% of our study area consisted of wooded and rugged protected land where most raptors breed, we found 95% of carcasses on the surrounding unprotected land, in open human-impacted areas selected for foraging.

Table 8. Species and number of birds we found electrocuted below the pylons during the 2 surveys of the experimental and control samples used to evaluate the reduction in mortality rates, Barcelona Pre-littoral Mountains, Catalonia, northeast Spain, in December 2007–December 2008. First survey: January 1999–May 2004; second survey: December 2007–December 2008.

Family	Species	Corrected sample		Control sample	
		Survey 1	Survey 2	Survey 1	Survey 2
Accipitridae	Short-toed eagle	1	0	0	0
	Northern goshawk	3	0	1	0
	Common buzzard	7	0	3	2
	Bonelli's eagle	2	0	0	0
Falconidae	Common kestrel	1	0	1	1
Columbidae	Wood pigeon	0	0	1	0
	Collared dove	0	0	0	4
Strigidae	Eurasian eagle owl	7	0	0	1
	Tawny owl	1	0	2	2
Corvidae	Eurasian jay	0	0	1	1
	Common magpie	3	0	2	2
	Carrion crow	1	0	5	7
	Common raven	3	0	7	9
Sturnidae	Common starling	0	0	2	0
Total		29	0	25	29

We found pylon design to be the main factor that makes pylons potentially dangerous for birds. The safest designs were unearthed pylons with suspended pin-insulators or jumpers, alternate cross-arm configurations, and no connector wires. Contrary to what has been found elsewhere (Guzmán and Castaño 1998), we found that vault designs caused many electrocutions, which could be the result of differences in the raptor community considered or habitat and behavioral differences between areas. Environmental variables were also important in explaining reported cases of electrocuted birds. Pylons with a dominant position in the landscape, especially those placed on hilltops and surrounded by low vegetation cover (scrubland), had higher electrocution rates. These pylons are often chosen by territorial bird species such as raptors as perching points because they are good places from which to detect potential prey items (Benson 1982). Another reason why these pylons are actively selected is that scrubland holds the highest abundances of rabbits and other raptor prey, which are also more accessible in open vegetation (Lombardi et al. 2003, APLIC 2006). As such, our results revealed that pylons placed in areas with high rabbit indices accumulated more carcasses of raptors that prey on rabbits, such as the endangered Bonelli's eagle (Real 1991, Moleón et al. 2009).

The predictive model selected fit the data well and enabled us to locate precisely the most dangerous pylons for birds, especially those pylons accumulating >1 carcass, and was able to correctly classify an independent sample of pylons. Our results indicate that a few pylons (<10% of those classified as of very high risk) accounted for much of the total mortality (>50%), which confirms that electrocution casualties obey an aggregated pattern (Benson 1982, Mañosa 2001). The model we developed worked well in a Mediterranean human-impacted area with a diversity of species of birds and habitats and we think the model could be useful in areas with similar landscapes and species such as southern France (Thiollay and Bretagnolle 2004) or the southeast coast of Spain (Martí and Del Moral 2003). Nevertheless, before using the model in areas with different target species or habitats, the model should be validated or new, specific models should be generated using our described approach. This work could provide specific tools for preventing electrocution in areas with high endangered bird species affected by electrocution such as imperial eagle (*Aquila heliaca*) and black vulture (*Aegypius monachus*) in Mediterranean open landscapes, osprey (*Pandion haliaetus*) and white-tailed eagle (*Haliaeetus albicilla*) in wetlands, and lammergeier (*Gypaetus barbatus*) and golden eagle in high mountain ranges.

MANAGEMENT IMPLICATIONS

Management institutions and governments should apply strategies that optimize efforts and resources involved in mitigating the impact of electrocution in birds (Mañosa 2001), especially in areas with many pylons and a diversity of technical designs, habitat features, and species of birds involved. Although the burial of new power lines is a definitive and permanent solution to the electrocution problem, alternative corrections can be used in existing ones (Janss and Ferrer 1999*b*). Substitution of dangerous pylons or cross-arm designs for safer ones may be preferable to insulation, which is not permanent and needs regular monitoring and repair. On the other hand, dangerous vault pylons should be avoided in new power lines and corrective measures should be applied to pylons of this type that already exist in areas with endangered species. In conclusion, our results indicate that electrocution of birds in a given area can almost be eliminated by means of a combination of an adequate pylon selection strategy with well-tested correction techniques, resulting in an optimal allocation of resources by public agencies and power line companies to bird conservation.

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