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Electrocution risk for the endangered Crowned Solitary Eagle and other birds in semiarid landscapes of central Argentina

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Summary

High mortality by electrocution has been suggested to be the main factor behind the reduction of several birds of prey populations across the world. Almost nothing is known, however, about the impact of power lines on this group of birds in the Neotropical Region. Here we estimate electrocution rates for birds on power lines covering both arid and semiarid biomes of central Argentina. We conducted six bi-monthly power line and raptor surveys throughout 355 km of lines and roads covering an area of approximately 12,000 km^2. We described the structural design of 3,118 surveyed electricity pylons. We found 34 electrocuted individuals of four bird families that constitute an annual bird electrocution rate of 0.011 bird/pylon/year. Bird electrocution occurred mostly on concrete pylons with jumpers above the cross-arm. Larger birds of prey had a higher electrocution rate than smaller species. The Crowned Solitary Eagle *Buteogallus coronatus* was disproportionately affected by this mortality source when compared with its low population density. Electrocution incidents occurred mostly in a few electric pylon designs that represent only 10.2 % of the power pylons monitored in the study area. Therefore, the change or modification of a small fraction of pylons would almost eliminate bird electrocution incidents in our study area. Our results prove that electrocution is a relevant cause of mortality for Crowned Solitary Eagles and urgent mitigating actions are needed to reduce this mortality factor.

Introduction

Infrastructures resulting from development and global human population growth represent an increasing cause of wildlife mortality. Birds in particular are killed on roads by motor vehicles (Guinard *et al.* 2012), in air strikes with aircraft (Dolbeer and Aviation 2015), and collision with buildings (Klem 1990, Machtans *et al.* 2013, Loss *et al.* 2014), with wind energy facilities (De Lucas *et al.* 2008, Smallwood and Thelander 2008, Loss *et al.* 2013), communication towers (Longcore *et al.* 2013), and more recently, solar power tower facilities (Diehl *et al.* 2016). Human-made structures and moving objects impacting flying vertebrates are a growing worldwide conservation concern (Lambertucci *et al.* 2015). For birds of prey, electrocution on power lines is one of the most important mortality factors associated with human-made structures (Van Rooyen and Ledger 1999, APLIC 2006, Lehman *et al.* 2007, Kemper *et al.* 2013). Bird of prey mortality by electrocution can wipe out some raptor populations from vast areas (Sergio *et al.* 2004) and was the main factor behind the decrease of several bird of prey populations across the world, some of them highly endangered (Bevanger and Overskaug 1998, Real *et al.* 2001, Angelov *et al.* 2012). Electrocution of birds of prey on power lines results from the interaction of three main components: biology, environment and engineering (APLIC 2006). The biology aspects that bias bird electrocutions are body size, age, behaviour and prey availability. Bird of prey vulnerability to electrocution is mainly driven by their body size as this group has several of the largest species among flying birds. Besides, birds of prey spend a considerable time perched and thus are prone to use power pylons as perching sites, especially in environments where natural perches are scarce (Dwyer *et al.* 2015). In North America and South Africa, size is the most important factor explaining bird electrocution risk (APLIC 2006). Thus, large eagles are the most common victims in USA while in South Africa the victims are vultures (Lehman *et al.* 2007). The environmental component includes habitat structure and characteristics of the location of the power lines. Electrocution is more common in open areas where high quality perching sites for birds of prey are scarce (Lehman *et al.* 2007). Within the engineering component, the material with which pylons are built, and their design are key factors that facilitate or prevent bird electrocution incidents. In Europe for example, the size of birds is less important in electrocution events than in the USA, because while in the latter most pylons are made of wood, in Europe most pylons are made of conductive steel or concrete with steel cross-arms (Negro and Ferrer 1995) and thus are earthed. When a bird of even small size perches on the pylon it can be electrocuted just by touching any conducted wire while perched (Negro *et al.* 1989). In the case of wooden poles, typically the bird needs to contact at least two wires to be electrocuted, meaning that it has to have a minimum wingspan to be at risk.

Avian electrocution, a recognised threat for birds in North America (Harness and Wilson 2001, Lehman 2001), Europe (Ferrer *et al.* 1991, Bevanger 1994, Negro 1999, Rollan *et al.* 2010), South Africa (Ledger and Annegarn 1981, Van Rooyen and Ledger 1999, Kruger *et al.* 2004) and Asia (Lasch *et al.* 2010, Shobrak 2012, Voronova *et al.* 2012, Harness *et al.* 2013), has been totally ignored in the Neotropics. For southern South America, there are just anecdotal reports referring to casual raptor electrocution events (Jiménez and Jaksic 1990, Alvarado Orellana and Roa Cornejo 2010, Nolazco and Conde 2010, Ibarra and De Lucca 2015) but no specific standardised assessment of the impact of this mortality factor has been done.

The endangered Crowned Solitary Eagle *Buteogallus coronatus* is one of the largest birds of prey ranging in South America. It is a long-lived raptor with delayed maturity and low fecundity (no more than one fledgling per pair can be produced each year as they lay a single egg) that inhabits open semi-arid forests in different biomes from southern and central Brazil, Bolivia and Paraguay to northern Patagonia in Argentina (Ferguson-Lees and Christie 2001, authors' unpubl. data). The species is listed as 'Endangered' by IUCN with a global reproductive population estimated at less than 1,000 mature individuals and a decreasing trend (BirdLife International 2016). Although the main factors threatening the species are thought to be high non-natural mortality by human persecution (Sarasola and Maceda 2006, Sarasola *et al.* 2010, Barbar *et al.* 2016) and habitat loss (Bellocq *et al.* 2002, Fandiño and Pautasso 2013), there is evidence that they suffer unquantified mortality by other human related factors such as electrocution in power lines (Chebez *et al.* 2008). Here we quantified susceptibility to electrocution and electrocution rates for birds of prey in arid and semi-arid biomes of central Argentina where we have been studying Crowned Solitary Eagles since 1999. In the area we have identified around 30 breeding territories of the Crowned Solitary Eagle. Our aim was estimate minimum yearly electrocution rates for this endangered species and other birds, as well as to assess some biotic and abiotic factors that may determine electrocution risk for birds in the area.

Material and methods

Study area

The study area covered approximately 12,000 km² in mid-western La Pampa province, central Argentina (Figure 1). The study area hold two ecoregions, the Espinal in the eastern portion and the Monte Desert towards the west (Brown *et al.* 2006). Typical vegetation within the Espinal includes xerophytic deciduous forests characterised by trees of the genus *Prosopis*. In its southern

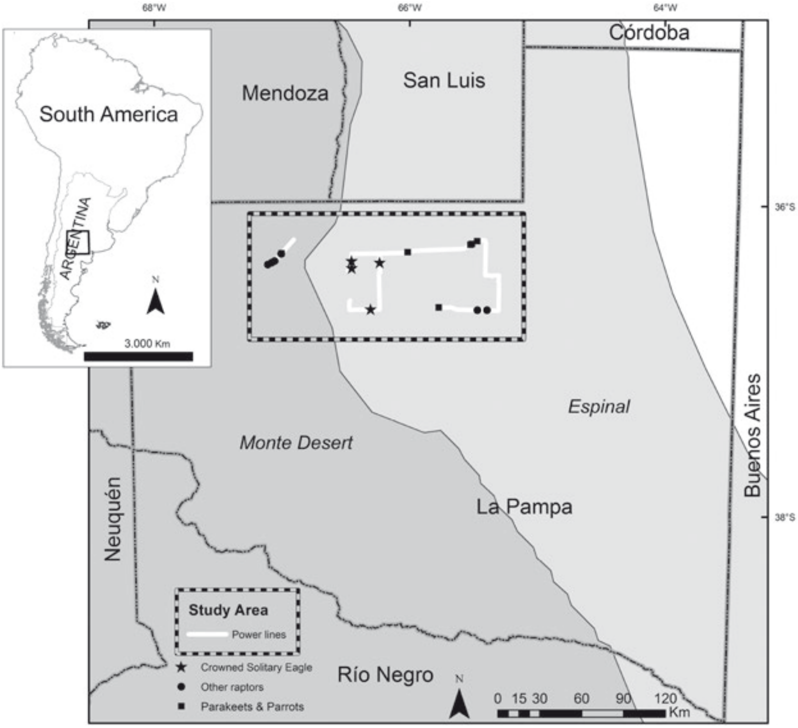

Figure 1. Power lines surveyed and electrocuted bird records in our study area in La Pampa province, Argentina, from November 2011 to December 2012.

portion, where our study area is located, the dominant tree is the Caldén *Prosopis caldenia*. The typical vegetation of the Monte Desert ecoregion is a high shrub steppe, mostly characterised by *Larrea* sp. communities with isolated *Prosopis* sp. trees. In both ecoregions, the climate is temperate-arid with very high temperatures in summer (up to 45° C) when most of the scarce rainfall falls (80–300 mm yr-1 for the Monte and 300–550 mm yr-1 for the Espinal region) (Fernandez and Busso 1997). In the study area we have been monitoring a variable number of breeding territories of the Crowned Solitary Eagle since 1999. We estimate that there may be around 30 territories although we have not found more than 10 active nests in a single year. Furthermore, genetic data under analysis suggest that some breeding pairs move between what we consider different breeding territories so the actual number of occupied territories could be lower than our estimates.

Power line surveys

From November 2011 to December 2012, we surveyed all the available power lines located along paved or dirt public roads on public land within the study area (Figure 1). The monitored power lines were all distribution lines of 13.2 kv voltage with a single or three phase distribution lines (energised conductors). Surveys were performed by an observer driving a motorcycle beneath the power lines and monitoring 3,118 pylons along 355 km. These surveys were repeated six times during the study period at an interval of two months between visits. On each visit we inspected a 10 m radius around each pylon looking for carcasses and searched for birds in the area below the line between pylons when vegetation and topography allowed motorcycle transit (Janss 2000, Kemper *et al.* 2013). Dead birds beneath pylons were considered electrocuted when we were able to unequivocally identify electrocution signs such as burned beaks, wings or legs. Carcasses without electrocution signs or uncertainty on the cause of death were not considered in the analyses. When possible we also recorded the age and sex of electrocuted birds.

In order to evaluate the electrocution risk for each pylon design present in the study area, we described its structural characteristics, including the type of material used for its construction (wood or concrete), presence/absence and position of jumpers, and type and position of insulators. In order to evaluate the effect of the surrounding vegetation on the electrocution cases, we determined the vegetation physiognomy in a radius of 50 m around each pylon surveyed. Vegetation physiognomy was classified in three main classes as grassland, scrubland or forest.

Abundance of birds of prey

To evaluate electrocution susceptibility of birds of prey in the area, we assessed their relative abundance by conducting raptor road surveys along the same roads where surveyed power lines were located. Road surveys were also carried at the same bi-monthly interval as power lines surveys. Bird of prey surveys were conducted by car at a constant speed of approximately 40 km/h (Fuller and Mosher 1987, Andersen 2007). We counted every individual observed along roads and their behaviour (perched on trees/pylons/ground or flying). We also recorded vegetation physiognomy surrounding observed birds. All the information on power lines and road surveys was georeferenced and stored in a tablet device with a built-in GPS (Global Positioning System) using the free software Cybertracker (CyberTracker Software (Pty), http://www.cybertracker.co.za).

Data analysis

We classified pylon designs in our study area according to all possible combinations of the following variables: the material of which the pylon was built, the number of electric phases, the type of insulators and the presence/absence of jumpers (Table 1, Figure 2). These combinations provided nine possible pylon designs named D1 to D9 (Table 1).Given that electrocution events are relatively rare events given the number of pylons (one approximately per 100 m of power line) our database had a large number of zeros (no event of electrocution detected) and a very small probability of actual electrocution. Therefore, to evaluate the effect of pylon design on bird electrocution probability we used Firth's penalised-likelihood logistic regression (Firth 1993), a modelling approach that allows reduction of small-sample bias in maximum likelihood estimation. The binary response variable took values of 0 (no electrocuted birds recorded in a particular pylon) and 1 (at least one electrocuted bird found below the pylon in at least one of the six bi-monthly surveys). The design of the pylon (categories D1 to D9) and the physiognomy of vegetation around the pylon were included in the models as categorical variables with nine and three levels, respectively.

Table 1. Models of power pylon designs observed in the study area defined by the type of material of the pylon, the number of phases, the type of insulators and the presence/absence of jumpers.

Designs	Tower	N Phases	Insulator Type	Jumpers	N
D1	Wood	3 phases	Pin insulator	Absence	2,736
D2	Wood	3 phases	Pin insulator	Presence	28
D3	Wood	3 phases	Horizontal insulator	Absence	15
D4	Wood	3 phases	Horizontal insulator	Presence	29
D5	Concrete	3 phases	Pin insulator	Absence	67
D6	Concrete	3 phases	Pin insulator	Presence	69
D7	Concrete	3 phases	Horizontal insulator	Absence	20
D8	Concrete	3 phases	Horizontal insulator	Presence	134
D9	Concrete	1 phase	Horizontal insulator	Presence	20

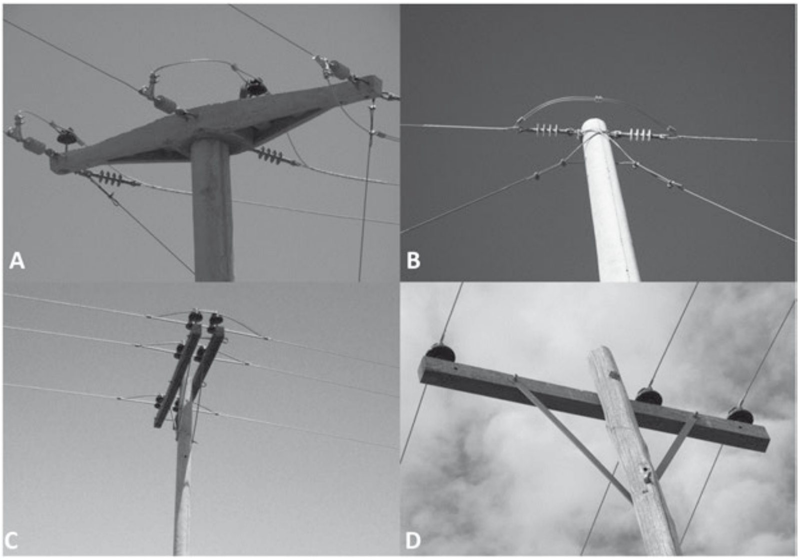

Figure 2. Typical power line designs in the study area: (A) concrete pylons with presence of jumpers above the cross-arm, horizontal insulators and three-phases (D8 design) or (B) single-phase (D9 design), (C) with pin insulators and jumpers above the cross-arm (D6 design) and (D) the most frequent design, wood pylon with pin insulators and without jumpers (D1 design).

We also built logistic regression models to evaluate which were the most dangerous components for birds in the power pylon design. The response variable was again the absence/presence of electrocuted birds while the explanatory variables were pylon material (concrete or wood), jumpers (presence or absence), type of insulators (pin or horizontal) and all the two-way interactions.

In all the analyses we followed a backward stepwise procedure starting from a full model which included the main effects as well as all the two-way interaction effects of the explanatory variables. Each variable was tested for statistical significance comparing the most general model including the variable with a simplified model without it. Significance was tested using ANOVA and only significant effects ($P < 0.05$) were retained in the final model. The statistical analyses were performed with the 'Logistf' package (Heinze *et al.* 2013) in R statistical software version 3.2.3 (R Development Core Team 2016). R Foundation for Statistical Computing, Vienna, Austria, www.R-project.org).

We estimated the bird electrocution rate by species (number of carcasses by species/year), and season (autumn-winter, spring-summer), by type of pylon design (number of carcasses/year) and by vegetation physiognomy. To evaluate whether species electrocution risk was related to the species size, we examined the relationship between species wingspan (i.e. maximum distance between wingtips) and the observed electrocution rate (ratio between species relative field abundance and number of electrocution events in which each of them was involved) using the Spearman correlation test.

Results

During systematic power line surveys we found 34 dead birds beneath 27 pylons (0.8%) of 3,118 monitored pylons and thus the minimum annual bird electrocution rate was 0.011 bird/pylon/year. Four of the electrocuted birds (11.76%) were Crowned Solitary Eagles (all electrocuted Accipitrids were of this species). Two were juveniles and two were adults. Besides Crowned

Table 2. Number and percentage of electrocuted birds in our study area from Spring 2011 to Spring 2012, segregated by season (autumn-winter, spring-summer) and by bird species.

Electrocuted Birds	Electrocution Rate			
	Autum-Winter	Spring-Summer	Total	Total Fam.
Cathartidae				12 (35.29%)
Turkey Vulture		5 (45.45%)	5 (14.71%)	
Black Vulture	7 (30.43%)		7 (20.59%)	
Accipitridae				4 (11.76%)
Crowned Solitary Eagle	2 (8.69%)	2 (18.18%)	4 (11.76%)	
Psittacidae				17 (50%)
Burrowing Parrot	10 (43.48%)	2 (18.18%)	12 (35.29%)	
Monk Parakeet	3 (13.04%)	2 (18.18%)	5 (14.71%)	
Strigidae				1 (2.94%)
Striped Owl	1 (4.35%)		1 (2.94%)	
Total	23	11	34	34

Solitary Eagles, five additional species corresponding to three additional families were electrocuted: Psittacidae (50%), Cathartidae (35.29%), and Strigidae (2.94%). The species with the highest electrocution rate was the Burrowing Parrot *Cyanoliseus patagonus* (rate = 12 birds/year) followed by the Black Vulture *Coragyps atratus* (rate = 7 birds/year) (Table 2). We found more electrocuted birds in autumn-winter ($n = 23$) than in spring-summer ($n = 11$). The only species that showed a balanced mortality between seasons was the Crowned Solitary Eagle with two dead eagles in each season (Table 2). Highest electrocution rates were observed in concrete pylons (D5, D6, D8 and D9 designs) with presence of jumpers above the cross-arm (D6, D8 and D9) (Table 3). Electrocution events on wood pylons were recorded in two (D1 and D2) out of three designs of pylons built with this material (Table 3).

Electrocution probability was determined by pylon design (Table 4). Wood-made pylons with three phases, pin-type insulators and without jumpers (D1) had a lower than expected probability of electrocution while five pylon designs (D2, D5, D6, D8 and D9) had a significantly high probability of bird electrocution. The most dangerous pylons included concrete pylons with jumpers above the cross-arm (three designs), concrete pylons with pin-type insulator and no jumper and wood pylons with pin-type insulator and jumper above the cross-arm (Table 4). Using a binomial approach taking only into account presence/absence of electrocuted birds could underestimate

Table 3. Number of electrocuted birds and electrocution rate of birds in the study area, from Spring 2011 to Spring 2012, segregated by pylon designs and vegetation physiognomy.

Variable levels	Pylons	Pylons with electrocution registers	Carcasses	Electrocution rate (Carcasses/Pylons)
D1	2736	1	5	0.002
D2	28	2	2	0.071
D3	15	0	0	0.000
D4	29	0	0	0.000
D5	67	1	1	0.015
D6	69	5	6	0.087
D7	20	0	0	0.000
D8	134	15	17	0.127
D9	20	3	3	0.150
Forest	640	3	5	0.008
Shrubland	1967	14	19	0.010
Grassland	511	7	10	0.020
Total	3118	27	34	0.011

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Table 4. Firth's penalized-likelihood logistic regression on electrocution probability for birds according to pylon design in La Pampa Province, Argentina. (*** = *P*-value < 0.01, + = *P*-value > 0.05).

	Coefficients	SE	Lower 0.95	Upper 0.95	Chi sq	P
(Intercept)	-7.509	0.817	-9.675	-6.242	Inf	***
Design2	5.148	1.059	3.098	7.564	1.774	***
Design3	4.075	1.694	-0.924	7.046	2.931	+
Design4	3.431	1.665	-1.560	6.383	2.315	+
Design5	3.716	1.166	1.196	6.237	7.105	***
Design6	5.047	0.931	3.417	7.334	3.383	***
Design7	3.795	1.679	-1.200	6.756	2.663	+
Design8	5.391	0.863	3.980	7.607	Inf	***
Design9	6.209	0.982	4.456	8.550	3.820	***

mortality risks associated to certain pylons if multiple individuals get electrocuted in the same pylon. Although multiple electrocuted birds under the same pylon were rarely found in our study (only three cases), we also modelled number of birds electrocuted on each pylon design against a Poisson distribution (Kemper *et al.* 2013). The results of these analysis were similar to the ones reported here, except that D5 pylon design, where a bird was found electrocuted and considered as dangerous in the logistic regression, was considered not dangerous (see Appendix S1 and Table S1 in the online supplementary material).

Electrocution rate on pylons located on grasslands was twice the electrocution rate on those located in scrublands or forests (Table 3). However, neither vegetation physiognomy ($\chi^2 = 0.99$, df = 2, $P = 0.6$) nor the interactions between physiognomy and pylon design were statistically significant ($\chi^2 = 8.74$, df = 14, $P = 0.85$).

The most dangerous components of power pylon designs were the building material and the presence of jumpers, with concrete pylons (coefficient = 1.45 ± 0.77, $\chi^2 = 4.66$, df = 1, $P = 0.03$) and pylons with jumpers (coefficient = 3.54 ± 0.91, $\chi^2 = 19.98$, df = 1, $P < 0.01$). Type of insulator was not selected by the model ($\chi^2 = 0.12$, df = 1, $P = 0.73$) neither their interaction with pylon material ($\chi^2 = 2.17$, df = 1, $P = 0.14$) nor presence of jumpers ($\chi^2 = 0.05$, df = 1, $P = 0.82$). The interaction between pylon material and presence of jumpers was not significant ($\chi^2 = 3.07$, df = 1, $P = 0.08$).

Bird of prey surveys and electrocution susceptibility

Twelve species of birds of prey were recorded in the road surveys conducted at the study area (Table 5). Abundance of birds of prey was higher in Spring-Summer than during Autumn-Winter seasons, with the American Kestrel *Falco sparverius* being the most abundant species followed by the Crested Caracara *Caracara plancus* and the Turkey Vulture *Cathartes aura*. Based on the abundance/mortality ratio, Crowned Solitary Eagles showed disproportionately higher electrocution susceptibility throughout the year than the rest of the species (Table 5).

Susceptibility to electrocution was positively and significantly correlated with the species wingspan (rho = 0.75, $P < 0.01$, $n = 12$). Larger birds of prey had higher electrocution rate than smaller species, and there were no records of electrocuted raptor species with wingspan values smaller than 120 cm (Table 5). This was more revealing considering not only the low frequency of records of large vs. small birds of prey (27.65% of observations corresponded to species with wingspan > 120 cm) but also comparing the behaviour of these birds. Only 7% of the largest birds of prey were recorded perched on power lines during road surveys in contrast with 58.6% of smaller birds of prey.

During the censuses, birds of prey were recorded evenly at the three types of vegetation physiognomies. However we did not find electrocuted birds of prey in forests. In contrast, we recorded

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Table 5. Birds of prey recorded (N) along road surveys and their relative abundance (RA) (individuals/km travelled) segregated by seasons (autumn-winter = AW, spring-summer = SS). Total number (TN), total relative abundance (TRA) as percentage as well as number of electrocuted birds (E), the ratio electrocuted/observed birds (E/TN) and mean wingspan (MW) expressed in cm. Wingspan data was extracted from Fergusson-Lees and Christie (2001).

Species	AW		SS		TN	TRA	E	E/TN	MW
	N	RA	N	RA					
Cathartidae	117	0.258	236	0.277	353	27.03			
Turkey Vulture	0	0.000	211	0.247	211	16.16	5	0.024	170.29
Black Vulture	117	0.258	25	0.029	142	10.87	6	0.042	145.26
Accipitridae	26	0.057	41	0.048	67	5.13			
Crowned Solitary Eagle	3	0.007	5	0.006	8	0.61	4	0.5	176.26
Red-backed Hawk	22	0.049	30	0.035	52	3.98	0	0	113.5
Harris Hawk	0	0.000	1	0.001	1	0.08	0	0	104.53
Cinereous Harrier	1	0.002	1	0.001	2	0.15	0	0	100.98
White-tailed Kite	0	0.000	4	0.005	4	0.31	0	0	94.48
Falconidae	301	0.664	516	0.605	817	62.56			
Crested Caracara	108	0.238	124	0.145	232	17.76	0	0	118.59
Chimango Caracara	15	0.033	121	0.142	136	10.41	0	0	88.49
Spot-winged Falconet	18	0.040	12	0.014	30	2.30	0	0	49.68
Aplomado Falcon	3	0.007	4	0.005	7	0.54	0	0	87.1
American Kestrel	157	0.347	255	0.299	412	31.55	0	0	56.14
Total	444		793		1237				

two electrocution events of Crowned Solitary Eagles on grassland where the species was not observed during road surveys (Figure 3).

Discussion

This study represents the first systematic assessment of electrocution risk for birds in South America. The electrocution rate found here, a minimum of 0.011 bird/pylon/year, is within the

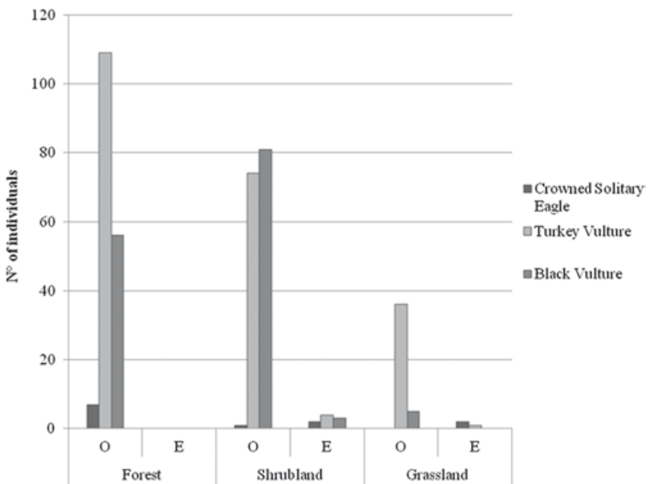

Figure 3. Number of Crowned Solitary Eagles, Turkey Vultures and Black Vultures electrocuted (E) and observed along road surveys (O) segregated by vegetation physiognomy (forest, scrubland and grassland).

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ranges found in other studies although in some cases well above them (Kemper *et al.* 2013). This suggest that at least in some areas, this mortality factor poses a significant risk to South American birds of prey, and particularly to endangered birds such as the Crowned Solitary Eagle but has been completely overlooked over the years.

Previous studies have shown that particular power pylon characteristics may increase or reduce the risk of bird electrocution (Negro 1987). Our results indicate that concrete pylons and the presence of jumpers above the cross-arms are the most dangerous characteristics in electric pylons in our study area. These two characteristics were found in the three most dangerous pylon designs identified. The two pylon designs with higher bird electrocution rates corresponded to those made of concrete with jumpers above the cross-arm and having horizontal insulators. The presence of jumpers above the cross-arm seems to be the most impacting factor as was present in four of the five pylon designs with significantly high electrocution rates. As expected, these jumpers above the cross-arms increase the probability of birds touching the electrified jumper and another structure, earthed or electrified, and thus closing the circuit. The building material and particularly those poles made of concrete were also very dangerous (present in four of the dangerous pylon designs) as they provided an earthed structure helping to close electric circuits. However, it should be noted that the four concrete pylons considered to be dangerous had also a structure above the cross-arm that helped to close the circuit like jumpers (3 cases) and pin type insulators. The only design of concrete with no structure on top of the pylon (D7) was safe. This suggests that concrete pylons become a threat when they have electrified structures above the cross-arms but can be safe if the cross-arm design is appropriate. Wooden pylons without jumpers and concrete pylons with horizontal insulators but without jumpers were the most secure pylon designs for birds of prey in our study. Our results once more point to the need to specifically assess the pylon designs used in each area to identify which particular designs are more dangerous so particular correction measures can be applied to already existing power lines.

The Crowned Solitary Eagle was disproportionately affected by this mortality source when compared with its low abundance. It was one of the birds of prey more frequently involved in electrocution events suggesting that this source of mortality is particularly high and worrisome for this endangered species. We estimate the existence of around 30 Crowned Solitary Eagle breeding territories in the area, although probably not all of them simultaneously occupied (we found only a maximum of 10 breeding pairs per year; authors' unpubl. data). Our data would indicate that a minimum of 3.33 % (considering 10 active breeding pairs per year, it would be 10%) of the breeding adults would die per year. In addition, mean yearly productivity in the area is 0.6 fledglings per pair (authors' unpubl. data) but our results indicate that 11.11% of the produced fledglings could die per year by electrocution. These high mortality values, and particularly adult mortality, are especially worrisome in the context of long-lived species with delayed maturity and low fecundity such as the Crowned Solitary Eagle that are especially vulnerable to increases in non-natural mortality. Other large eagles formerly threatened by electrocution in Europe have increased their populations after mitigation measures were applied to dangerous power lines (e.g. López-López *et al.* 2011, Chevallier *et al.* 2015). Therefore, besides assessing the impact of this mortality factor in other areas of the country and in other type of pylons, it is critical to take action and start to retrofit dangerous pylons in our study area.

We found a high relative frequency of Psittacids among electrocuted birds. Electrocution of Monk Parakeets *Myiopsitta monachus* has been recorded in the introduced populations in the United States where their large communal nests can cause outages and fires (APLIC 2006). However, Psittacids are rarely found as victims of electrocution elsewhere. We found electrocuted individuals of two of the three species of Psittacids that regularly occur in the study area, suggesting that power lines can be an important mortality factor for this group of birds in certain circumstances. Given the high rate of endangered species among parrots, we suggest that special attention should be paid to this mortality factor in other areas where endangered parrots occur.

Seasonal changes in species composition and weather may produce variations in bird electrocution rate (Lehman *et al.* 2007). In our study, even when some migratory species like Turkey

Vultures were only present in the study area in spring-summer, the highest electrocution rates were found in autumn-winter. This result may be explained by particularities of the two species with higher electrocution rates, Burrowing Parrot and Black Vulture. The Burrowing Parrot *Cyanoliseus patagonus* makes seasonal movements with some populations going to north and central Argentina from southern locations (Collar 1997). High numbers concentrate in some parts of our study area in winter, probably explaining the seasonal electrocution pattern found in this species. The Black Vulture is resident in our study area (Ferguson-Lees and Christie 2001, Narosky and Izurieta 2010). However, raptor surveys indicated that the species was four times more abundant in autumn-winter than in spring-summer, suggesting the arrival of vultures from other areas in the colder season. Higher abundance in autumn-winter as well as its sociality could partially explain the seasonal bias in mortality in this species.

Size of birds of prey was another relevant factor in explaining their probability of electrocution, as the largest, Crowned Solitary Eagles, Black Vultures and Turkey Vultures, were the birds most susceptible to electrocution. Some species-specific traits, such as social behaviour and gregariousness, seem to facilitate electrocution susceptibility in some of them, even in the less dangerous pylon designs. Burrowing Parrots tend to perch in large numbers in wires and poles, usually very close (literally touching each other) increasing the chances of touching two powered or a powered and an earthed element of the pylon, producing a mortality event that can involve more than one bird. Five Black Vultures died together on the same pylon in the largest multiple electrocution event we found. This electrocution event happened in the neighbourhood of a predictable and abundant food source, a slaughterhouse. The pylon was a D1 design pylon, supposedly one of the safest. However, interactions of birds, typical of social species such as Black Vultures may produce electrocutions incidents in otherwise safe places. Aggregations of individuals can create authentic electrocution black spots and therefore particular attention should be paid to power lines in areas where those aggregations are expected to occur.

Our results are worrisome and have highlighted a so far overlooked mortality source for birds in South America. However, we did not perform any analysis of carcass removal by scavengers and we could not estimate the incidence of crippling (Dwyer and Bednarz 2006) and thus our results should be taken as a minimum estimate of the actual number of electrocuted birds. The removal rate of bird carcasses by scavengers can be very high, up to 70% in some cases (Ferrer *et al.* 1991) so the absolute number of electrocuted birds is surely underrepresented in this study, especially for smaller electrocuted birds that will probably disappear quicker by scavenger removal.

Besides the unnecessary death of a wild bird, electrocution events can produce cuts or peaks in energy supply affecting the quality of the service provided by electricity companies (Harness and Wilson 2001), and even wild fires in natural or urban areas when electrocuted birds sometimes fall on fire (Lehman and Barrett 2000, APLIC 2006). The implementation of measures to mitigate bird electrocutions is thus relevant not only for conservation biologists, but for electricity companies and entire local communities. Usually electrocution incidents occur in a few pylon designs. In our study area, these pylons were only 10.2 % of the power pylons systematically monitored. Therefore, the change or modification of a small fraction of pylons would severely reduce electrocution incidents. Besides modifying already installed lines, it would be necessary to use safe designs for birds in new lines. Particularly, jumpers above the cross-arm or any electrified structure that could increase electrocution probability for birds should be avoided or modified.

Further studies identifying dangerous power pylon designs across ecosystems and countries in South America are urgently needed, so proper modifications can be applied in each case. Furthermore, new legal dispositions should be established to ensure that from now on, new power lines are designed not only to give a secure and reliable service for humans but also safe for wildlife.

Supplementary Material

To view supplementary material for this article, please visit https://doi.org/10.1017/S0959270917000272

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