

Landscape-scale reduction of raptor electrocution hotspots through targeted mitigation and utility-company collaboration

Zníženie výskytu kritických miest elektroúcie dravcov v krajinej mierke prostredníctvom cieľných mitigačných opatrení a spolupráce s energetickou spoločnosťou

José Rafael GARRIDO * & Víctor FISCAL

Abstract: Electrocution on power lines is one of the main anthropogenic causes of mortality in birds of prey worldwide and represents a major conservation concern for long-lived raptor species. Because mortality is spatially aggregated, a relatively small number of dangerous pylons can account for a disproportionate share of electrocution events, suggesting that targeted mitigation strategies may substantially improve conservation efficiency. We evaluated the effectiveness of a collaborative mitigation agreement between the Andalusian Government and the main electricity company in southern Spain (ENEL-ENDESA) by analysing temporal changes in the prevalence of electrocution blackspots. Using the official long-term electrocution database of Andalusia, we compared the proportion of 10×10 km UTM grid cells classified as mortality blackspots in 2014–2019 and during implementation of the agreement (2020–2025). Blackspots were defined as grid cells with more than 10 electrocuted raptors (orders Accipitriformes, Falconiformes and Strigiformes) recorded during both study periods. The proportion of blackspot grid cells decreased from 14.9% (44/295) before the agreement to 7.3% (28/381) during the mitigation period, despite increased sampling effort in the latter period. Differences between periods were significant, and the estimated odds ratio (OR = 0.45; 95% CI: 0.27–0.74) indicated a reduction of approximately 45% in the odds of a grid cell being classified as a blackspot. Importantly, this reduction was achieved after retrofitting only 13,166 hazardous pylons, representing approximately 5.2% of the estimated dangerous poles in Andalusia. Our results demonstrate that scientifically guided, spatially targeted mitigation programs developed through coordinated collaboration between conservation authorities and electricity companies can efficiently reduce the risk of electrocution at the landscape scale and help lower extinction risk for some endangered predator species.

Abstrakt: Elektroúcia na elektrických vedeniach je jednou z hlavných antropogénnych príčin úmrtnosti dravých vtákov na celom svete a predstavuje závažný problém pre ochranu dlhovekých druhov dravcov. Keďže úmrtnosť je priestorovo agregovaná, relatívne malý počet nebezpečných stĺpov elektrického vedenia môže spôsobovať nepomerne veľký podiel prípadov úrazu prúdom. To naznačuje, že cieľné mitigačné stratégie môžu výrazne zvýšiť efektivitu ochrany prírody. Vyhodnotili sme účinnosť dohody o spolupráci na zmierňovaní dopadov medzi andalúzsou vládou a hlavnou elektrárenskou spoločnosťou v južnom Španielsku (ENEL-ENDESA) analýzou časových zmien v prevalencii kritických miest úmrtnosti spôsobených elektrickým prúdom. Na základe databázy úrazov elektrickým prúdom v Andalúzii sme porovnali podiel štvorcov siete UTM s rozmerom 10×10 km klasifikovaných ako kritické miesta úmrtnosti v rokoch 2014–2019 a počas vykonávania dohody (2020–2025). Ako kritické miesta boli definované štvorce siete, v ktorých bolo v oboch sledovaných obdobiach zaznamenaných viac ako 10 usmrtených dravcov a sov (radu *Accipitriformes* – dravce, *Falconiformes* – sokolotvaré a *Strigiformes* – sovy). Podiel štvorcov s kritickým výskytom klesol zo 14,9 % (44/295) pred uzavretím dohody na 7,3 % (28/381) počas obdobia aplikácie opatrení, a to aj napriek zvýšenému úsiliu pri zbere dát v druhom období. Rozdiely medzi obdobiami boli štatisticky významné a odhadovaný pomer šancí (OR = 0,45; 95 % CI: 0,27–0,74) poukazuje na približne 45 % zníženie šance, že štvorec siete bude klasifikovaný ako kritické miesto. Dôležité je, že toto zníženie sa dosiahlo po technickom zabezpečení iba 13 166 rizikových stĺpov, čo predstavuje približne 5,2 % z odhadovaného celkového počtu nebezpečných stĺpov v Andalúzii. Výsledky ukazujú, že vedecky riadené a priestorovo cieľné mitigačné programy vyvinuté v rámci spolupráce medzi orgánmi ochrany prírody a energetickými spoločnosťami dokážu efektívne znížiť riziko úrazu elektrickým prúdom v krajinnom mierke a pomôcť znížiť riziko vyhynutia niektorých ohrozených druhov dravých vtákov.

Key words: power lines, raptors mortality, retrofitting programs, extinction risk, Andalusia

Agencia de Medio Ambiente y Agua, Junta de Andalucía. C/ Johan Gutenberg, 41092 Sevilla. Andalucía. Spain.

*E-mail: jrafaelgarrido@juntadeandalucia.es

Introduction

Electrocution on power lines is widely recognised as one of the main anthropogenic causes of mortality in birds worldwide, affecting millions of individuals annually (Prinsen et al. 2011, Dwyer et al. 2023, Serratos et al. 2024). Among birds, raptors are particularly vulnerable because of their large body size, wingspan and behavioural ecology, especially their tendency to perch while hunting or scanning the environment (Ferrer 2012, Dwyer et al. 2015). In open landscapes with limited availability of natural perches, power poles are heavily used by raptors, substantially increasing the risk of electrocution (Godino et al. 2016, Angelov et al. 2013, Dixon et al. 2017). Consequently, electrocution has become a major conservation concern for many threatened birds of prey and has contributed to population declines across several continents (Ferrer 2012, Eccleston & Harness 2018, Martín Martín et al. 2022).

Electrocution is a particularly important conservation threat to long-lived raptor species, as relatively small increases in adult mortality can strongly affect population dynamics and elevate extinction risk. Power-line electrocution has consistently been recognised as one of the principal anthropogenic pressures affecting both widespread and threatened birds of prey, and the identification and mitigation of hazardous electrical infrastructures have become fundamental components of modern raptor conservation programs (Dwyer 2009, Gális et al. 2019, Martín Martín et al. 2022).

Most electrocutions occur on medium-voltage distribution lines where birds simultaneously contact two energised conductors or an energised and a grounded component. However, mortality is not homogeneously distributed across electrical networks. Instead, electrocution events are strongly associated with specific support designs and landscape contexts, generating spatially aggregated mortality hotspots, so-called “blackspots” (Tintó et al. 2010, Pérez-García et al. 2015, Martín Martín et al. 2026). In practice, a relatively small proportion of pylons may account for a disproportionately high share of total mortality, producing highly skewed mortality distributions in which a few dangerous structures concentrate most casualties (López López et al. 2011, Bedrosian et al. 2020, Martín Martín et al. 2026).

The aggregation of mortality in a relatively small number of hazardous structures has major implications for conservation management. Since most electrocution events are concentrated in a limited proportion of pylons, prioritising the identification and retrofitting of the highest-risk support designs has emerged as one of the

most effective strategies for reducing avian mortality (Janss & Ferrer 1999, Lehman et al. 2007, Martín Martín et al. 2022). Targeted mitigation actions focused on electrocution hotspots have been shown to significantly decrease mortality rates and support the recovery of threatened populations (Guil et al. 2011, López López et al. 2011, Chavko et al. 2022, 2025). In Andalusia, for instance, the correction of high-risk pylons led to a reduction of more than 80% in electrocution mortality of the Spanish imperial eagle (*Aquila adalberti*) (López López et al. 2011), illustrating the effectiveness of strategically focused mitigation measures (Fig. 1).

Different approaches have been developed to address this problem. However, legal frameworks in several countries, including Spain, establish mandatory correction of dangerous power lines, particularly within protected areas or zones of high conservation value (Ferrer et al. 2026). Therefore, collaborative agreements between public administrations and electricity companies have emerged as a complementary and often more flexible mechanism to accelerate mitigation at large spatial scales (Ferrer et al. 2026). These agreements facilitate the prioritisation of high-risk areas, the optimisation of economic resources, and the implementation of corrective measures beyond the minimum legal requirements.

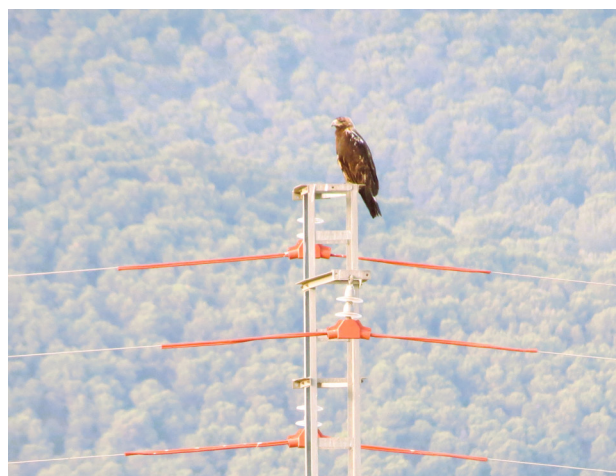


Fig. 1. Spanish imperial eagle (*Aquila adalberti*) perched on a retrofitted power line pylon designed to prevent electrocution in Andalusia (southern Spain). These measures have been one of the main drivers of the increase in the species' breeding population in Spain (© Jesus Bautista).

Obr. 1. Orol iberský (*Aquila adalberti*) sediaci na upravenom stĺpe elektrického vedenia navrhnutom tak, aby sa zabránilo zásahu elektrickým prúdom v Andalúzii (južné Španielsko). Tieto opatrenia boli jedným z hlavných hýbateľov nárastu hnieznej populácie tohto druhu v Španielsku (© Jesus Bautista).

Despite the widespread implementation of mitigation measures, robust quantitative evaluations of their effectiveness at the landscape scale remain relatively scarce, particularly under real-world monitoring conditions where sampling effort varies through time (Gális et al. 2019). This limitation reduces our ability to determine whether mitigation programs are effectively decreasing electrocution risk and contributing to reduced extinction risk in threatened raptor populations.

Andalusia, the southernmost autonomous region of Spain, supports an exceptionally rich raptor community (SEO/BirdLife 2022) and several threatened species of conservation concern, including the Spanish imperial eagle, Bonelli's eagle (*Aquila fasciata*), bearded vulture (*Gypaetus barbatus*), and Egyptian vulture (*Neophron percnopterus*) (SEO/BirdLife 2021).

The electrical distribution network in Andalusia is extensive and highly developed, comprising nearly 40,000 km of power lines and approximately 500,000 utility poles. Around 95% of this infrastructure is owned and managed by a single electricity company, ENEL-ENDESA, making the region particularly well-suited for evaluating the effectiveness of large-scale collaborative mitigation programs to reduce the risk of avian electrocution.

The local extensive electricity network contains many potentially dangerous pylons and has caused the electrocution of thousands of birds across dozens of species (Ferrer 2012). To reduce electrocution mortality, the Government of Andalusia and ENEL-ENDESA signed a memorandum of understanding in 2019 to reduce avian mortality from electrical infrastructure through scientifically guided, targeted, and prioritised mitigation (Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible 2019). The agreement is based on the analysis of cumulative mortality data, the identification and remediation of blackspots, and the correction of the most hazardous support configurations, all under fluid, ongoing communication between the parties. It establishes two priority categories for adaptation: urgent, referring to structures that must be modified immediately because they have already caused electrocutions or pose a direct threat to breeding populations of endangered raptors; and planned, referring to structures that must be adapted within no more than three months because they present hazardous configurations and are located in open areas within the distribution range of endangered species.

In this study, we assessed the effectiveness of a mitigation agreement established with the main electricity company in Andalusia by comparing the

spatial prevalence of electrocution blackspots before and after its implementation. Specifically, we tested whether the agreement resulted in a reduction in the occurrence of electrocution blackspots at the regional scale. We hypothesised that the prevalence of electrocution blackspots would be significantly lower following the implementation of the agreement and, consequently, that this would address one of the principal threats affecting raptor populations.

Material and methods

The study area was Andalusia, the southernmost region of Spain, located in the western Mediterranean Basin and covering approximately 87,600 km², comparable in area to countries such as Portugal or Austria. It includes a wide diversity of habitats, ranging from Mediterranean forests and mountain systems to extensive agricultural landscapes, wetlands, and semi-arid areas.

Analyses were based on the official electrocution database maintained by the Andalusian Government, which compiles long-term records of avian electrocution incidents detected through systematic monitoring (Fig. 2), wildlife recovery centres, field inspections and reports from environmental officers (Table 1, Regional Ministry of Sustainability and Environment of the Regional Government of Andalusia, unpublished data). For each incident, the database includes species identification, the number of individuals affected, the geographic location, and the year of occurrence. For the purposes of this study, raptor species belonging to the orders Accipitriformes,



Fig. 2. Golden eagle (*Aquila chrysaetos*) electrocuted on a support of the power line in Andalusia, where the regional government maintains a database which compiles long-term records of avian electrocution incidents detected in the region (© Jesus Bautista).
Obr. 2. Orol skalný (*Aquila chrysaetos*) usmrtený elektrickým prúdom na stĺpe elektrického vedenia v Andalúzii, kde regionálna vláda spravuje databázu o prípadoch elektrokúcie vtákov zistených v tomto regióne (© Jesus Bautista).

Tab.1. Number of electrocuted birds per species recorded in the official long-term electrocution database of the Andalusian Government.

Tab.1. Počet usmrtených jednotlivých druhov vtákov zaznamenaný v oficiálnej databáze úrazov elektrickým prúdom vlády Andalúzie.

Scientific name	Common name	Threat category	No. of electrocutions	%
<i>Ciconia ciconia</i>	white stork	Not Threatened	2,401	25
<i>Bubo bubo</i>	Eurasian eagle-owl	Not Threatened	1,221	13
<i>Corvus corax</i>	northern raven	Not Threatened	1,046	11
<i>Buteo buteo</i>	common buzzard	Not Threatened	1,004	11
<i>Gyps fulvus</i>	griffon vulture	Not Threatened	434	5
<i>Circaetus gallicus</i>	short-toed snake eagle	Not Threatened	330	3
<i>Milvus migrans</i>	black kite	Not Threatened	316	3
<i>Aquila fasciata</i>	Bonelli's eagle	Vulnerable	277	3
<i>Falco tinnunculus</i>	common kestrel	Not Threatened	200	2
<i>Aquila adalberti</i>	Spanish imperial eagle	Endangered	144	2
<i>Falco naumanni</i>	lesser kestrel	Not Threatened	141	1
<i>Hieraaetus pennatus</i>	booted eagle	Not Threatened	138	1
<i>Aquila chrysaetos</i>	golden eagle	Not Threatened	128	1
<i>Milvus milvus</i>	red kite	Endangered	60	1
<i>Ciconia nigra</i>	black stork	Endangered	31	0
<i>Pandion haliaetus</i>	osprey	Vulnerable	26	0
<i>Aegypius monachus</i>	cinereous vulture	Vulnerable	16	0
<i>Neophron percnopterus</i>	Egyptian vulture	Endangered	7	0
<i>Circus pygargus</i>	Montagu's harrier	Vulnerable	6	0
Other species (n = 48)	-	-	860	9
Total (n = 67 species)	-	-	9,548	100

Falconiformes and Strigiformes were included in the analyses. Only electrocutions recorded from 2014 onwards were included in the analysis, as this marks the point at which systematic data collection began, carried out by administrative staff, NGOs, and naturalists alike, alongside a growing awareness of the scale of the problem, which has driven a progressive increase in monitoring effort over the years.

Spatial analyses were conducted using 10×10 km UTM grid cells as the sampling unit. Grid-based approaches are widely used in large-scale biodiversity monitoring and spatial risk assessment because they standardise sampling units and facilitate comparisons across regions and time periods.

Two temporal periods were compared: the pre-agreement period (2014–2019) and the agreement period (2020–2025), which corresponds to the implementation of the mitigation agreement between the Andalusian Government and ENEL-ENDESA (Fig. 3).

Mortality blackspots were defined as UTM grid cells in which more than 10 electrocuted raptors were recorded during each temporal period. This threshold was selected to identify areas with recurrent and spatially aggregated mortality associated with hazardous electrical infrastructures, consistent with the hotspot-based approach commonly applied in electrocution risk

assessment (Janss & Ferrer 1999, Tintó et al. 2010, Pérez-García et al. 2015). Sampling effort was quantified as the total number of surveyed 10 × 10 km UTM grid cells in each period. A total of 295 grid cells were surveyed during 2014–2019 and 381 during 2020–2025. Because sampling effort increased during the agreement period, the detection probability of blackspots would also be expected to increase. Consequently, any reduction in the proportion of blackspot grid cells during the second period should be interpreted as a conservative estimate of the true mitigation effect rather than an artefact derived from reduced monitoring intensity.

To evaluate whether the prevalence of blackspots changed following implementation of the mitigation agreement, we compared the number and proportion of blackspot cells between periods using a 2×2 contingency table and a chi-square test of independence.

The effect size was quantified with an odds ratio and its 95% confidence interval. Odds ratios are widely used in ecological and epidemiological analyses because they provide an intuitive measure of the magnitude and direction of treatment or management effects (Rita & Komonen 2008). An odds ratio below 1 indicates a reduction in the probability that a grid cell will be classified as a mortality blackspot during the agreement period. Survey effort was treated as the number of

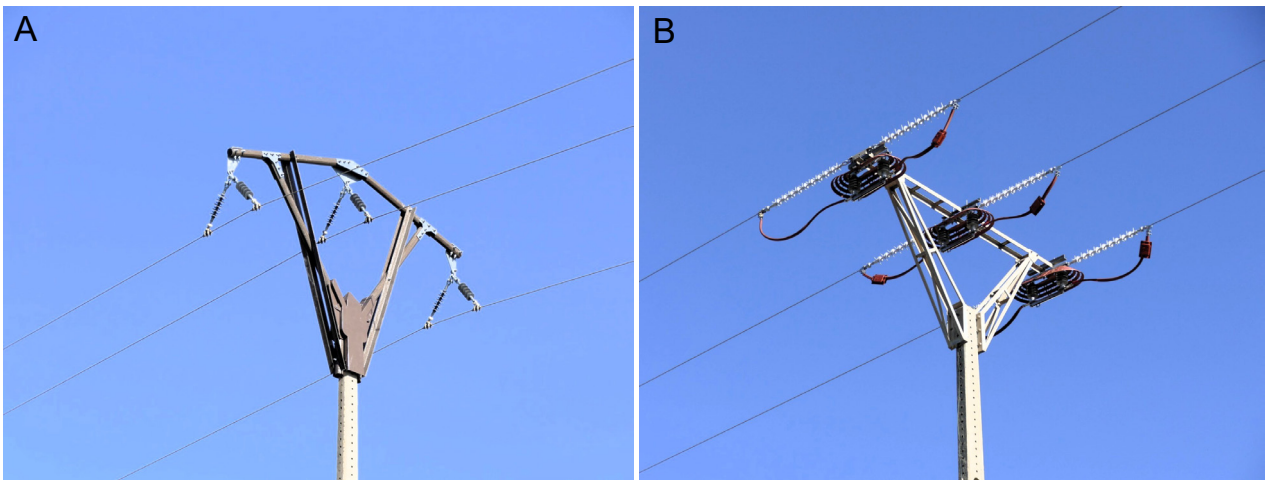


Fig. 3. Electrical pylon crossarms retrofitted to prevent bird electrocution in Andalusia. The left image (A) shows a crossarm constructed from insulating material, preventing electric current from passing through the body of any bird perched on it. The right image (B) illustrates several mitigation measures, including one-meter structural extensions that increase the clearance between the conductor and the metallic crossarm, insulating covers installed on conductors, and insulation fitted to disconnectors (© Jose Rafael Garrido).

Obr. 3. Konzoly stĺpov elektrického vedenia upravené s cieľom zabrániť elektrokúcii vtákov v Andalúzii. Obrázok vľavo (A) znázorňuje konzolu vyrobenú z izolačného materiálu, ktorá zabraňuje prechodu elektrického prúdu telom vtáka, ktorý na nej sedí. Obrázok (B) vpravo ilustruje niekoľko mitigačných opatrení vrátane metrových konštrukčných predĺžení, ktoré zväčšujú vzdialenosť medzi vodičom a kovovou konzolou, izolačných krytov nainštalovaných na vodičoch a izolácie umiestnenej na odpájačoch (© Jose Rafael Garrido).

grid cells surveyed in each period; because effort was higher during 2020–2025, the analysis is conservative, since increased effort should increase the probability of detecting blackspots.

All analyses were conducted at the grid-cell level, considering the presence or absence of mortality blackspots as the response variable. Statistical significance was assessed at $\alpha = 0.05$.

ChatGPT (OpenAI) was used to improve the English language and assist with statistical analyses. The authors reviewed, verified, and incorporated the resulting outputs into the text.

Results

A total of 4,876 electrocuted birds of prey from 30 species were registered from 1990 to 2025, 1,847 from 27 species in the pre-agreement period (2014–2019) and 1,675 from 26 species during the agreement period (2020–2025). The most affected species were Eurasian eagle-owl (*Bubo bubo*) and common buzzard (*Buteo buteo*) but also threatened species like Bonelli's and Spanish imperial eagles (Table 2).

Survey coverage increased by approximately 29% between study periods, from 295 (10×10 km UTM) grid cells in the pre-agreement period (2014–2019) to 381 cells during the agreement period (2020–2025).

A total of 44 grid cells (14.9%) were classified as mortality blackspots during the pre-agreement period, whereas only 28 grid cells (7.3%) met the blackspot criterion during the agreement period (Fig. 4). This represents an approximate 51% reduction in blackspot prevalence. Many fatalities occurred outside protected areas (Fig. 5).

Pearson's chi-square test indicated that the proportion of blackspot grid cells differed significantly between the two study periods ($\chi^2 = 10.0$, $df = 1$, $p = 0.0015$).

Effect size analyses showed that the odds of a grid cell being classified as a mortality blackspot during 2020–2025 were substantially lower than before the agreement's implementation (2014–2019) (Odds ratio = 0.45; 95% CI: 0.27–0.74). In practical terms, this corresponds to a reduction of approximately 55% in the odds of blackspot occurrence following implementation of mitigation measures.

During the agreement period, the number of electrocution blackspots decreased significantly despite mitigation actions being applied to only a small fraction of the potentially hazardous electrical infrastructure. A total of 13,166 dangerous pylons were selectively retrofitted through a highly targeted strategy, representing approximately 5.2% of the estimated 250,000 hazardous poles present in Andalusia. The estimate aligns with MAGRAMA's (2014) finding that approximately half

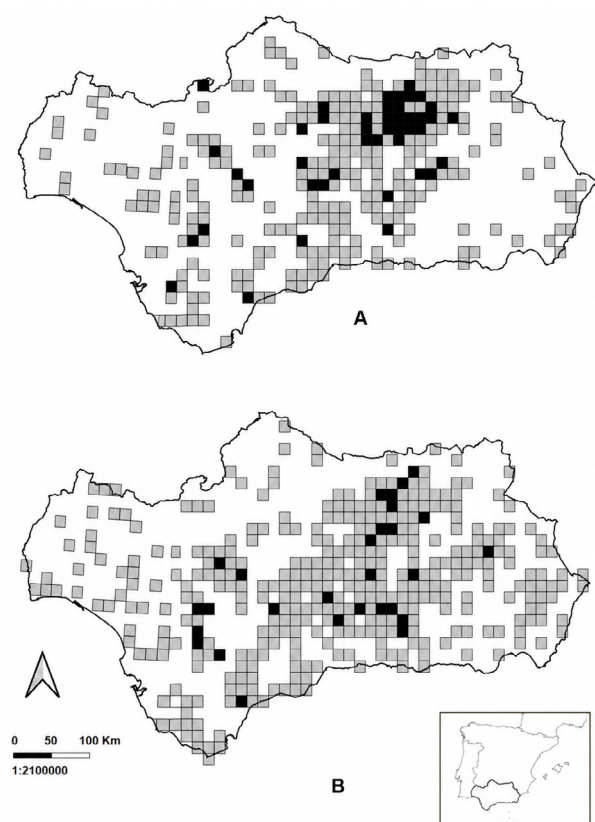


Fig. 4. The 10×10 km UTM grid cells with recorded electrocutions of birds of prey in Andalusia (Spain) during the pre-agreement period (2014–2019) (panel A) and during the agreement period (2020–2025) (panel B). Grid cells considered black spots for bird-of-prey electrocution (with 10 or more electrocuted raptors) are shown in black.

Obr. 4. Štvorce siete UTM s rozmerom 10×10 km so zaznamenanými prípadmi elektrokcúie dravých vtákov v Andalúzii (Španielsko) v období pred uzavretím dohody (2014–2019) (časť A) a počas platnosti dohody (2020–2025) (časť B). Štvorce siete považované za kritické miesta (tzv. blackspoty) pre elektrokcúiu dravcov (s 10 alebo viacerými usmrtenými dravcami) sú zobrazené čiernou farbou.

of all distribution infrastructure in Spain is configured to pose an electrocution risk to birds. In line with the reduction in blackspots, the total number of raptor electrocutions has also decreased by nearly 10% following the agreement, although fatalities are now more widely distributed across the territory (Fig. 4). At the species level, electrocutions have declined in 65% of species; however, they have increased in threatened species such as the Spanish imperial eagle (nearly 100%) and the red kite (500%). Other species showing a marked increase in electrocutions include, for instance, the booted eagle (*Hieraetus pennatus*) (94%; Table 2).

Discussion

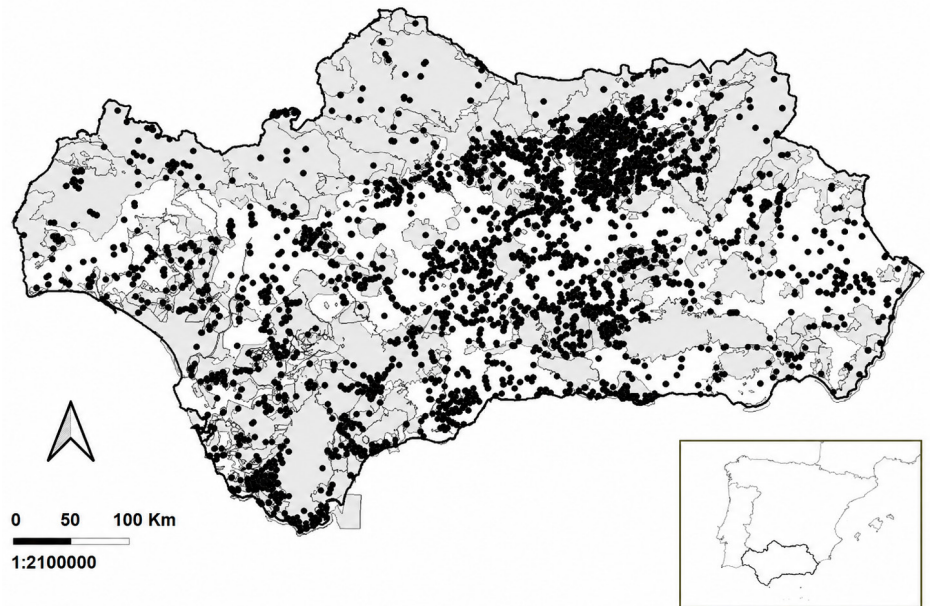
The results supported our hypothesis that the prevalence of electrocution hotspots decreased during the agreement period, despite increased survey effort. So, this observed decline cannot reasonably be attributed to reduced detection probability, and the results strongly suggest a real decrease in the spatial concentration of electrocution mortality following implementation of targeted corrective measures under the agreement with ENEL-ENDESA and should therefore be interpreted as a conservative estimate of the effectiveness of those mitigation measures.

Importantly, this decline was achieved by retrofitting only 5.2% of potentially dangerous pylons in Andalusia. This underscores a central principle of effective electrocution mitigation: fatalities are not randomly distributed across electrical networks but are spatially concentrated in a small number of particularly hazardous structures (Janss & Ferrer 1999, Tintó et al. 2010, López López et al. 2011). Consequently, selectively targeting high-risk infrastructure generates disproportionately large conservation returns. Prioritising mortality hotspots over broad, non-selective network-wide correction therefore maximises conservation benefit while optimising economic and technical investment (Ferrer 2012, Martín Martín et al. 2022). Most species affected by electrocution currently show growing or stable populations, although mortality levels remain high, a particular concern for threatened species such as the Spanish imperial eagle, Bonelli's eagle, and the red kite (Table 2). In some cases, such as the Spanish imperial eagle and the red kite, this high mortality could be related to the increase in breeding and wintering populations (see below). However, this is not the case for the Bonelli's Eagle, which has shown a stable population trend.

The success of this strategy also underscores the value of institutional cooperation. Regional and national regulations establish technical requirements to reduce the risk of electrocution; however, in practice, many fatalities occur outside protected areas, where legal obligations alone are insufficient to ensure the timely correction of hazardous infrastructure (Fig. 5). Legal action alone, therefore, is not enough to address this conservation challenge. Effective implementation of corrective measures at large spatial scales requires sustained coordination among conservation authorities, researchers, and electricity companies. The agreement evaluated here demonstrates how collaborative frameworks can facilitate prioritisation, accelerate implementation, and optimise investment in biodiversity conservation. Moreover, when private funds are directed toward mitigating the

Fig. 5. Location of raptor electrocution sites on power lines in Andalusia, Spain (black dots) and protection zones where power lines must be made safe according to Spanish and Andalusian legislation (grey areas).

Obr. 5. Lokalizácia miest elektrokúcie dravých vtákov na elektrických vedeniach v Andalúzii v Španielsku (čierne body) a ochranné zóny, v ktorých musia byť elektrické vedenia zabezpečené v súlade so Španielskou a Andalúzskou legislatívou (sivé plochy).



problem, they translate into direct investment in repairing dangerous power lines, whereas if that same money were channelled into fines, it would flow into regional budgets rather than being applied directly to fixing the hazardous infrastructure.

Beyond its direct effect on local mortality rates, reducing the spatial concentration of electrocution risk has important consequences for the population dynamics of birds of prey. Long-lived species are particularly sensitive to changes in adult survival, with even modest decreases in non-natural mortality translating into big benefits for population viability and substantial reductions in extinction risk (Newton 1998, Newton et al. 2016). Although eliminating electrocution incidents is an unrealistic goal while power lines remain in service, the main objective is to reduce mortality to levels low enough that it no longer limits raptor populations, ensuring that deaths due to power lines no longer threaten the long-term viability of any species.

This is indeed the case for the bird-of-prey community in Andalusia, where, currently, few species face an extinction risk from power-line electrocution. The case of the Spanish imperial eagle illustrates both the challenge and the progress achieved. Despite a recent increase in recorded electrocution events, reflecting demographic success, the regional population has grown from fewer than 50 to nearly 200 breeding pairs over the past two decades, and from approximately 200 to nearly 1,000

pairs nationally (MITECO, 2023). This expansion has been driven in large part by the insulation of power lines at key mortality hotspots, which facilitated range expansion into areas with previously unknown hazardous infrastructure generating density-dependent mortality without threatening population viability (CMS, 2024). A similar pattern may also be occurring with the booted eagle, which likewise shows an increase in recorded electrocutions concurrent with clear population growth across Spain (SEO/BirdLife 2022). The same may apply to the red kite, another species showing an increase in electrocution events, despite its small, threatened resident breeding population in Andalusia (fewer than 50 breeding pairs, Consejería de Sostenibilidad y Medio Ambiente 2025). The region receives a large wintering influx from European breeding populations that are currently expanding (BirdLife International, 2021), which would similarly produce a density-dependent increase in electrocution mortality.

We conclude that our results demonstrate that a targeted mitigation strategy based on the identification and correction of electrocution blackspots can substantially reduce the risk of electrocution at a regional scale. The marked decline in blackspot prevalence following the implementation of the Andalusian agreement provides strong empirical evidence that sustained collaboration between conservation authorities and electricity companies can effectively mitigate one of the main human-

Tab. 2. Number of raptors electrocuted by species recorded in Andalusia in total (1990–2025), during the pre-agreement period (2014–2019), and the agreement period (2020–2025). The trend of the breeding population in the region is also indicated, according to the Regional Ministry of Sustainability and Environment of the Regional Government of Andalusia (2025) and SEO/BirdLife (2022): increasing trend (↑), decreasing trend (↓), stable (=), unknown trend (?), no breeding population in Andalusia (-). Species catalogued as threatened in the region are shown in bold.

Tab. 2. Počet usmrtených dravcov podľa jednotlivých druhov zaznamenaný v Andalúzii celkovo (1990–2025), v období pred uzavretím dohody (2014–2019) a počas platnosti dohody (2020–2025). Uvedený je aj trend hniezdnej populácie v regióne podľa Regionálneho ministerstva udržateľnosti a životného prostredia vlády Andalúzie (2025) a SEO/BirdLife (2022): rastúci trend (↑), klesajúci trend (↓), stabilný (=), neznámy trend (?), v Andalúzii nehniedzdi (-). Druhy zaradené v regióne medzi ohrozené sú vyznačené tučným písmom.

Species		1990-2025		2014-2019		2020-2025		Breeding trend
		Number	%	Number	%	Number	%	
<i>Bubo bubo</i>	Eurasian eagle-owl	1,221	25	406	22	466	27.8	↑
<i>Buteo buteo</i>	common buzzard	1,004	20.6	431	23.3	283	16.9	=
<i>Gyps fulvus</i>	griffon vulture	434	8.9	170	9.2	203	12.1	↑
<i>Circaetus gallicus</i>	short-toed snake eagle	330	6.8	141	7.6	89	5.3	↑
<i>Milvus migrans</i>	black kite	316	6.5	133	7.2	107	6.4	=
<i>Aquila fasciata</i>	Bonelli's eagle	277	5.7	101	5.5	92	5.5	=
<i>Falco tinnunculus</i>	common kestrel	200	4.1	76	4.1	65	3.9	↓
<i>Aquila adalberti</i>	Spanish imperial eagle	144	3	36	1.9	70	4.2	↑
<i>Falco naumanni</i>	lesser kestrel	141	2.9	90	4.9	19	1.1	↓
<i>Hieraaetus pennatus</i>	booted eagle	138	2.8	36	1.9	70	4.2	↑
<i>Aquila chrysaetos</i>	golden eagle	128	2.6	56	3	42	2.5	↑
<i>Accipiter gentilis</i>	northern goshawk	62	1.3	24	1.3	23	1.4	=
<i>Milvus milvus</i>	red kite	60	1.2	7	0.4	39	2.3	↓
<i>Elanus caeruleus</i>	black-winged kite	35	0.7	21	1.1	3	0.2	=
<i>Pandion haliaetus</i>	osprey	26	0.5	5	0.3	8	0.5	=
<i>Strix aluco</i>	tawny owl	20	0.4	2	0.1	6	0.4	↑
<i>Falco peregrinus</i>	peregrine falcon	18	0.4	6	0.3	7	0.4	=
<i>Aegypius monachus</i>	cinereous vulture	16	0.3	2	0.1	8	0.5	↑
<i>Tyto alba</i>	barn owl	12	0.2	4	0.2	1	0.1	↓
<i>Circus aeruginosus</i>	western marsh harrier	10	0.2	3	0.2	4	0.2	↓
<i>Athene noctua</i>	little owl	8	0.2	5	0.3	2	0.1	↓
<i>Neophron percnopterus</i>	Egyptian vulture	7	0.1	3	0.2	2	0.1	↓
<i>Parabuteo unicinctus</i>	Harris's hawk	7	0.1	5	0.3	2	0.1	-
<i>Circus pygargus</i>	Montagu's harrier	6	0.1	3	0.2	0	0	↓
<i>Accipiter nisus</i>	Eurasian sparrowhawk	5	0.1	3	0.2	1	0.1	=
<i>Asio otus</i>	long-eared owl	4	0.1	3	0.2	0	0	?
<i>Pernis apivorus</i>	European honey buzzard	3	0.1	3	0.2	0	0	-
<i>Gyps rueppellii</i>	Rüppell's vulture	2	0	0	0	2	0.1	-
<i>Asio flammeus</i>	short-eared owl	1	0	0	0	0	0	-
<i>Falco biarmicus</i>	lanner falcon	1	0	0	0	1	0.1	-
Non identified	-	240	5	72	4	60	3.6	-
Total		4,876	-	1,847	-	1,675	-	-
No. of species		30	-	27	-	26	-	-

induced causes of raptor mortality. While electrocution events are unlikely to be eliminated, conservation efforts should focus on ensuring they no longer limit population viability. We therefore recommend maintaining long-term mortality monitoring programmes, regularly updating spatial risk assessments, and prioritising corrective actions in newly colonised areas and remaining high-risk sectors. The Andalusian model offers a cost-effective

and transferable framework that can be applied in other regions to maximise conservation benefits while optimising management resources.

Competing interest

The authors declare no competing interests. The study was conducted under the appropriate permits and in accordance with current ethical standards.

References

- Angelov I, Hashim I & Oppel S 2013. Persistent electrocution mortality of Egyptian Vultures *Neophron percnopterus* over 28 years in East Africa. *Bird Conservation International* 23(1), 1–6. DOI:10.1017/S0959270912000123
- Bedrosian G, Carlisle J, Woodbridge B, Dunk JR, Wallace ZP, Dwyer JF, ... & Jones T 2020. A spatially explicit model to predict the relative risk of Golden Eagle electrocutions in the Northwestern Plains, USA. *Journal of Raptor Research* 54(2): 110–125. DOI:10.3356/0892-1016-54.2.110
- BirdLife International 2021. European Red List of Birds. Luxembourg: Publications Office of the European Union.
- CMS 2024. Power line impact mitigation: Saving the Spanish Imperial Eagle. Fact Sheet on Addressing the Impact of Linear Infrastructure on Migratory Species. Convention on the Conservation of Migratory Species of Wild Animals. Retrieved March 30, 2024 from https://www.cms.int/sites/default/files/publication/infrastructure_fact_sheet_dec2024_part2.pdf
- Dixon A., Rahman ML Galtbalt B, Gunga A, Sugarsaikhan B & Batbayar N 2017. Avian electrocution rates associated with density of active small mammal holes and power-pole mitigation: implications for the conservation of threatened raptors in Mongolia. *Journal for Nature Conservation* 36: 14–19.
- Dwyer JF 2009. Raptor electrocution: a case study on ecological traps, sinks, and additive mortality. *Journal of Natural Resources and Life Sciences Education* 38(1): 93–98.
- Dwyer JF, Karyakin IV, Garrido López JR & Nikolenko EG 2023. Avian Electrocutions on Power Lines in Kazakhstan and Russia. *Ardeola* 70(1): 3–27. DOI:10.13157/arla.70.1.2023.rp1
- Dwyer JF, Kratz G E, Harness RE & Little, SS 2015. Critical dimensions of raptors on electric utility poles. *Journal of Raptor Research* 49: 210–216. DOI:10.3356/0892-1016-49.2.210
- Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible 2019. Convenio de colaboración entre la Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible de la Junta de Andalucía y Enel-Endesa para promover medidas de protección de la avifauna. Unpublished document, Ministry of Agriculture, Livestock, Fisheries and Sustainable Development of the Regional Government of Andalusia (Spain).
- Consejería de Sostenibilidad y Medio Ambiente 2025. Medio Ambiente en Andalucía. Edición 2024. Regional Ministry of Sustainability and Environment of the Regional Government of Andalusia (Spain), Retrieved March 30, 2024 from <https://www.juntadeandalucia.es/medioambiente/portal/documents/20151/215324300/Informe-Medio-Ambiente-Andalucia-edicion-2024.pdf/b28be815-01a8-634c-80fd-f2aba48a6587?t=1740405242145>
- Eccleston D T & Harness R E 2018. Raptor Electrocutions and Power Line Collisions. 273–302. In: Sarasola J H, Grande JM & Negro JJ (eds.) *Birds of Prey. Biology and conservation in the XXI century*). Springer. DOI:10.1007/978-3-319-73745-4_12
- Ferrer, M 2012. Aves y tendidos eléctricos. Del conflicto a la solución. Endesa S.A. and Fundación Migres.
- Ferrer M, Iglesias Lebrija JJ, Álvarez E & Morandini V 2026. La historia española de las líneas eléctricas y las aves, 250-254. In: Martín Martín J, Garrido López JR & Clavero Sousa H (eds.) *Líneas eléctricas y vida silvestre. Directrices para prevenir y mitigar la mortalidad de la fauna asociada a las redes aéreas de electricidad*. First edition. UICN
- Gális M & Ševčík M 2019. Monitoring of effectiveness of bird flight diverters in preventing bird mortality from powerline collisions in Slovakia. *Slovak Raptor Journal*, 13, 45–59. DOI: 10.2478/srj20190005
- Godino A, Garrido JR, El Khamlichi R, Burón D, Machado C, Amezian M, ... & Barrios V 2016. Identificación de mortalidad por electrocución de aves rapaces en el sudoeste de Marruecos. UICN, Retrieved March 30, 2024 from <https://portals.iucn.org/library/node/4626>.
- Guil F, Fernández-Olalla M, Moreno-Opo R, Mosqueda I, Gómez ME, Aranda A, ... & Margalida A 2011. Minimising mortality in endangered raptors due to power lines: the importance of spatial aggregation to optimize the application of mitigation measures. *PLoS one* 6(11) e28212
- Janss GFE & Ferrer M 1999. Mitigation of raptor electrocution on steel power poles. *Wildlife Society Bulletin* 27(2): 263–273.
- Lehman RN, Kennedy P L & Savidge J A 2007. The state of the art in raptor electrocution research: A global review. *Biological Conservation* 136(2): 159–174. DOI:10.1016/j.biocon.2006.09.015
- López López P, Ferrer M, Madero A, Casado E & McGrady MJ 2011. Solving man-induced large-scale conservation problems: the Spanish imperial eagle and power lines. *PLoS One* 6(3) e17196. DOI:10.1371/journal.pone.0017196

- MAGRAMA 2014. Estudio de integración de necesidades de financiación impuestas por el R.D. 1432/2008, con el mecanismo previsto a través de un Plan de Impulso al Medio Ambiente Tragsatec / Ministry of Agriculture, Food and Environment. Government of Spain, Retrieved March 30, 2024 from https://www.miteco.gob.es/es/biodiversidad/temas/conservacion-de-especies/estudioincidenciatendidoscambioclimatico_tcm30-379323.pdf.
- Martín Martín J, Garrido López JR & Clavero Sousa H (eds.) 2026. Líneas eléctricas y vida silvestre. Directrices para prevenir y mitigar la mortalidad de la fauna asociada a las redes aéreas de electricidad. First edition. UICN
- Martín Martín J, Garrido López JR, Clavero Sousa H & Barrios V (eds.) 2022. Wildlife and power lines. Guidelines for preventing and mitigating wildlife mortality associated with electricity distribution networks. IUCN. DOI:10.2305/IUCN.CH.2022.10.en
- MITECO 2023. El águila imperial cuenta ya con 841 parejas. *Quercus* 447: 34–35.
- Newton I 1998. Population Limitation in Birds. Academic Press, London.
- Newton I, McGrady MJ & Oli MK 2016. A review of survival estimates for raptors and owls. *Ibis* 158: 227–248
- Pérez-García JM, Botella F, & Sánchez-Zapata JA 2015. Modelos predictivos aplicados a la corrección y gestión del impacto de la electrocución en tendidos eléctricos sobre las aves. *Revista Catalana d'Ornitologia* 31: 61–83.
- Prinsen HAM, Boere GC, Pires N & Smallie JJ 2011. Review of the conflict between migratory birds and electricity power grids in the African-Eurasian region. Bonn, Germany.
- Rita H & Komonen A 2008. Odds ratio: an ecologically sound tool to compare proportions. *Ann. Zool. Fenn.* 45(1): 66–72. DOI:10.5735/086.045.0106.
- SEO/BirdLife (Molina B, Nebreda A, Muñoz AR, Seoane J, Real R, Bustamante J & Del Moral JC eds.) 2022. III Atlas de aves en época de reproducción en España. SEO/BirdLife. Madrid, from <https://atlasaves.seo.org/>
- SEO/BirdLife (López-Jiménez N ed.) 2021. Libro Rojo de las aves de España. SEO/BirdLife. Madrid.
- Serratos J, Oppel S, Rotics S, Santangeli A, Butchart S H, Cano-Alonso LS, Tellería JL, Kemp R, Nicholas A, ... & Jones VR 2024. Tracking data highlight the importance of human-induced mortality for large migratory birds at a flyway scale. *Biological Conservation* 293: 110525. DOI:10.1016/j.biocon.2024.110525
- Tintó A, Real J & Mañosa S 2010. Predicting and correcting electrocution of birds in Mediterranean areas. *Journal of Wildlife Management* 74(8): 1852–1862. DOI:10.2193/2009-521