

Bird collisions with power lines: Prioritizing species and areas by estimating potential population-level impacts

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Abstract

Aim: Power lines can represent an important source of bird mortality through collision. The identification of more susceptible species, in terms of expected population-level impacts, requires detailed biological and mortality information that is often difficult to obtain. Here, we propose a species prioritization method based on relatively easily accessed information, aimed to identify both species and areas with the potentially highest extinction risk due to collision with power lines.

Location: As a case study, we applied this method to the communities of resident breeding birds of Spain and Portugal.

Methods: For each considered species, the method takes into account the morpho-behavioural susceptibility to collision with power lines, the susceptibility to extinction and the spatial exposure to collision with power lines.

Results: Our method highlighted that the most susceptible species were large, long-lived and slow-reproducing birds, often habitat specialists with hazardous behavioural traits (especially flight height and flocking flight), with high spatial exposure to collision risk with power lines and unfavourable conservation status. Based on the distribution ranges of these species, we produced a map of hotspots for extinction risk due to collision of such priority species for each country. These areas should be considered a priority for the implementation of mitigation measures including route planning and wire marking.

Main conclusions: Overall, the proposed method can be applied to any bird community in any geographic area of the world where information on power-line distribution and published information on species traits, distribution and conservation status is available, generating valuable lists of both priority species and areas in which collision risk with power lines can potentially produce local or even global extinctions.

KEYWORDS

collision, exposure, extinction risk, life-history traits, power lines, susceptibility

1 | INTRODUCTION

Human population growth has led to the worldwide proliferation of power lines during the last century, especially in developed countries. Only considering medium- and high-tension infrastructures, there is over 65 million km of power lines currently in use around the world, and this grid increases at a rate of about 5% annually (ABS Energy Research, 2008; Jenkins, Smallie, & Diamond, 2010). These infrastructures have well-recognized negative impacts on birds, and one of the most investigated is the direct mortality through collision with overhead wires (Bernardino et al., 2018; Bevanger, 1994; Loss, Will, & Marra, 2014). Mitigation efforts aimed to reduce collision rates are increasing worldwide, especially through the implementation of wire markers (Barrientos, Alonso, Ponce, & Palacín, 2011; Janss & Ferrer, 1998). Although these mitigation measures can reduce collision risk, in most cases they cannot eliminate it (Barrientos et al., 2011, 2012; Bernardino et al., 2018). Routing electricity infrastructures avoiding potential collision hotspots (e.g., protected areas or migratory corridors) can furtherly reduce this risk (Bagli, Geneletti, & Orsi, 2011; Bernardino et al., 2018; Morkill & Anderson, 1991), and the undergrounding of conflictive power-line spans eliminates the residual hazard (Bevanger & Brøseth, 2001; Jenkins et al., 2010; Bernardino et al., 2018). Nevertheless, undergrounding is a really expensive mitigation measure, and for this reason, it is rarely implemented (Bernardino et al., 2018; Bevanger, 1994; Raab, SchütZ, Spakovszky, Julius, & Schulze, 2012).

The key challenge of estimating power-line impacts on birds is to assess under which circumstances they can negatively affect whole-population trends (D'Amico et al., 2018). Due to time and funding limitations, this is very difficult to achieve in the field, although a few attempts have been carried out for emblematic species or areas (Janss & Ferrer, 2000; Shaw, Jenkins, Smallie, & Ryan, 2010). An alternative approach is to develop macroecological methods to identify species expected to suffer potential impacts on population persistence (i.e., local or global extinction) based on relatively more easily obtained surrogate variables. This approach has been recently implemented, for example to global collision risk with wind-energy developments (Thaxter et al., 2017), to electrocution risk by electricity pylons in south-eastern Spain (Pérez-García, Sebastián-González, Botella, & Sánchez-Zapata, 2016) and to road-kill risk in California (Brehme, Hathaway, & Fisher, 2018). A similar study carried out in the United States proposed a method to prioritize bird species based on their risk of population-level impact from wind-energy developments (Beston, Diffendorfer, Loss, & Johnson, 2016). In the present study, we propose an adaptation of this method focused on power lines. For each considered species, the method takes into account: the morpho-behavioural susceptibility to collision with power lines, the susceptibility to extinction (depending on breeding parameters, habitat selection and conservation status) and the spatial exposure to collision with power lines (by calculating the overlap between species distribution range and electricity infrastructures).

As a case study, we applied this method to the communities of resident breeding birds of Spain and Portugal. The Iberian Peninsula

is a biodiversity hotspot (Myers, Mittermeier, Mittermeier, Fonseca, & Kent, 2000) with several endangered bird species (Cabral et al., 2005; Madroño, González, & Atienza, 2004). Both countries share virtually the same community of resident breeding birds, but there are differences in species distribution patterns and conservation status, and also in density and spatial distribution of the electricity grids. In both countries, collision impacts for local bird populations have been already described in the past (Barrientos et al., 2012; Moreira et al., 2017). Based on the identification of priority species with the highest extinction risk due to potential collision with power lines, we have highlighted the geographic areas in Spain and Portugal that concentrate more of these species, and that should be the main focus for the implementation of mitigation measures. Overall, the method we propose can be easily applied to any geographic area of the world where information on power-line distribution and published information species traits, distribution and conservation status is available, generating valuable lists of priority species potentially prone to population-level impacts and allowing the identification of areas in which collision risk with power lines can potentially produce local or global extinctions.

2 | METHODS

2.1 | Data on species distribution and the electricity grids

For each bird species, distribution ranges of Spanish and Portuguese populations were collected from the respective Atlases of Breeding birds, which provide occurrence data during the breeding season in 10 × 10 km grid cells (Martí & Del Moral, 2003; Equipa Atlas, 2008). We excluded introduced, marine, occasional and migratory breeders, resulting in 231 species for Spain and 183 species for Portugal (with 48 resident breeding species only occurring in Spain).

We focused only on transmission power lines (i.e. very-high-voltage power lines: 150–400 kV) because of the lack of spatial-explicit information on the distribution grid (i.e. power lines with medium or high voltage, e.g. 15–60 kV) at the country level. The layouts (vectorial format) of transmission power lines at the country level were extracted from maps (raster format) of the grids from January 2016 that were available at both Spanish and Portuguese transmission power-line companies.

2.2 | Overall prioritization approach

Based on Beston et al. (2016), our approach included five steps (Figure 1):

1. Calculation of four metrics for each species: three of them related to collision risk with power lines and the last one regarding conservation status. If a given metric varied among countries, the calculation was performed separately for Spain and Portugal;

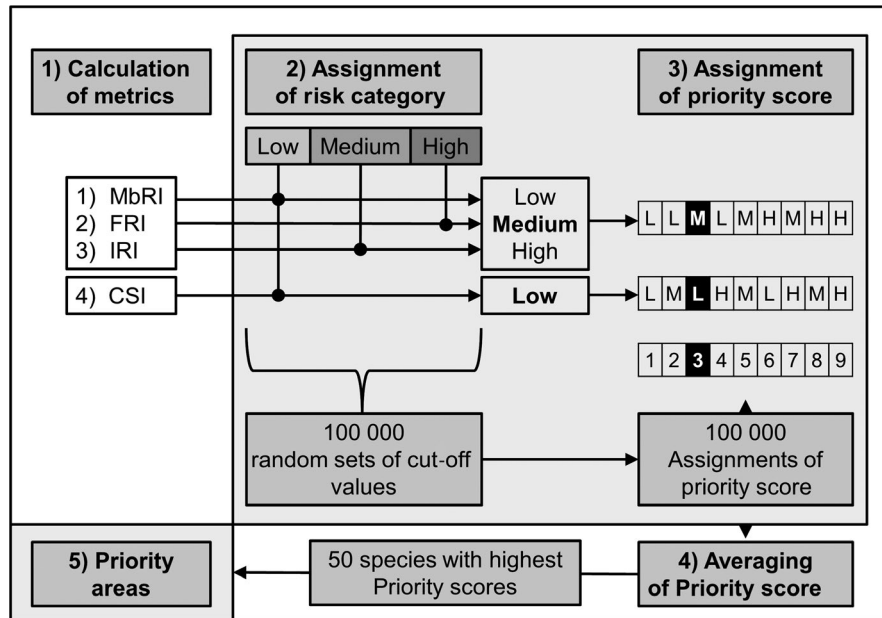


FIGURE 1 Prioritization workflow in five steps. (1) Calculation of four metrics for each species (separately for each country). (2) Assignment of Risk category for a given species and country. The random cut-off values are repeatedly drawn (100 000 times) to assign each metric value to a low, medium or high category. (3) For each simulation, the resulting combination of collision risk and conservation status categories is used to estimate a Priority score. (4) Averaging of the 100 000 Priority scores for a given species and country. (5) Priority areas for collision mitigation are identified in both Spain and Portugal by overlapping the distribution ranges of the 50 species with the highest final priority scores

- Implementation of Monte Carlo simulation approach to assign a risk category (low, medium or high risk) for each species, metric and country;
- Combination of collision-risk and conservation-status risk categories to assign a priority score for each species and country, ranging from 1 (lowest risk) to 9 (highest risk), using a lookup table. This scoring system gave more weight to collision-risk than conservation status metrics;
- Averaging (across Monte Carlo simulations) of the final priority score for each species and country, to derive an indicator of the species susceptibility to potential population-level impact by collision with power lines (i.e. local or global extinction risk).
- Identification of priority areas for collision mitigation (in each country) by overlapping the distribution ranges of the 50 species with the highest final priority scores.

2.3 | Calculation of metrics

We estimated four metrics to our study species, in order to produce a prioritization list based on their potential extinction risk, in our case by collision with power lines. The first metric implemented by Beston et al. (2016) was the proportion of Fatalities due to Turbines (FT), based on the estimate of the number of individuals annually killed by turbines as a function of total population size. In the case of power lines, available data did not allow this estimate for a large number of species, at least in our geographic area. We therefore replaced this metric with a new one focused on power lines: the

MbRI (Morpho-behavioural Risk Index), used as a surrogate alternative of species collision risk. We maintained the other three metrics: the Fatality Risk Index (FRI), the Indirect Risk Index (IRI) and the Conservation Status Index (CSI), with the adaptations described below. The values of all metrics (and submetrics) for all considered species are listed in the Appendix S1.

- Morpho-behavioural Risk Index (MbRI). This new metric represents a measure of species susceptibility to collision with power lines, considering both morphological and behavioural traits (Morphological Risk Index—MRI and Behavioural Risk Index—BRI, respectively). The available scientific literature highlights that the wing loading (i.e., body mass of a given bird species divided by the area of its wing) is the most relevant morphological trait predicting species probability to collide with electricity infrastructures (Bevanger, 1998; Janss, 2000). The ratio of body mass (in g) to wingspan (in cm) is a proxy of wing loading. Species with high values for this ratio have low manoeuvrability in flight, and therefore, they are more susceptible to collision with power lines (Bevanger, 1998; Janss, 2000). Visual perception is another morphological trait affecting species probability to collide with power lines, because binocular vision is more suitable than peripheral vision for the detection of obstacles (Martin, 2011; Martin & Shaw, 2010). In our dataset, visual perception was included as an ordinal variable (binocular vision = 1; peripheral vision = 2). MRI was estimated as the product of the two morphological factors and represents a measure of species morphological susceptibility to collision

with power lines. Species with high MRI have low manoeuvrability in flight and peripheral vision, and therefore, they were assumed to be more susceptible to collision with power lines.

The available scientific literature highlights five behavioural traits that can affect species probability to collide with electricity infrastructures: flight height, flocking flight, foraging in flight, circadian activity and use of power lines for hunting or nesting purposes (reviewed by: Bernardino et al., 2018; D'Amico et al., 2018). In our dataset, we included these behavioural traits as ordinal variables, with higher values representing higher risk. Flight type was implemented as a proxy of flight height, because soaring birds spent most time flying higher than power-line height (soaring flight = 1; flapping flight = 2). Species usually flying in flocks have higher collision probability than solitary species (solitary flight = 1; flocking flight = 2). Species foraging in flight usually has high manoeuvrability in flight, and therefore, they have lower collision probability than other species (foraging in flight = 1; not foraging in flight = 2). Overhead wires are less visible at night, and consequently nocturnal species can suffer higher collision mortality than diurnal species (diurnal = 1; nocturnal = 2). Finally, the use of power lines for hunting or nesting purposes obviously increases collision probability (avoidance or indifference towards power lines = 1; use of power lines = 2). BRI was estimated as the product of all behavioural factors and represents a measure of species behavioural susceptibility to collision with power lines. Species with high BRI were assumed to be more susceptible to collision with electricity infrastructures. Finally, we derived MbRI as the product of MRI and BRI. Species with high MbRI were assumed to be more susceptible to extinction risk by power lines. Data related to body mass, wingspan, visual perception and different behaviours for all considered species were collected from Cramp (1977). MbRI was a function of species and therefore did not differ across countries.

2. Fatality Risk Index (FRI). This metric represents a measure of both Population Exposure to Collision with power lines (PEC) and species extinction risk due to life-history traits related to breeding strategy. PEC was expressed as the density of power lines ($\text{km}/100 \text{ km}^2$) in the distribution range of the considered species and was calculated using a Geographic Information System (GIS). Species with high PEC were assumed to have more probability to cross power lines and therefore to collide. PEC was then divided by an index of life-history strategy, contrasting long-lived and slow-reproducing species (with higher extinction risk) with short-lived and fast-reproducing species (with lower extinction risk; González-Suárez, Gómez, & Revilla, 2013; Beston et al., 2016). For each species, we estimated a Breeding Ratio (BrR) of annual fecundity (clutch size per number of clutches per year per female) to the year of first reproduction (Beston et al., 2016). Species with low BrR are mainly long-lived and slow-reproducing birds and therefore assumed to be more susceptible to extinction risk. All these breeding parameters were collected from Cramp (1977). Finally, FRI was the ratio of PEC to BrR. Species

with high FRI were assumed to be more susceptible to extinction risk by collision with power lines, either because they occur in regions with higher power-line density or because their life-history strategy is slow and population will take more time to recover if affected. Because PEC differs across countries, the resulting FRI was also different between Spain and Portugal, for any given species.

3. Indirect Risk Index (IRI). This metric represents a measure of both PEC and species extinction risk due to life-history traits related to habitat selection. The available scientific literature shows that habitat-specialist species are more sensitive to habitat degradation than habitat-generalist species (Beston et al., 2016; González-Suárez & Revilla, 2013). In case of high density of power lines in a given area, habitat-specialist species are expected to be more sensitive to collision risk than habitat-generalist species. For this reason, we characterized all the considered species according to the Number of Selected Habitats (NSH), considering six broad habitat categories (farmland, agroforest, forest, scrubland, wetland and cliffs), according to both Spanish and Portuguese Atlases of Breeding Birds (Martí & Del Moral, 2003; Equipa Atlas, 2008). Species with low NSH are habitat specialists, and therefore, they were assumed to be more susceptible to extinction risk by collision with power lines. IRI was calculated as the ratio of PEC to NSH. Species with high IRI were assumed to be more susceptible to extinction risk by power lines either because they occur in regions with higher power-line density or because they have restricted habitat requirements. As before, because PEC differs across countries, the resulting IRI for each species was also different between Spain and Portugal.

4. Conservation Status Index (CSI). This metric represents a measure of general extinction risk for all considered species. CSI was assigned to each species considering five categories (i.e. 1 = Least Concern and Data Deficient; 2 = Near Threatened; 3 = Vulnerable; 4 = Endangered; and 5 = Critically Endangered), according to both Spanish and Portuguese Red Data Books (Cabral et al., 2005; Madroño et al., 2004). Species with high CSI were assumed to be more susceptible to extinction risk.

Overall differences in FRI, IRI and CSI between Spain and Portugal were tested through generalized linear mixed models (GLMM; Procedure GLIMMIX, SAS software, version 9.3) using country as a categorical explanatory variable and species as random factor.

2.4 | Final prioritization

The four implemented metrics determined four lists of species. Based on Beston et al. (2016), we categorized these four lists in order to determine the species with low, medium and high-risk values for each metric. Rather than using arbitrary cut-off values to set these three risk categories, we created 100,000 random sets of cut-off values and estimated, for each run, the classification of the species as low, medium or high risk (separately for each metric), according to each random pair of cut-off values. Pairs of

values (to define the three categories) were sampled from a uniform distribution bounded by the minimum and maximum values for each metric, with the restriction that no class should result empty in terms of species. In each run, for the three power-line risk metrics, the final risk category to combine with the conservation status category was the median value of the three metrics. The combination of the final power-line risk category and conservation-status risk category yielded a priority score (range = 1–9), which was then averaged across all runs. An illustrative example of this process is depicted in Figure 1. All calculations were performed in R.

2.5 | Identifying priority areas for mitigation measures

As a final step in our approach, we overlapped the distribution ranges of the 50 species with the highest final priority scores to identify the geographic areas with higher concentration of potentially susceptible species (i.e., species with the highest extinction risk due to potential collision with power lines), therefore, identifying hotspots of overall risk that should be targeted for impact mitigation planning. The resulting map was built by averaging the number of species within a circular window of 20-km-radius centred on each data point. This was done separately for the two countries.

3 | RESULTS

3.1 | Morpho-behavioural Risk Index MbRI

Average MRI was 6.90 (median = 3.08), ranging from 0.73 for the Eurasian firecrest *Regulus ignicapilla* to 65.66 for the great bustard *Otis tarda*, which was the species with the most susceptible morphology to collision risk with power lines. Average BRI was 3.39 (median = 2.00), ranging from 1 for 15 species, all of them diurnal raptors, to 16 for three species, all of them corvids. As a result of MRI and BRI, average MbRI was 31.94 (median = 7.62), ranging from 1.46 for the Eurasian firecrest to 517.24 for the great bustard, which was the species with the most susceptible morpho-behavioural traits to collision risk with power lines.

3.2 | Fatality Risk Index FRI

Average Population Exposure to Collision with power lines (PEC) was 8.51 km/100 km² (median = 8.58 km/100 km²) for resident bird species breeding in Spain, ranging from 0 km/100 km² for the white-backed woodpecker *Dendrocopos leucotos* to 22.21 km/100 km² for the European grasshopper-warbler *Locustella naevia*. For Portugal, average PEC was 7.05 km/100 km² (median = 7.51 km/100 km²), ranging from 0 km/100 km² for the lesser short-toed lark *Calandrella rufescens* and to 12.79 km/100 km² for the western marsh-harrier *Circus aeruginosus*. Average Breeding Ratio (BrR) was 5.96 (median = 4.92), ranging from 0.18 for the Eurasian cinereous vulture *Aegypius monachus*, which was the species with the most susceptible breeding strategy, to 36 for the bearded reedling *Panurus biarmicus*.

As a result of PEC and BrR, the average FRI was 3.28 in Spain (median = 1.70) and 2.75 in Portugal (median = 1.49), with significant differences between countries ($p < 0.0001$; Figure 2). The Spanish FRI ranged from 0 for the white-backed woodpecker to 27.79 for the European short-toed snake-eagle *Circaetus gallicus*, which was the most susceptible species in Spain. Comparatively, the Portuguese FRI ranged from 0 for the lesser short-toed lark to 23.04 for the Eurasian griffon *Gyps fulvus*, which was the most susceptible species in Portugal.

3.3 | Indirect Risk Index IRI

The average Number of Selected Habitats (NSH) was 1.94 habitats (median = 2 habitats), ranging from 1 habitat for 99 species with a relatively more susceptible habitat-selection strategy (e.g., the European northern goshawk *Accipiter gentilis*, which breeds exclusively in forests) to 4 habitats for 13 species with a relatively less susceptible habitat-selection strategy (e.g., the Eurasian blackbird *Turdus merula*, which can use farmlands, agroforests, forests and scrublands for breeding).

As a result of PEC and NSH, the average IRI was 5.46 in Spain (median = 4.44) and 4.25 in Portugal (median = 3.09), with significant differences between countries ($p < 0.0001$; Figure 2). The Spanish IRI ranged from 0 for the white-backed woodpecker to 14.15 for the tufted duck *Aythya fuligula*, which was the most susceptible species in Spain. Comparatively, the Portuguese FRI ranged from 0 for the

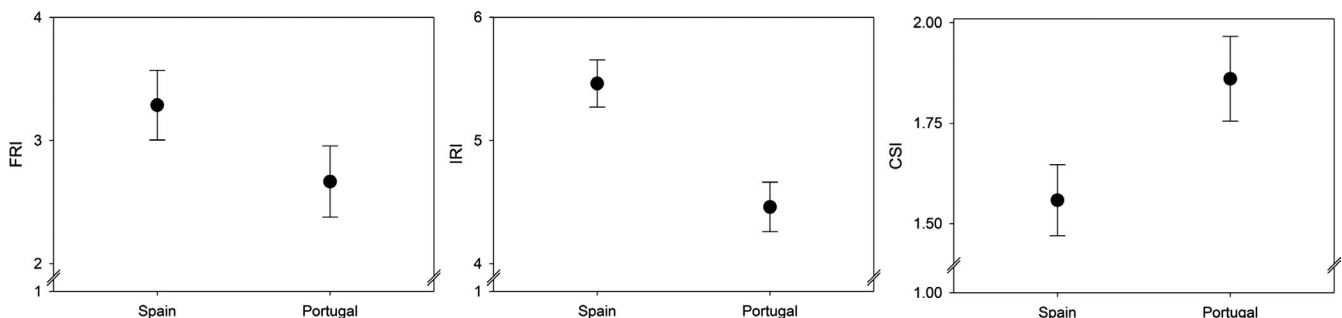


FIGURE 2 Differences in prioritization metrics between Spain and Portugal. Means (and standard errors) of prioritization metrics in both countries: Fatality Risk Index (FRI), Indirect Risk Index (IRI) and Conservation Status Index (CSI)

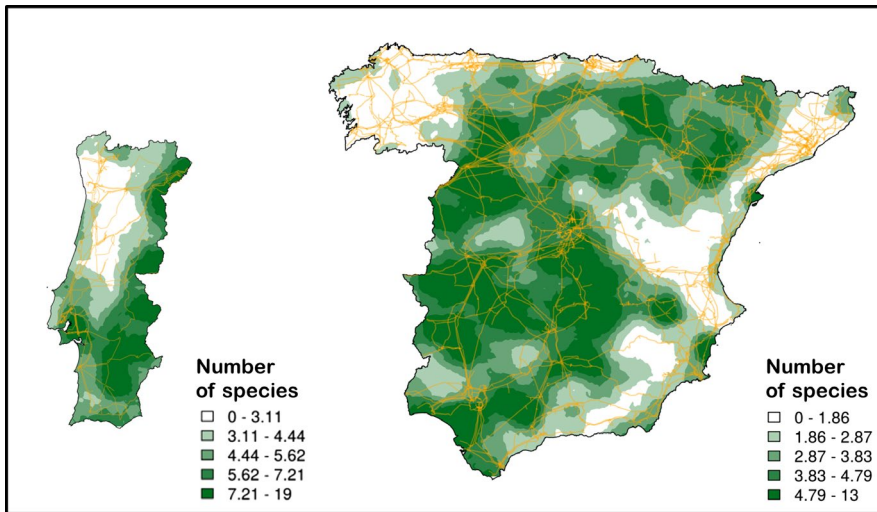


FIGURE 3 Identification of priority areas for collision mitigation. The identification of these areas in both Portugal (left) and Spain (right) was carried out by overlapping the distribution ranges of the 50 species with the highest final priority scores for each country, respectively. Map shading depicted the average number of species (0–14 in Spain, 0–18 in Portugal), averaged within a circular moving window of radius 20 km centred on each data point. Class breaks corresponded to the 20% quantiles of the distribution of these means

lesser short-toed lark to 12.79 for the western marsh-harrier, which was the most susceptible species in Portugal.

3.4 | Conservation Status Index CSI

According to Spanish Red Data Book (Madroño et al., 2004), 69% of resident bird species breeding in Spain were listed as Least Concern species (CSI = 1; e.g. the European northern goshawk), 11% were listed as Near Threatened species (CSI = 2; e.g. the boreal owl *Aegolius funereus*), 12% as Vulnerable species (CSI = 3; e.g. the Eurasian moustached warbler *Acrocephalus melanopogon*), 6% as Endangered species (CSI = 4; e.g. the Iberian imperial eagle *Aquila adalberti*) and 2% as Critically Endangered species (CSI = 5; e.g. the ferruginous pochard *Aythya nyroca*). According to Portuguese Red Data Book (Cabral et al., 2005), 60% of resident bird species breeding in Portugal were listed as Least Concern species (CSI = 1; e.g. the Eurasian sparrowhawk *Accipiter nisus*), 10% were listed as Near Threatened species (CSI = 2; e.g. the Eurasian reed-warbler *Acrocephalus scirpaceus*), 15% as Vulnerable species (CSI = 3; e.g. the European northern goshawk), 9% as Endangered species (CSI = 4; e.g. the water pipit *Anthus spinoletta*) and 6% as Critically Endangered species (CSI = 5; e.g. the Eurasian cinereous vulture). Average CSI was significantly higher in Portugal than in Spain ($p = 0.0369$; Figure 2).

3.5 | Final prioritization of species and identification of priority areas for mitigation

As a result of the final prioritization, considering a list of 50 priority species with the highest final priority scores for each country (see Appendix S1), Spain and Portugal shared 29 priority species. The most sensitive species (i.e. with the highest extinction risk due to potential collision with power lines) were the osprey *Pandion haliaetus* in Spain and the red-billed cough *Pyrrhocorax pyrrhocorax* in Portugal. Primary areas for collision mitigation focused on priority species in both Spain and Portugal are shown in Figure 3.

4 | DISCUSSION

The method we propose in the present study enabled, with a relatively easily accessed information, the identification of both priority species and areas in which collision risk with power lines can potentially produce population-level impacts (i.e., local or even global extinctions, depending on the distribution range of the target species). We applied such method to two neighbouring countries, which represent a relevant case study because both of them are located in a biodiversity hotspot (i.e., the Iberian Peninsula; Myers et al., 2000) including several bird species threatened by collision risk (Barrientos et al., 2012; Moreira et al., 2017; Moreira, Martins, Catry, & D'Amico, 2018).

Overall differences between countries could be explained by three main factors. The first factor was the list of resident breeding species of each country: Spain had a subset of exclusive species, whereas all Portuguese species occurred in Spain. The second factor was the density of transmission power lines, which was higher in Spain than in Portugal, directly causing higher FRI and ISI in Spain. Finally, the third factor was the conservation status of the considered species, which was more alarming in Portugal than Spain. This is likely because of the smaller area and resulting smaller bird population sizes in Portugal, even for the same set of species. In fact, several Least Concern species in Spain were listed as threatened in Portugal, especially the species reaching in Portugal their peripheral distribution, such as for example the Eurasian griffon or the western swamphen *Porphyrio porphyrio*.

In spite of the aforementioned factors, the proposed method showed that Spain and Portugal shared approximately half of their priority species, the main differences between countries being mostly due to priority species in Spain that did not occur (as resident breeders) in Portugal, such as the osprey or the bearded vulture *Gypaetus barbatus*. Both priority lists of Spain and Portugal included three major groups of species: steppe birds (e.g., the great bustard), large waterbirds (e.g., the Eurasian spoonbill *Platalea leucorodia*) and large raptors (e.g., the Eurasian cinereous vulture). They mostly shared low manoeuvrability in flight, hazardous behavioural traits (especially flight height and flocking

flight), long-lived and slow-reproducing life-history strategy, habitat specialization and unfavourable conservation status. Furthermore, the high density of power lines into the species distribution range greatly contributed to the species inclusion into priority list. This was particularly obvious for several waterbird species, probably because the density of power lines tends to be higher in wetlands as these lowland environments are often free from topographic obstructions to construction, often located near urban areas but, at the same time, away from public view (Azous & Horner, 2000; Thibodeau & Nickerson, 1986). Some of the species in our priority list are scarce or unknown power-line collision victims, and they have morpho-behavioural traits that make them not much prone to collisions. However, they usually have both a threatened conservation status and high power-line density in their breeding range. In such conditions, even rare collision events (which might be unnoticed due to the scarcity and restricted distribution ranges of the species) may produce consequences at the population level.

By compiling the information of the distribution range of priority species with the highest extinction risk due to potential collision with power lines, we were able to identify geographic hotspots in which a higher number of these species co-occurred. In our case study, those hotspots corresponded with several protected areas already known for the presence of threatened bird species, including wetlands (e.g., Doñana Biosphere Reserve and Tagus Estuary Natural Reserve), suitable cliff areas for breeding birds (e.g., Monfragüe National Park, International Douro Natural Park and International Tagus Natural Park) and some of the most conserved Mediterranean and even farmland areas (e.g., Alcornocales Natural Park, Guadiana Valley Natural Park and Castro Verde Biosphere Reserve). Importantly, the highlighted hotspots were not restricted to the legally protected areas, also including considerable areas without any protection status. The identified hotspots indicate the more important areas for the mitigation of collision risk, in particular at the stage of route planning of new electricity infrastructures and for the identification of priority lines for wire marking. In some cases, the undergrounding of most conflictive power-line spans should be considered.

We proposed a simple method that enables the identification of priority species potentially more affected, at a population level, by the impact of collision with power lines, and also the identification of priority regions (hotspots) of co-occurrence of a higher number of these species. Overall, this method can be applied to any bird community in any geographic area of the world where information on power-line distribution and published information species traits, distribution and conservation status is available, generating valuable lists of both priority species and areas in which collision risk with power lines can potentially produce local or even global extinctions. These identified species and areas will remain valid until further expansion of the electricity grid (resulting in changes in power-line densities in distribution ranges) or changes in species conservation status. Further improvements of the used approach could include: (a) incorporating, if available, the information on the electricity distribution grid (lower voltage) in the estimate of population exposure to collision; and (b) including information on species distribution outside the breeding season (e.g. wintering or migration). In any case,

the incorporation of metrics based on real mortality data will be a required major step towards improved estimates of population-level impacts and a more accurate identification of priority species.

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REFERENCES

- ABS Energy Research (2008). *The T&D Report*. London UK: ABS Energy Research.
- Atlas, E. (2008). *Atlas das Aves nidificantes em Portugal (1999-2005)*. [Atlas of Breeding birds of Portugal (1999-2005)]. Lisbon, Portugal: Instituto de Conservação da Natureza e da Biodiversidade (ICNF), Sociedade Portuguesa para o Estudo das Aves (SPEA), Parque Natural da Madeira, Secretaria Regional do Ambiente e do Mar, Assírio & Alvim.
- Azous, A., & Horner, R. R. (2000). *Wetlands and urbanization: Implications for the future*. Olympia: State Department of Ecology.
- Bagli, S., Geneletti, D., & Orsi, F. (2011). Routeing of power lines through least-cost path analysis and multicriteria evaluation to minimise environmental impacts. *Environmental Impact Assessment Review*, 31(3), 234–239. <https://doi.org/10.1016/j.eiar.2010.10.003>
- Barrientos, R., Alonso, J. C., Ponce, C., & Palacín, C. (2011). Meta-analysis of the effectiveness of marked wire in reducing avian collisions with power lines. *Conservation Biology*, 25(5), 893–903. <https://doi.org/10.1111/j.1523-1739.2011.01699.x>
- Barrientos, R., Ponce, C., Palacín, C., Martín, C. A., Martín, B., & Alonso, J. C. (2012). Wire marking results in a small but significant reduction in avian mortality at power lines: A BACI designed study. *PLoS ONE*, 7(3), e32569. <https://doi.org/10.1371/journal.pone.0032569>
- Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J. F., Marques, A. T., Martins, R. C., ... Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, 222(1), 1–13. <https://doi.org/10.1016/j.biocon.2018.02.029>

- Beston, J. A., Diffendorfer, J. E., Loss, S. R., & Johnson, D. H. (2016). Prioritizing avian species for their risk of population-level consequences from wind energy development. *PLoS ONE*, *11*(3), e0150813. <https://doi.org/10.1371/journal.pone.0150813>
- Bevanger, K. (1994). Bird interactions with utility structures: Collision and electrocution, causes and mitigating measures. *Ibis*, *136*(4), 412–425. <https://doi.org/10.1111/j.1474-919X.1994.tb01116.x>
- Bevanger, K. (1998). Biological and conservation aspects of bird mortality caused by electricity power lines: A review. *Biological Conservation*, *86*(1), 67–76. [https://doi.org/10.1016/S0006-3207\(97\)00176-6](https://doi.org/10.1016/S0006-3207(97)00176-6)
- Bevanger, K., & Brøseth, H. (2001). Bird collisions with power lines - an experiment with ptarmigan (*Lagopus* spp.). *Biological Conservation*, *99*, 341–346.
- Brehme, C. S., Hathaway, S. A., & Fisher, R. N. (2018). An objective road risk assessment method for multiple species: Ranking 166 reptiles and amphibians in California. *Landscape Ecology*, *33*(6), 911–935. <https://doi.org/10.1007/s10980-018-0640-1>
- Cabral, M. J., Almeida, J., Almeida, P. R., Dellinger, T., Ferrand de Almeida, N., Oliveira, M. E., ... Santos-Reis, M. (2005). *Livro vermelho dos vertebrados de Portugal [Red Data Book of Vertebrates of Portugal]*. Lisbon, Portugal: Instituto da Conservação da Natureza.
- Cramp, S. (1977). *Handbook of the Birds of Europe, the Middle East, and North Africa: The Birds of the Western Palearctic*. Oxford, UK: Oxford University Press.
- D'Amico, M., Catry, I., Martins, R. C., Ascensão, F., Barrientos, R., & Moreira, F. (2018). Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines. *Ambio*, *47*(6), 650–656. <https://doi.org/10.1007/s13280-018-1025-z>
- González-Suárez, M., Gómez, A., & Revilla, E. (2013). Which intrinsic traits predict vulnerability to extinction depends on the actual threatening processes. *Ecosphere*, *4*(6), 1–16. <https://doi.org/10.1890/ES12-00380.1>
- González-Suárez, M., & Revilla, E. (2013). Variability in life-history and ecological traits is a buffer against extinction in mammals. *Ecology Letters*, *16*(2), 242–251. <https://doi.org/10.1111/ele.12035>
- Janss, G. F. E. (2000). Avian mortality from power lines: A morphologic approach of a species-specific mortality. *Biological Conservation*, *95*(3), 353–359. [https://doi.org/10.1016/S0006-3207\(00\)00021-5](https://doi.org/10.1016/S0006-3207(00)00021-5)
- Janss, G. F. E., & Ferrer, M. (1998). Rate of bird collision with power lines: Effects of conductor-marking and static wire-marking. *Journal of Field Ornithology*, *69*(1), 8–17. <https://www.jstor.org/stable/4514280>
- Janss, G. F. E., & Ferrer, M. (2000). Common crane and great bustard collision with power lines: Collision rate and risk exposure. *Wildlife Society Bulletin*, *28*(3), 675–680. <https://www.jstor.org/stable/3783619>
- Jenkins, A. R., Smallie, J. J., & Diamond, M. (2010). Avian collisions with power lines: A global review of causes and mitigation with a South African perspective. *Bird Conservation International*, *20*(3), 263–278. <https://doi.org/10.1017/S0959270910000122>
- Loss, S. R., Will, T., & Marra, P. P. (2014). Refining estimates of bird collision and electrocution mortality at power lines in the United States. *PLoS ONE*, *9*(7), e101565. <https://doi.org/10.1371/journal.pone.0101565>
- Madroño, A., González, G. G., & Atienza, J. C. (2004). *Libro rojo de las Aves de España [Red Data Book of the Birds of Spain]*. Madrid, Spain: Organismo Autónomo Parques Nacionales.
- Martí, R., & Del Moral, J. C. (2003). *Atlas de las Aves reproductoras de España [Atlas of Breeding birds of Spain]*. Madrid, Spain: Dirección General De Conservación De La Naturaleza & Sociedad Española De Ornitología (SEO).
- Martin, G. R. (2011). Understanding bird collisions with man-made objects: A sensory ecology approach. *Ibis*, *153*(2), 239–254. <https://doi.org/10.1111/j.1474-919X.2011.01117.x>
- Martin, G. R., & Shaw, J. M. (2010). Bird collisions with power lines: Failing to see the way ahead? *Biological Conservation*, *143*(11), 2695–2702.
- Moreira, F., Martins, R. C., Catry, I., & D'Amico, M. (2018). Drivers of power line use by white storks: A case study of birds nesting on anthropogenic structures. *Journal of Applied Ecology*, *55*(5), 2263–2273. <https://doi.org/10.1111/1365-2664.13149>
- Moreira, F., Encarnação, V., Rosa, G., Gilbert, N., Infante, S., Costa, J., ... Catry, I. (2017). Wired: Impacts of increasing power line use by a growing bird population. *Environmental Research Letters*, *12*(2), 024019. <https://doi.org/10.1088/1748-9326/aa5c74>
- Morkill, A. E., & Anderson, S. H. (1991). Effectiveness of marking power lines to reduce sandhill crane collisions. *Wildlife Society Bulletin*, *19*(4), 442–449. <https://www.jstor.org/stable/3782156>
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858. <https://doi.org/10.1038/35002501>
- Pérez-García, J. M., Sebastián-González, E., Botella, F., & Sánchez-Zapata, J. A. (2016). Selecting indicator species of infrastructure impacts using network analysis and biological traits: Bird electrocution and power lines. *Ecological Indicators*, *60*(C), 428–433. <https://doi.org/10.1016/j.ecolind.2015.07.020>
- Raab, R., Schütz, C., Spakovszky, P., Julius, E., & Schulze, C. H. (2012). Underground cabling and marking of power lines: Conservation measures rapidly reduced mortality of West-Pannonian great bustards *Otis tarda*. *Bird Conservation International*, *22*(3), 299–306. <https://doi.org/10.1017/S0959270911000463>
- Shaw, J. M., Jenkins, A. R., Smallie, J. J., & Ryan, P. G. (2010). Modelling power-line collision risk for the blue crane *Anthropoides paradiseus* in South Africa. *Ibis*, *152*(3), 590–599. <https://doi.org/10.1111/j.1474-919X.2010.01039.x>
- Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., ... Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1862), 20170829. <https://doi.org/10.1098/rspb.2017.0829>
- Thibodeau, F. R., & Nickerson, N. H. (1986). Impact of power utility rights-of-way on wooded wetland. *Environmental Management*, *10*(6), 809–814. <https://doi.org/10.1007/BF01867733>

BIOSKETCH

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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