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Using risk prediction models and species sensitivity maps for large-scale identification of infrastructure-related wildlife protection areas: The case of bird electrocution

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ABSTRACT

The use of systematic area-selection procedures to design protected areas can help optimize conservation actions. However, this process has rarely been used to identify high-risk mortality areas to protect wildlife from human impacts. Electrocution on power lines is one the most important human-related causes of bird mortality worldwide, especially for raptors. Identifying and correcting dangerous individual pylons can significantly reduce the number of electrocution victims, but applying this procedure at a large spatial scale is impractical. In this paper we describe a new selection process that allows for identification of high-risk mortality areas at large scales, combining spatial electrocution risk models with maps of species sensitivity to such an impact. We used the Valencia Region (eastern Spain) as our study system. The risk prediction map was built using bird electrocution records on 1 km × 1 km grids from 2000 to 2009 and the species sensitivity map was built using data on presence and use of four raptor species. The combination of both maps was compared to the distribution of Special Protected Areas and validated by local experts to identify prediction errors or gaps. The final proposal of high priority areas to protect birds from electrocution covered 16.3% of the Valencia Region. Our work supports the use of predictive models and sensitivity maps in the decision-making process to locate high priority infrastructure-related wildlife protection areas at a large scale.

1. Introduction

The use of protected areas can efficiently reduce diversity loss (Lovejoy, 2006), but identifying and establishing protected areas is a complex process (Vane-Wright et al., 1991). Systematic area-selection procedures to design protected areas can help optimize conservation actions in priority areas based on scientific criteria (Margules and Pressey, 2000; Possingham et al., 2001; Groves et al., 2002), which also reduces subjectivity and information biases (Wilson et al., 2006; Schmolke et al., 2010). For example, species distribution prediction models have been widely applied to optimize the design of protected aeas, e.g. marine reserves (Nur et al., 2011; Arcos et al., 2012; O'Brien et al., 2012), or to identify potential areas for protection in poorly-known terrestrial ecosystems (e.g. Raxworthy et al., 2003; Ortega-Huerta and Peterson, 2004). However, systematic area-selection processes have seldom been used to locate high-risk mortality areas to protect wildlife from human impacts, such as roads, wind farms, or bird electrocutions on power lines (e.g. Malo et al., 2004; Langen et al., 2009; Carrete et al., 2012; Santos et al., 2013). The implementation of systematic area-selection processes combining spatial risk models of wildlife mortality at a large spatial scale with data on presence or abundance of species sensitive to such an impact would help to optimize mitigation of widespread human infrastructure impacts, especially those affecting a large number of species.

Interaction with power lines is one the most important human-related causes of bird mortality worldwide (Bevanger, 1994, 1998; APLIC, 2006; Prinsen et al., 2011; Loss et al., 2014, 2015). Electrocution is especially problematic for threatened species, particularly raptors (Ferrer et al., 1991; Bayle, 1999; Janss, 2000; Lehman et al., 2007; Hernández-Matías et al., 2015). Work by researchers, managers,

Abbreviations: AUC, area under the curve; ERM, Electrocution Risk Map; HPA, High Priority Areas; IIA, Insufficient Information Areas; PPA, Potential Priority Areas; ROC, receiver operating characteristic; SPA, Special Protected Area; SSM, Species Sensitivity Map; sSi, species sensitivity index

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and conservationists during the past few decades has led to an increased understanding of the factors that influence the risk of bird electrocution, such as bird size and behaviour, design and types of materials used in pylons, and the surrounding habitat (Olendorff et al., 1981; Janss and Ferrer, 1999, 2001; Mañosa, 2001; APLIC, 2006; Lehman et al., 2007; Tintó et al., 2010; Guil et al., 2011; Dwyer et al., 2014). Identifying and correcting the most dangerous pylons has been shown to reduce the number of electrocution victims (Tintó et al., 2010; López-López et al., 2011; Guil et al., 2011; Chevallier et al., 2015).

The process of identifying dangerous pylons generally follows a bird hazard assessment based on characterization of individual pylons by modelling technical characteristics and habitat variables, resulting in a pylon-based risk model (Izquierdo et al., 1997; Janss and Ferrer, 2001; Mañosa, 2001; Tintó et al., 2010; Guil et al., 2011; Dwyer et al., 2014). However, applying this selection procedure is impractical on a large spatial scale because of the time and economic resources needed to characterize and potentially modify all existing dangerous pylons. Moreover, electrocution risk is determined not only by hazards associated with individual pylons; the exposure to sensitive birds is also important. Thus, the likelihood of electrocution risk is higher when dangerous pylons are located in areas where electrocution-sensitive birds are present (Fernández-García, 1998; Mañosa, 2001; Tintó et al., 2010; Guil et al., 2011; Dwyer et al., 2014, 2016).

To address the challenges outlined above, Dwyer et al. (2016) proposed the use of a regional prediction model using power pole density as a surrogate of bird electrocution, combined with a foraging map of a sensitive species, to locate priority areas for mitigating avian electrocution. Although this proposed procedure is promising for identifying priority areas, some limitations include the assumption of homogeneity in power pole design and the linear relationship between power pole density and avian electrocution mortality. Furthermore, a procedure to reduce avian electrocutions on power lines ideally should allow for not only prioritization of existing high risk powerlines for mitigation, but also should identify areas that should be prioritized for protection in the future.

In this study we describe a systematic selection process to identify high priority areas for protection of birds from power lines at a regional scale. This process is composed of two parts. The first is a general procedure combining spatial electrocution risk models of bird mortality with occupancy data on birds sensitive to such an impact. The second part of our process involves the integration of data inherent to our particular study system (national and regional infrastructure composition and environmental regulations) with other independent sources of information including mortality records and expert knowledge to validate the models. Incorporating expert knowledge is accepted as a suitable method to complement reserve selection processes based on mathematical models (Store and Kangas, 2001; Cowling et al., 2003; Elbroch et al., 2011). Our systematic selection process could improve the design of protected areas and also help managers and power line companies prioritize mitigation and corrective actions, saving time and money.

We used the Valencia Region in eastern Spain as our model study area. This region has experienced the highest bird mortality rate from electrocution in the Iberian Peninsula (Izquierdo et al., 1997; Pérez-García, 2009), and detailed information on the presence of threatened birds and environmental variables is available. Our specific objectives were to i) analyze the relationship between bird electrocution and landscape configuration; ii) build a large-scale electrocution risk map and sensitivity map for a set of species of interest according to their conservation status, and iii) according to the Spanish national policies concerning protection against bird electrocution, identify a network of high priority areas for bird electrocution protection.

2. Material and methods

2.1. Study area

The Valencian Autonomous Community (hereafter Valencia Region) covers 23,655 km^2 and lies in the eastern Iberian Peninsula. It is a relatively mountainous region; mean elevation is 396 m asl, and maximum elevation is 1839 m asl. The climate across most of the study area is typically Mediterranean. Mean annual precipitation is between 20 and 85 cm. Natural overstory vegetation is predominantly *Pinus halepensis* and *P. sylvestris*, interspersed with Mediterranean scrub.

The Valencia Region has experienced a high bird mortality rate from electrocution on power lines (Izquierdo et al., 1997; Pérez-García, 2009). Until 2008, no mitigation strategy existed on a regional scale and only local mitigation actions had been conducted (Pérez-García, 2009). In 2008 a national law (RD 1432/2008) regarding the protection of birds against electrocution and collision on power lines was adopted in Spain. This regulation designated priority areas for mitigating power line infrastructure and included two categories: existing protected areas and specific areas to be identified by a regional manager. Existing protected areas included Spatial Protected Areas (SPAs) and areas used for implementation of action plans for threatened species. Specific areas to be designated by a regional manager included important areas for breeding, feeding, dispersal and concentration of species included in the catalogue of endangered species. Such areas could be delimited following a systematic selection process to target resources available for retrofitting power poles and to optimize the effectiveness of the regulation, and in our current study have been designated as High Priority Areas (HPA).

2.2. Modelling methodology

To identify High Priority Areas (HPA) for bird protection against electrocution, we employed a two-part process (a conceptual graphic of this is shown in Fig. 1). In the first, we constructed a map of Potential Priority Areas (PPA) for bird electrocution by combining two spatial models: 1) an Electrocution Risk Map (ERM) that related observed bird mortality with environmental variables, and 2) a Species Sensitivity Map (SSM) that identified the presence of sensitive birds based on the potential risk of electrocution and conservation status (Pérez-García et al., 2016), as determined by species-specific traits.

In the second part of the process, HPA were further identified by integrating into the PPA the specific features related to power line wildlife-impact regulations and a model validation. To adapt the PPA to specific national regulations (in this case RD 1432/2008), areas specifically included in the regulation, and therefore targets for corrective actions, were excluded. Subsequently, to validate the PPA located outside specific regulation areas and detect gaps or errors, a validation was performed using expert knowledge and supplementary mortality information not used for modelling the ERM. This evaluation identified two PPA groups: areas that were confirmed as HPA for bird protection against electrocution, which were directly incorporated into the final HPA proposal, and a second group that was designated as Insufficient Information Areas (IIA). For the latter, field sampling was conducted to determine if each IIA should be included in the HPA proposal (Fig. 1). Aditionally, experts could propose some areas that, despite not being identified within the PPA, were known for high mortality of birds by electrocution.

2.3. Bird electrocution and environmental variables

We collected all bird electrocution fatalities recorded by wildlife recovery centres and principal electric distribution companies between January 2000 and July 2009 in the study area. After we filtered and eliminated duplicate records among information sources, a total of 1098 records of electrocutions from 51 bird species was collected.

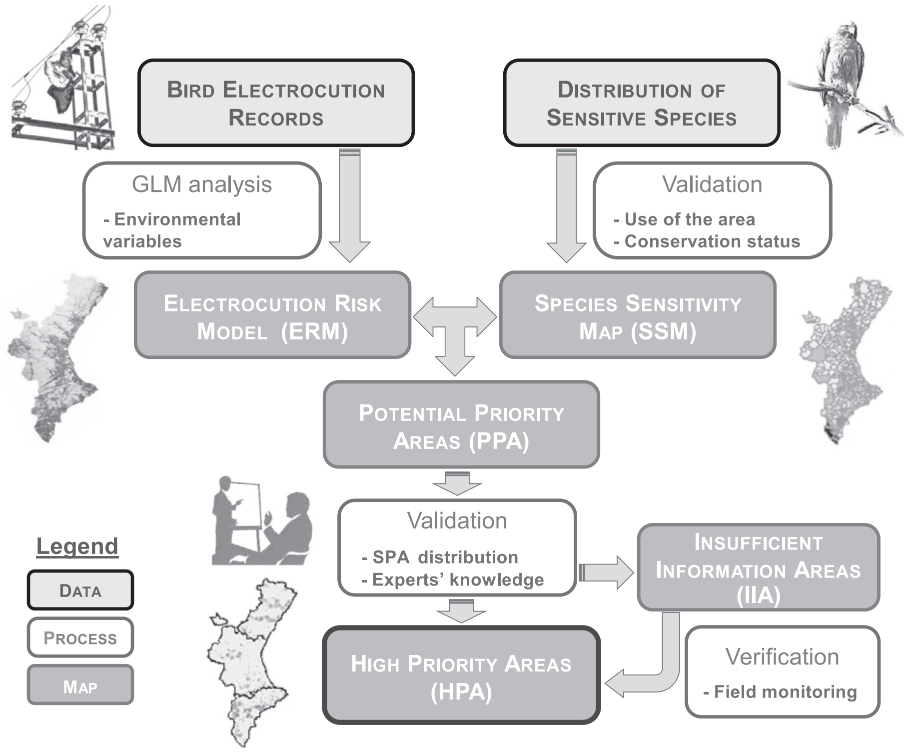

Fig. 1. Diagram of the identification process for high priority areas for bird protection from electrocution on power lines in the Valencia Region (Eastern Spain).

Raptors and owls represented 80% of all electrocutions, followed by herons and storks (6.1%), corvids (4.1%), and pigeons (3.5%). Electrocution records were grouped by precise spatial information; 38.1% (n = 419) were georeferenced and 61.9% (n = 679) had only spatial information at the municipality scale.

We divided the study area into a 1 km × 1 km grid in which 24 environmental variables with potential influence on the risk of electrocution were characterized. These included topographic and land-use (landscape) variables, anthropic variables consisting of linear infrastructure and human settlement distribution, and spatial coordinates (see Table S1 of Supplementary material). We included the distribution power line network that supplies low voltage (< 66 kV) from the transmission system to individual consumers. These low voltage power lines cause more wildlife electrocution accidents than high voltage power lines because conductors are placed closer together on the former (Olendorff et al., 1981; APLIC, 2006). The distribution power line network was obtained from the two main electric distribution companies operating in the study area (Iberdrola S.A. and Eléctrica del Maestrazgo S.A.). Land use and topographical variables were obtained from the Valencia Regional Government's webserver (http://www.icv.gva.es/). All environmental variables were organized with ArcGIS 9.1 (ESRI, 2005).

2.4. Analyzing the bird electrocution–landscape relationship

We used univariate models to study the relationship of bird electrocution fatalities with each of the environmental variables separately. Generalized Linear Models (GLMs, McCulloch and Searle, 2000) were employed to analyze the pattern of bird electrocution in each 1 km × 1 km grid section (using only the bird electrocution records with precise spatial information) with an equal number of randomly chosen grid sections without mortality records (Jones, 2001). Both linear and quadratic relationships were studied for all variables except for spatial coordinates, for which cubic distributions were also included (Legendre and Legendre, 1998). For all GLMs we used binomial error distribution and logit as the link function. Data overdispersion was also checked, and when detected, quasi-likelihood (binomial) models were used (Cameron and Trivedi, 1998; Hinde and Demétrio, 1998).

2.5. Electrocution risk map

A multivariate bird electrocution risk model was built using all the environmental variables without interactions. In this case, the analysis was conducted by comparing a sample of 75% of the mortality grid sections with an equal number of non-mortality grid sections (Jones, 2001). Both grid sections (mortality and non-mortality) were randomly chosen within the study area. Before beginning the analysis, we assessed multicollinearity of all variables with Pearson's correlations (Graham, 2003). Two variables showed a strong correlation ($> |0.7|$) with others and were eliminated (distance to nearest urban area and average elevation). The multivariate model was obtained by eliminating variables stepwise (backwards elimination) and using Akaike's information criterion for variable selection (AIC, Burnham and Anderson, 2002).

Because power line distribution might significantly influence our risk model (Dwyer et al., 2014, 2016), we conducted a deviance partioning analysis (Bocard et al., 1992) to disentangle the relative weight of power line distribution with respect to the other landscape variables and the spatial autocorrelation intrinsic to our data. We calculated the deviance explained using a multivariate model, including all variables together and then pairwise. The percentage of pure deviances was obtained for each group of variables (landscape, power lines and spatial coordinates) following the steps described in Anderson and Cribble (1998) and Cushman and McGarigal (2002).

The multivariate model's predictive power was estimated by calculating the area under the curve (AUC) in a receiver operating characteristic (ROC) analysis (Fielding and Bell, 1997; Manel et al., 2001) using the remaining 25% of mortality grid sections and an equal number of non-mortality grid sections (Anadón, 2007). ROC analysis represented specificity, defined as the percentage of correctly predicted absences (in this case, grid sections with non-mortality), and the model's sensitivity, defined as the percentage of correctly predicted presences (grid sections with electrocution). AUC values from 0.5 to 0.7 indicated poor predictive power, values between 0.7 and 0.9 indicated moderate predictive power, and those over 0.9 indicated good predictive power (Swets, 1988; Boyce et al., 2002). To facilitate the interpretation and hierarchy of the risk areas predicted by the model, the electrocution risk map was classified into three categories: low, medium, and high. We calculated two threshold values (Pearson et al., 2004). For the medium threshold value we selected the model prevalence value which maximized the sum of sensitivity and specificity (Liu et al., 2005), whereas for the high threshold value we selected the value that reached 90% of sensitivities (Pearson et al., 2004).

All statistical procedures were performed using R software (version R 2.14, http://www.r-project.org/). The p.ROC library was used to calculate the ROC curves, as well as the AUC and threshold values (Robin et al., 2011).

2.6. Species Sensitivity Map

The SSM was obtained by applying an objective method to evaluate the spatial information concerning sensitive species employed as indicator/focal species (Andelman and Fagan, 2000; Favreau et al., 2006; Bright et al., 2008). Focal species were selected according to two criteria: conservation status in Spain and sensitivity to electrocution (Madroño et al., 2004). Based on these criteria, the selected species were griffon vulture (*Gyps fulvus*), golden eagle (*Aquila chrysaetos*), Bonelli's eagle (*Aquila fasciata*), and Eurasian eagle owl (*Bubo bubo*). For each species, information available on nesting, foraging, dispersal and roosting areas was collected from a specialized bibliography and official censuses conducted by the Regional Government (http://bdb.cma.gva.es). For three species (griffon vulture, golden and Bonelli's eagles) detailed monitoring reports on their distribution and population sizes are periodically carried out, so the available information was of high quality. For the Eurasian eagle owl, the quality of the information differed across the study area, but this species' high sensitivity to electrocution a priori made it a good candidate indicator species (Rubolini et al., 2001; Martínez et al., 2006; Pérez-García et al., 2016).

For these four species, a 1 km × 1 km grid map was built within the sensitive areas. These areas were defined according to Spanish national legislation of bird protection on power lines (RD 1430/2008) as areas where breeding and foraging commonly occurred, where juveniles and non-breeding birds dispersed, or where large groups of birds gathered. According to this we established three main types of areas according to their utilization by our focal species: nest, home, and dispersal areas.

To delimit each of these areas spatially, we determined specific radii for nest and home range around each nest-site and for dispersal areas using information from previous studies. The nesting area value was applied only to the 1 km × 1 km grid sections where the nest was located. The home range radius sizes were assigned according to annual home range studies carried out close to our study area as follows: golden eagle, 5 km (Fraguas et al., 2001); Bonelli's eagle, 4 km (Sanz et al., 2005; Pérez-García et al., 2013); and Eurasian eagle owl, 2 km (Delgado et al., 2009; Campioni et al., 2013). For griffon vulture, we considered only a protection area of 1 km around colonies because of the vast home range associated with this species (> 4000 km^2, García-Ripollés et al., 2011, Zuberogoitia et al., 2012). Juvenile dispersal areas were identified based on Bonelli's eagle and golden eagle tracking studies (Cadahía et al., 2005, 2010; Soutullo et al., 2006a, 2006b).

Each 1 km × 1 km grid section inside of the sensitive area delimited was scored according to the species' conservation status, as indicated by the National Endangered Species Catalogue (RD 139/2011) and the Red Book of Spanish birds (Madroño et al., 2004), and the type of utilization of the area. Therefore, score values applied to species considered under the "Vulnerable" category (Bonelli's eagle) were as follows: home range 4 points, nest-site 3 points, and dispersion area 2 points. The score values applied to "Near Threatened" species (golden eagle) were as follows: home range 3 points, nest-site 2 points, and dispersion area 2 points. The score values applied to "Least Concern" species (griffon vulture and Eurasian eagle owl) were as follows: home range 2 points and nest-site 1 points. The species sensitivity index (sSi) of each grid section was obtained by computing all the sensitivity scores of all sensitive areas for all four species (sSi = $\Sigma_{sp.}$ (nest-site + home range + dispersion area)). Finally, the total sensitivity map was classified according to this range of species sensitivity index values: Null 0; Low 1–3; Medium 4–6; High > 6.

2.7. Selecting, validating and delimiting high priority areas

Potential Priority Areas (PPA) were obtained by overlapping the Electrocution Risk Map (ERM) and the Species Sensitivity Map (SSM). On the PPA first we deleted grid sections that had a low electrocution risk (< threshold value) or with a low value of sensitivity (< 4). We then discarded grid sections that overlapped with SPAs because those areas had been directly included in the bird protection against power lines state regulation (RD 1432/2008).

The validation of the selected PPA network was based on an evaluation by experts in threatened species and power line impacts and the verification by a new mortality dataset not included in predictive models. During this process we evaluated whether specific areas with high concentrations of electrocuted birds were not included in the PPA, or whether areas without mortality records or sensitive birds were included. For expert evaluation, we selected five professionals experienced in the distribution of threatened species (2), bird electrocution (1), and design of protected areas and natural environment management (2) in our study region. For completing the validation of the PPA, two maps were built. The first was a bird mortality map at the municipality level consisting of all electrocution records without precise locations (n = 679), whereas the second included all locations of electrocution for selected sensitive species.

The experts scored all the PPA and assigned each a value from 0 to 2. PPA with a mean value over 1 were included in the final proposal as High Priority Areas (HPA). Areas included on the PPA map, but for which no mortality records had been determined or all the experts scored with a zero value, were categorized as Insufficient Information Areas (IIA). New areas of bird electrocution proposed by local experts but not included on the PPA map also were included as IIA. In these areas, field sampling was carried out to determine whether the lack of information was due to a prediction error in the model or a lack of field data. Sampling was carried out between November 2009 and May 2010, covering at least 70% of the power line network in potential PPA to check for the presence of electrocuted birds. Visual inspections made under pylons and the surrounding area lasted 3–5 min, depending on the presence of bushy cover. Once field sampling was completed, areas in which at least one electrocution of an enlisted species in Spain was located were also included in the final proposal of HPA.

3. Results

The 419 georeferenced electrocutions occurring between January 2000 and July 2009 were located in 187 1 km × 1 km grid sections. This implies a mean mortality record of 2.01 ± 1.37 electrocutions/grid section (range 1 to 45), although 63.9% of the 1 km × 1 km grid sections recorded only one electrocution (all species affected were included in Table S2 in the Supplementary material).

3.1. Bird electrocution and landscape relationship

Presence of electrocuted birds in each 1 km × 1 km grid section was related significantly to 13 of the 24 environmental variables selected (Table 1). Distance to irrigated crops had the highest explained deviance (D^2 = 16.9%). Grid sections located closer to power lines and with medium values of electric power network density (kilometres

Table 1
Summary of univariate logistic models that relate the occurrence of electrocution in 1 km × 1 km grids with each environmental variable. We only show models for which deviation explained was > 1%. D^2 = deviance explained. Type of response: "−" = negative, "+" = positive, "+ −" = positive quadratic, "− +" = negative quadratic and "− + −" cubic negative. Significance (Sig) = *p < 0.05 and **p < 0.01.

Environmental variables	D^2 (%)	Type	Sig.
Dist. Irrigation crop	16.9	− +	**
Dist. Power line	12.8	−	**
Latitude	11.8	− + −	**
Mean elevation	9.7	−	**
% Irrigation crop	8.9	+ −	**
Power line length	8.0	+ −	**
Mean slope	7.1	−	**
Dist. Road	4.5	−	**
% Shrubland	2.8	−	**
Dist. Urban	2.4	−	**
% Aband. crop	2.3	+ −	*
% Quercus forest	1.8	−	*
% Pine forest	1.3	+ −	*

of power line per grid; km/grid) had a higher probability of electrocution occurrence, with an explained deviance of 12.8% and 8%, respectively. Electrocution occurrence in 1 km × 1 km grid sections was higher close to irrigated crops and roads, and in plain areas with mixed cover of irrigated crops, pine forest and abandoned croplands. In contrast, areas occupied mainly by scrubs and *Quercus* forest had low risk of bird electrocutions. Also, we found that the presence of 1 km × 1 km grid sections with electrocution was higher in the southern than the northern part of the study area (Table 1).

3.2. Electrocution risk model

The best multivariate logistic model reached an explained deviance of 26.9% and included four variables: distance to near irrigation crop, distance to power lines, latitude, and percentage of *Quercus* forest. These results are similar to those obtained in the previous univariate models (a summary is included in the Supplementary material Table S3). Deviance partioning revealed that most of the variation was explained by the interaction of landscape variables with the other two groups: power lines distribution (13.3%) and spatial coordinates (7.6%). In contrast, the percentage of deviance explained by landscape and power lines separately was very low (0.7% and 1.2%, respectively). The percentage of variance explained by spatial trend (5.0%) suggested a noticeable effect of spatial aggregation in those grid sections with mortality (Fig. 2).

The model showed moderate predictive power (AUC 0.78; ROC, Fig. S1 in the Supplementary material). The ERM calculated using the thresholds on the ROC curves correctly classified 66.4% of the grid sections in which an electrocuted bird was found and 81.0% of the grid sections without mortality at the medium risk threshold (0.42). At the high threshold (0.63), the model correctly classified 76.8% of the grid sections in which an electrocuted bird was found and 62.3% of the grid sections without mortality. The ERM classified 42.1% in low-risk territory, 21.1% with a medium risk and 36.8% at high risk (Fig. 3).

3.3. Species sensitivity map, potential priority areas and high priority areas

The SSM classified 38.4% of the study area with a medium sensitivity value and 13.6% with a high value (Fig. 3). The map obtained from the intersection of the ERM and the SSM covered an area of 7020 km^2, where the risk of electrocution of a sensitive species is high. This represents 29.0% of the study area (Fig. 3), of which 39.6% was located within an SPA. Subsequently, the PPA map was obtained by overlapping the ERM with the SSM. To adapt the PPA to specific national regulations, the SPA distribution was removed and isolated grid sections (i.e. groups with fewer than three adjacent individual grid sections) were excluded from the final PPA map. Thus, the final PPA map used for validation comprised 22 defined areas (Fig. 4).

We found a total of 176 electrocutions of sensitive species, of which 128 (72.7%) were Eurasian eagle owl, 19 (10.8%) were Bonelli's eagle, 19 (10.8%) were griffon vulture, and 10 (5.7%) were golden eagle. A map of bird electrocution abundance per municipality (n = 679) was built and provided to the experts to validate the PPA. The experts' validation verified 17 of the 22 PPA which were directly selected as HPA. The remaining five did not fulfill the criteria and were selected as IIA for evaluation in the field. In addition, local experts proposed two potential areas of high mortality that our model had not detected. These two areas were also included as IIA to be sampled in the field (Fig. 4).

In the seven IIAs sampled, 2352 power pylons were checked. In four of the sampled IIAs 24 electrocuted birds were found, including two common buzzards (*Buteo buteo*) and two short-toed eagles (*Circaetus gallicus*). Species listed in the Spanish National Endangered Species Catalogue (RD 439/1990) were located in three of them, which were also included in the final proposal of HPAs. The final proposal of HPAs for bird protection against electrocution included 20 areas which covered 3937 km^2, representing the 16.3% of the study region (Fig. 4).

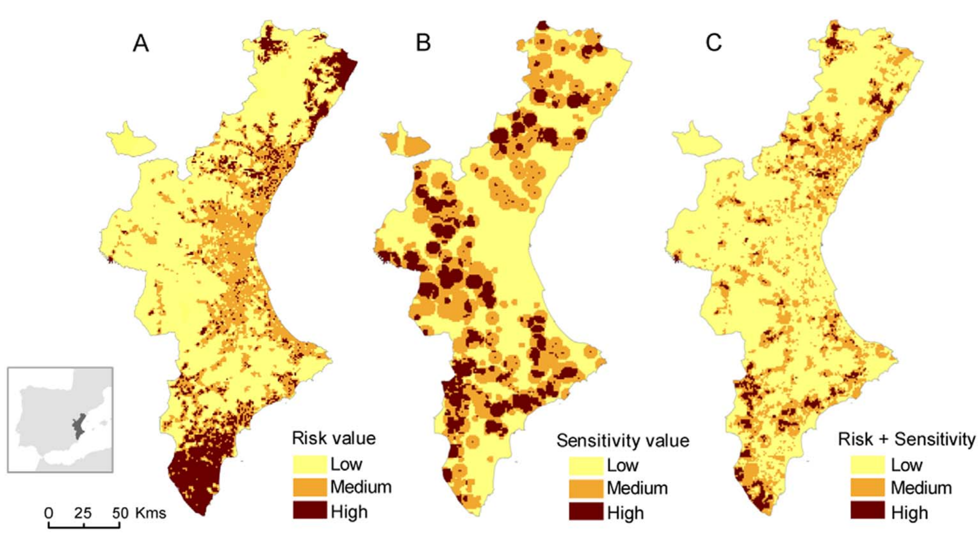

Fig. 2. Partial explained deviance between spatial coordinates, landscape and power line distribution variables of bird electrocution ocurrence in 1 km × 1 km grids from 2000 to 2009 in the Valencia Region (Eastern Spain).

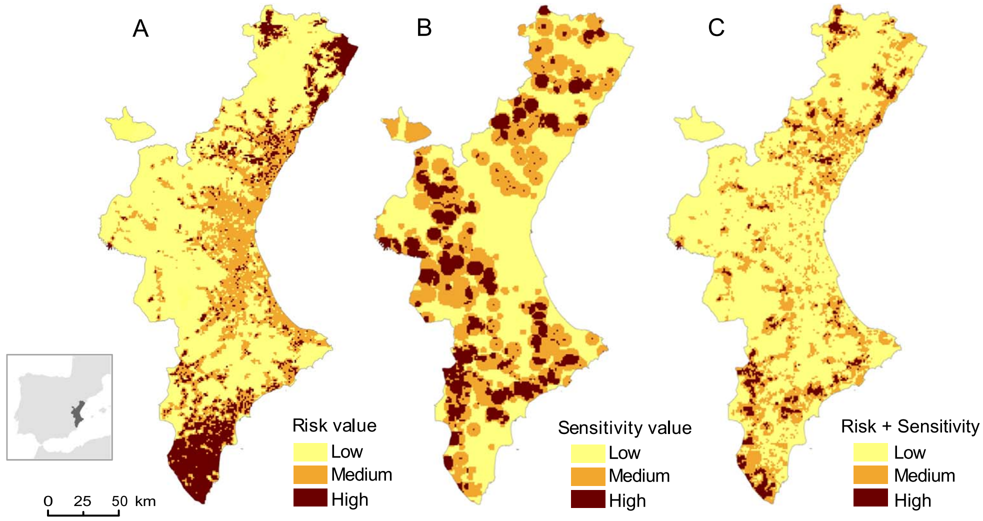

Fig. 3. A) Electrocution Risk Map (ERM) obtained from the multivariate model (Dist. Irrg. + Dist. PowLin + Lat + % Querc) for the Valencia Region (E. Spain) from 2000 to 2009. B) Species Sensitivity Map (SSM) in Valencia Region (E. Spain) based on the values of the breeding, foraging and dispersal of four sensitive species (golden eagle, Bonelli's eagle, griffon vulture and Eurasian eagle owl). C) Overlapping of Electrocution Risk Map (ERM) and Species Sensitivity Map (SSM). Areas were classified in high, medium and low risk (see Material and methods section for further details).

4. Discussion

The systematic selection process employed in our study allowed us to prioritize areas to mitigate bird electrocutions in accordance with national policies. The models also helped identify variables involved in electrocutions on a landscape scale, allowing for a better understanding of bird electrocutions from a spatial perspective.

Observed electrocution incidence showed a patchy distribution across the study area. In most of the study area the incidence was low (0.1 birds/100 km^2/year), whereas high values were evident in specific regions. Especially high was the southermost part of the Valencian Region, where maximum values of up to 45 electrocutions per 1 km^2 and mortality rates of 102 electrocutions per 100 pylons were documented by Izquierdo et al. (1997). This represents one of the highest mortality values recorded in Spain (Guil et al., 2015), and appears to have resulted from the spatial co-ocurrence of an outdated electrical distribution network and an abundant population of raptors. In fact, this area commonly holds a high concentration of dispersing juvenile and non-breeding adults of Bonelli's eagle and golden eagle, and also has one of the densest Eurasian eagle owl populations in Europe (Pérez-García et al., 2012).

We did not use our electrocution risk model to obtain estimates of electrocution incidence, given the lack of published studies on scavenging removal rate and imperfect search detection biases that would allow us to relate observed electrocution incidences with total mortality (Lehman et al., 2007; Ponce et al., 2010). Additionally, several authors have recommended against making generalizations on mortality rates for large geographical areas (Moleón et al., 2007; Guil et al., 2011).

4.1. Bird electrocution and landscape configuration

On a large spatial scale, bird electrocutions in the Valencia Region were related mainly to forest-crop ecotones and power line density. Similar results have been found in studies at the pylon scale (Mañosa, 2001; Janss and Ferrer, 2001; Tintó et al., 2010; Guil et al., 2011) and the regional scale (Dwyer et al., 2016).

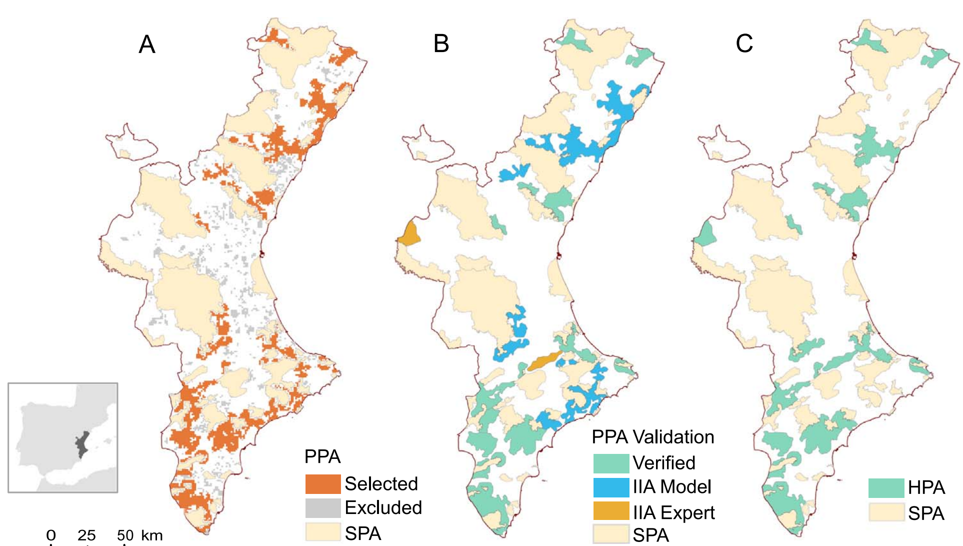

Fig. 4. A) Selection of Potential Priority Areas (PPA) according to geographical integrity and Special Protection Area (SPA) distribution in the Valencia Region. B) PPA validation map by experts. We show PPA mortality verified and two categories of Insufficient Information Areas (IIA), one obtained from the model (IIA model) and other proposed by local experts (IIA expert). C) Final proposal of High Priority Areas (HPA) against bird electrocution in Valencia Region after IIA field validation.

The relationship between landscape composition and electrocution mortality is heavily influenced by the species involved. In our study, 77% of electrocuted birds were raptors, many of which are sit-and-wait hunters and use mainly forest-crop ecotones (Sánchez-Zapata and Calvo, 1999). Both features are closely linked, given that ecotones are preferred habitats for European rabbits (*Oryctolagus cuniculus*), the key prey for raptors in the Mediterranean ecosystem (Monzon et al., 2004, Delibes-Mateos et al., 2008, 2009). Presence of prey around pylons is a well-documented predictor of electrocution risk (Tintó et al., 2010; Guil et al., 2011). Furthermore, natural perches are often reduced in ecotones, whereas power lines are common in such areas. In areas where natural and human-modified habitats intersect, the combination of abundant prey, few natural perches, and a high density of power pylons can greatly increase electrocution risk for sit-and-wait raptors (Pérez-García et al., 2011).

Human-dominated habitats and linear infrastructure presence and density appear to play an important role in the occurrence of bird electrocution in the Valencia Region. Our results showed that the highest probability of bird electrocution was reached in grid sections with a medium density of power lines. Power line density is an indirect measure of land use intensification; therefore, our results suggest that the highest electrocution risk occurs in medium intensified landscapes or transitional areas such as ecotones where power lines and sensitive species co-exist (Pérez-García et al., 2011). This argument seems logical because in natural areas the probability of finding a dangerous pylon is low; whereas highly intensified areas were avoided by most birds of prey (Sánchez-Zapata and Calvo, 1999; Palomino and Carrascal, 2007). Otherwise, bird electrocution ocurrence also increased near roads, consistent with previous studies (Guil et al., 2011; Dwyer et al., 2014). A high abundance of prey near roadsides, as well as the common co-occurrence of roads and power lines (Dwyer et al., 2016), could explain this relationship, although a search bias in the exploration of these areas cannot be ruled out.

The analysis of variance partitioning allowed us to unravel the linked effects of power line distribution and landscape configuration on bird electrocution occurrence. Interestingly, the explanatory power of both groups of variables separately was very low, confirming that power line distribution does not effectively predict bird electrocution if the surrounding landscape configuration is not taken into account. This result could compromise the use of power pole density as a unique surrogate for bird electrocutions.

4.2. Identifying high priority areas for bird electrocution protection

Most of the potential priority areas (PPA) identified in the electrocution risk map (ERM) had mean sizes covering 20–40 km^2 (similar to data reported in Guil et al., 2011), which may be related to areas with a high abundance of prey where sensitive birds tend to concentrate. Furthermore, 60.4% of the PPA was outside SPA, which confirms their poor performance as target areas for power line mitigation (i.e. Tintó et al., 2010; Pérez-García et al., 2011). This result could be related to the way protected areas have been established in Spain, where rural and naturalised areas, which are easier to protect, have been promoted (Pérez-García et al., 2011). In contrast, ecotones between natural habitats and intense farming zones, where our model indicates a higher electrocution risk, are generally excluded by regional authorities in the design of Special Protected Areas in Spain.

Although our model appears robust, it has some limitations. First of all, 49% of the electrocutions used to build the ERM belonged to two raptor species, common kestrel (*Falco tinnunculus*) and Eurasian eagle owl. This could result in a bias in locating risk areas owing to specific habitat selection and the distribution of these species. Nevertheless, previous research has suggested that these species, and particularly the Eurasian eagle owl, could be used as a good indicator of electrocution mortality for all birds in this study region (Pérez-García et al., 2016). The use of indicator species can improve the predictive power of species richness models (e.g. Nally and Fleishman, 2002, 2004; Fleishman et al., 2005), therefore it could help overcome the lack of mortality data in other rarer species. The second limitation was related to the construction of the SSM. This process was subjected to a strong component of management and conservation policies; that is, the species selection and the quantitative weighting of habitat use were influenced by particular management and conservation criteria.

4.3. Conservation implications of predictive risk electrocution models

The Valencia Region is one of the primary breeding areas for some of Europe's most threatened bird species, such as Bonelli's eagle (del Moral, 2006). Improving methods to detect and mitigate high mortality areas could effectively contribute to threatened species recovery (López-López et al., 2011). To date, mitigation actions have been focused on power lines where high mortality is known a priori (Tintó et al., 2010; Guil et al., 2011; López-López et al., 2011). Such a strategy could overlook less accessible areas or those which have simply not been explored, but might experience high mortality. Combining predictive models and species sensitivity maps has proven efficient when selecting priority zones to rectify electric power poles or delimiting areas for bird safety in accordance with the Spanish national regulations of protection on power lines (RD 1432/2008). The incorporation of expert knowledge allowed us to include information not available from predictive models and served as an independent validation of our results. This external evaluation allowed us to verify some of the potential biases that could be present in our work, such as the scores applied to build the specific sensitivity map.

Correctly identifying priority zones for conservation purposes is essential to optimize the resources invested in them (Vane-Wright et al., 1991; Margules and Pressey, 2000). In the case of the power line infrastructure we studied, a clear example is the discrepancy between the areas determined a priori by the national regulations (i.e. the SPA) and the priority areas obtained from the systematic selection process. In the absence of our approach, economic resources and conservation efforts could be invested in non-priority areas. Usually the budget available is not sufficient to correct all power lines in HPA, or these funds are not available at one time. By means of the ERM and SSM it is possible to prioritize management tasks in each selected area; e.g., calculating an index based on electrocution risk values, sensitivity and number of electrocutions recorded. It also helps to establish the HPA after an evaluation of the IIAs which, due to sampling biases, may reveal deviations between mortality predictions and records of electrocuted birds. Subsequently validating the areas identified by the model is highly recommended to check actual mortality in the field and to adopt specific mitigation measures for each area.

We also note that predictions obtained from our models are not static (Rothley, 2002). Electrocution risk can vary widely due to changes in land use, species distribution and alterations in the electric power line network configuration. For this reason, it is necessary to reanalyze data periodically to incorporate any changes in the spatial distribution of both bird electrocution and the sensitive species to adjust the spatial arrangement of the high risk mortality areas (Costello and Polasky, 2004). Regular monitoring in all high priority areas should be also included as a part of an adaptive reserve selection process.

To reduce conflict between the production of electricity and wildlife preservation, improvements in the identification of priority conservation areas are important, but must be accompanied by improvements in environmental regulations around the world. Conservation policies aimed at reducing power line mortality should be focused on long-term mitigation, including prohibition of installation of new power lines unsafe for birds, and ideally promoting the burial of all overhead power lines. Although fiscal and economic constraints during specific time periods may limit implementation of ideal conservation actions, managers and government officials should find mechanisms to use available resources for the best possible end results (Naidoo et al., 2006).

Finally, the systematic selection process proposed herein can potentially be applied to other types of impacts from human infrastructure on wildlife, e.g., to aid the planning and management of wind farms or roads (Langen et al., 2009; Santos et al., 2013). However, these applications will depend on increasing availability of mortality data over large regions that allow the construction of reliable risk models.

5. Conclusions

Large-scale spatial patterns of bird mortality from electrocutions depend mainly on the combination of two factors: how the electric distribution network is arranged, and the land use configuration. These risk factors are often closely related because they are directly associated with the presence of power lines, especially in some land uses such as irrigated crops (Dwyer et al., 2016).

The combination of risk prediction models and species sensitivity maps helps optimize the identification of areas with high bird mortality from power lines. In order to maximize the fitting process, analyzing sensitivity and making field validations are suitable measures which allow us to evaluate model fit compared to actual data (Oreskes et al., 1994).

Finally, our work strengthens the idea that the use of predictive models in the decision-making process of conservation actions would save resources (i.e. money or time) and will optimize the design of protected areas (Pullin et al., 2004; Costello and Polasky, 2004).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2017.04.033.

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