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Bonelli's Eagle electrocution risk in Israel can be reduced by 80% by insulating only 4% of the pylons

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ABSTRACT

The Bonelli's Eagle (*Aquila fasciata*) is a critically endangered species in Israel, with electrocution on power lines posing a serious threat to its population. Because retrofitting of electricity pylons to prevent mortality is a slow and costly process, it is important to prioritize the pylons in the network for quick and efficient mitigation of eagle mortality. To determine which pylons need to be retrofitted, we applied a three-stage maximum entropy modeling process for identifying the risk factors posed by different environmental variables. The environmental feature with the highest correlation to electrocution is the distance to reservoirs (i.e., many electrocution events occur near water reservoirs). The reservoirs are foraging hotspots for Bonelli's Eagles in Israel's arid environment. Electricity pylons powering the reservoirs' pumping facilities tend to be the highest perches in the vicinity of many of the reservoirs, creating an ecological trap. The strong attraction of reservoirs to eagles may explain the high level of selectivity indicated by the model, suggesting that retrofitting only 3.6% of the pylons in the network would achieve 77% reduction in eagles' electrocution probability. Moreover, insulating pylons according to the model will also likely reduce electrocutions of other avian species, including Eastern Imperial Eagle (*Aquila heliaca*) and White-tailed Eagle (*Haliaeetus albicilla*). The modeling process presented here yielded 2 electrocution risk maps, one to facilitate prioritization of mitigation in Israel's existing power network and the second to support planning and designing new infrastructure. The model may help reach conservation goals for the Israeli Bonelli's Eagle and the modeling approach may also be useful in prioritizing pylon retrofitting in other arid landscapes.

Keywords: bird electrocution, eagles, ecological trap, electricity pylons, Israel, MaxEnt model, mitigation measures, power lines, raptors, spatial risk prediction

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LAY SUMMARY

- Raptor electrocution on power lines is a major mortality cause, negatively affecting many of their populations worldwide. In order to halt this problem, it is necessary to correct the electricity pylons by changing their structure or insulate their energized parts.
- In this study, we used a geographic model to prioritize the insulation of pylons in the Israeli electricity grid in order to enable the recovery of the locally endangered Bonelli's Eagle and bring remedy for other eagle species that share the same habitats.
- The results show that the eagles are especially prone to get electrocuted near water reservoirs that are favored by them for foraging, but where electricity pylons are the only tall perch available, because all the trees were removed when the reservoirs were initially constructed.
- The model suggests that retrofitting only 4% of the pylons in the network would achieve ~80% reduction in eagles' electrocution, aiding their conservation.

El riesgo de electrocución de *Aquila fasciata* en Israel puede reducirse en un 80% aislando solo el 4% de los postes

RESUMEN

Aquila fasciata es una especie en peligro crítico de extinción en Israel, representando la electrocución en líneas eléctricas una seria amenaza para su población. Debido a que la renovación de postes eléctricos para prevenir la mortalidad es un proceso lento y costoso, es importante priorizar los postes en la red para mitigar de forma rápida y eficiente la mortalidad de las águilas. Para determinar qué postes deben ser adaptados, aplicamos un proceso de modelado de Máxima Entropía de tres etapas para identificar los factores de riesgo planteados por diferentes variables ambientales. La característica ambiental con la correlación más alta con la electrocución es la distancia a los embalses (i.e.,

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muchos eventos de electrocución ocurren cerca de los embalses de agua). Los embalses son puntos de alimentación clave para *A. fasciata* en el entorno árido de Israel. Los postes eléctricos que alimentan las instalaciones de bombeo de los embalses tienden a ser los lugares más altos en las cercanías de muchos embalses, creando una trampa ecológica. La fuerte atracción de los embalses para las águilas puede explicar el alto nivel de selectividad indicado por el modelo, sugiriendo que adaptar solo el 3.6% de los postes en la red lograría una reducción del 77% en la probabilidad de electrocución de las águilas. Además, el aislamiento de los postes según el modelo también probablemente reducirá las electrocuciones de otras especies de aves, incluyendo a *A. heliaca* y *Haliaeetus albicilla*. El proceso de modelado presentado aquí produjo dos mapas de riesgo de electrocución, uno para facilitar la priorización de la mitigación en la red eléctrica existente de Israel y el segundo para respaldar la planificación y diseño de nueva infraestructura. El modelo puede ayudar a alcanzar los objetivos de conservación para *A. fasciata* y también puede ser útil para priorizar la adaptación de postes en otros paisajes áridos.

Palabras clave: águilas, electrocución de aves, Israel, líneas eléctricas, medidas de mitigación, modelo MaxEnt, postes eléctricos, predicción espacial de riesgos, rapaces, trampa ecológica

INTRODUCTION

Avian electrocution by power lines has detrimental consequences for population dynamics and viability (Bevanger 1998, Guil et al. 2011, López-López et al. 2011, Hernández-Matías et al. 2015) and thus constitutes a major conservation issue on a global scale (Lehman et al. 2007, Loss et al. 2014, Harness et al. 2016). In Israel, electrocution on power lines has been recorded as an important cause of mortality for almost all medium and large birds of prey that are breeding or wintering in the country (Bahat 1994, Hatzofe 2013). For example, from 2011 to 2020, ~1,095 birds were incidentally found injured or dead after being electrocuted (Israeli Nature and Parks Authority, unpublished data), including 58 individuals of the genus *Aquila*. Almost all involved medium-voltage (22 or 33 kV) distribution power lines (Hatzofe 2013). Given that only ≤ 10% of avian electrocutions cause outages (Dwyer and Mannan 2009, Kemper et al. 2013), and consequently most are never found, these incidental observations suggest far more electrocutions are occurring than are detected.

Although bird electrocution is a known problem in Israel, it remains unresolved. The main solution is reactive insulation with insulating plastic sleeves on the pylons where electrocutions occur (Figure 1). This addresses pylon-specific risk (López-López et al. 2011, Hatzofe 2013, Chevallier et al. 2015), but only at 100–150 pylons yr^{-1} (out of more than 140,000 pylons in the electricity distribution network). There is no proactive mitigation strategy and dangerously designed pylons continue to be included in new construction (Israel Electric Corporation, personal communication), compounding the problem.

Among raptors, the Bonelli's Eagle (*Aquila fasciata*) is especially prone to electrocution (Real et al. 2001, Hernández-Matías et al. 2015). More than 70% of all injured or dead Bonelli's Eagles found in Israel have been electrocuted. Moreover, a population viability analysis (PVA) predicted that this species would become extinct in the region within the next 30 years, if electrocutions continue unabated (Mayrose et al. 2019).

The probability of avian electrocution on a power pylon depends on a combination of environmental factors and structural elements (Dwyer et al. 2013, Eccleston and Harness 2018). Environmental factors can include the presence of tall trees and proximity to breeding grounds or migration corridors (González et al. 2007, Cadahia et al. 2010, Bedrosian et al. 2020). Structural elements can include pylon configuration and the presence of energized equipment (Tintó et al. 2010, Dwyer et al. 2013, 2016). Retrofitting occurs at the pylon level, but in many cases geospatial data describing electricity networks is not available, so planning retrofitting often occurs at larger scales (as by Dwyer et al. 2013, 2016, Bedrosian et al. 2020). This approach has not yet been implemented in Israel, so in this study we developed a spatial prioritization model based on partial data describing Israel's electric power grid, combined

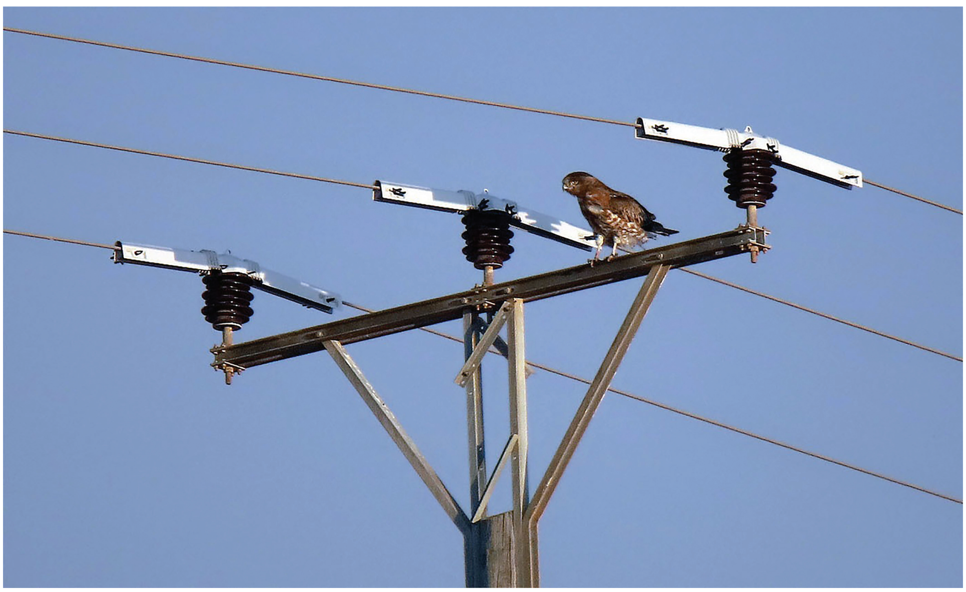

FIGURE 1. A Short-toed Eagle (*Circaetus gallicus*) perched on a pylon with plastic sleeve insulators mounted over the three phase conductors (photo: Yosi Atias).

with the distribution of Bonelli's Eagles. The advantage of this approach was the production of a continuous risk map for all of Israel, enabling the identification of existing electrocution hotspots, and prediction of future hotspots associated with ongoing expansions of the electric system.

The modeling approach included the use of maximum entropy modeling (MaxEnt) (Elith et al. 2006, Phillips et al. 2006), which combines observation records with environmental layers (such as topography, climate, land-use/cover, etc.), to yield a map of the relative probability for a species' presence over a defined range. This type of model is commonly used in ecological studies, including those dealing with risk assessment of power lines to birds of prey (Bedrosian et al. 2020, Crespo-Luengo et al. 2020).

In this study, we sought to define the environmental factors that are influencing the risk of Bonelli's Eagle electrocution, to identify the most electrocution-prone areas in Israel and to quantify the number of medium-voltage pylons that needs to be retrofitted in order to reduce electrocution risk to a substantial degree (e.g., by ≥ 75%). When incorporated into the species' management plan, this approach is expected to facilitate a population recovery, such that its extinction risk would be lowered to the point of down-listing it from its current national status of "Critically endangered" (Mayrose et al. 2017).

MATERIALS AND METHODS

Study Area

The study included all of Israel (~28,000 km^2). The country's geomorphology consists of 3 biogeographic zones: (1) Mediterranean woodland and scrubland, which covers ~34% of the country and has largely (60%) been converted to agriculture; (2) Irano-Turanian steppe, which covers a smaller portion (~13%) of the country; and (3) the Saharo-Arabic desert, which covers 53% of the country and holds most of the raptor populations that still breed in the country (Yom-Tov and Tchernov 1988, Mayrose et al. 2017). In the Mediterranean woodland and scrubland, the overuse of pesticides in the agriculture has led to a dramatic decline in the raptor populations of this region, but many non-adult Bonelli's Eagles from other regions are still dispersing to the law-laying Mediterranean valleys, where most of the electrocutions occur. The country is highly populated, especially in its central and northern parts, and has a dense network of power lines that are managed almost solely by the Israeli Electrical Corporation (Sorek and Shapira 2018, Israel Central Bureau of Statistics 2023).

Study Species and Conservation Measures

The Bonelli's Eagle is a medium-sized raptor distributed from Southeast Asia through the Middle East to the Western Mediterranean (Orta et al. 2020). Its IUCN status is Least-Concern, although the population is thought to be declining throughout its range (BirdLife International 2020). In Israel, the Bonelli's Eagle has declined from ~60 pairs during the 1950s to 12–19 pairs during the last decade and is listed as regionally Critically Endangered (Leshem 1976, Shirihai 1996, Mayrose et al. 2017).

The life cycle of Bonelli's Eagles is composed of 2 major stages, which have markedly different ecologies (Hernández-Matías et al. 2015, Morollon et al. 2022). After the post-fledging period, eagles undergo a transient nomadic phase in which they undertake long-distance movements and show no territorial behavior (Real and Mañosa 2001, Cadahia et al. 2010, Hernández-Matías et al. 2010). By contrast, territorial Bonelli's Eagles (mostly 3-year-old or older) are sedentary, with strong site fidelity and territoriality (Bosch et al. 2010, Martínez-Miranzo et al. 2016, Morollon et al. 2022). As these 2 life stages occupy different areas, electrocution mitigation must consider both. The analysis presented here is intended to direct mitigation of the electrocution problem over the nonbreeding ranges, whereas electrocution mitigation in breeding ranges is addressed by a different method, as described by Rollan et al. (2016) and Hernández-Matías et al. (2020).

Presence Data

Presence data were obtained from 2 sets of records: (1) 39 non-adult Bonelli's Eagle electrocution records from the years, 2015–2021 (INPA database); (2) GPS data of non-adult nature-born (n = 11) and released captive-bred (n = 18) Bonelli's Eagles, tagged during 2015–2019, with a total of 8,547 GPS locations. Data were collected by 30-g solar-powered GPS-GSM transmitters (Ornitela OT-30; see Supplementary Material for the data-filtering process). Each individual was tracked for 28–957 days (mean = 268 days) after dispersal from natal territories. It is worth noting that the dispersal patterns of the 2 groups (captive vs. wild born) within the area of Israel were found to be very similar, and models including separate data from each group were nearly identical.

Model Construction and Exploration

The maximum entropy algorithm was used, as implemented in MaxEnt version 3.4 (Phillips et al. 2006), to model the likely distribution of Bonelli's Eagles in Israel, and their potential electrocution risk. The most important environmental variables for explaining the modeled patterns were evaluated by both percent contribution to the model and the jackknife test (Phillips et al. 2006). The effects of the environmental variables on the MaxEnt logistic prediction were evaluated using the response curves, which depicted the relationship between the species' probability of occurrence (or in our case, species' probability of electrocution) and the values of a given variable.

The MaxEnt model was applied in 3 stages to predict 3 different distributions; each stage was based on different sets of presence records and explanatory variables. The Bonelli's Eagle dispersal distribution produced by the first stage was used as an explanatory variable in the next stages. The stages were as follows:

Stage 1: Predicting the spatial distribution of non-adult Bonelli's Eagles

The dependent variable here was the relative probability for Bonelli's Eagle presence, estimated at the scale of 0–100, with values assigned to each pixel in the map. Telemetry records served as true presence observations for this predictive model.

Stage 2: Predicting the spatial distribution of eagle electrocution risk

The aim of this stage was to predict Bonelli's Eagle electrocution risk throughout Israel, including in areas where electricity lines do not yet exist. The product of this stage is meant to serve for planning and correct routing of new distribution lines likely to be built in the future; hence, the model was built without any variable that is related to the existing network. Documented Bonelli's electrocution events served as the set of observation records, with the same set of explanatory variables that were used in stage 1, plus the predicted eagle distribution (produced in stage 1). The dependent variable in this stage was the relative probability for Bonelli's Eagle electrocution.

Stage 3: Predicting the spatial distribution of electrocution risk from existing power lines

The aim of this stage was to predict Bonelli's Eagle electrocution risk on currently existing electricity distribution lines. Documented electrocution events served as the set of observation records, with all the explanatory variables of stage 2, together with the density of existing power pylons. Pylon's density was set as the number of pylons in 500-m radius from the center of each 100 × 100 m pixel (due to confidentiality reasons, the GIS layer of the electricity grid was not available for the study, but only a layer of pylon density). Again, the dependent variable was the relative eagle electrocution probability, estimated et the scale of 0–100.

The Explanatory Variables

Ten independent environmental variables were used for the prediction of electrocution risk (Supplementary Material Table 1). These variables related to climatic conditions, topography, human influence, land-use, and land-cover. As noted earlier, the GIS layer of the electricity grid was not available for the study, and only a layer of pylon density in the electricity grid could be used. These variables were inserted into the model, which determined if and how they affect the risk of electrocution of non-adult Bonelli's Eagles. The spatial resolution of the explanatory variables was set to 100 m (see Supplementary Material for the filtering process of the explanatory variables).

Setting Risk Categories

In order to set priorities for pylon retrofitting and to simplify the description of the risk map, the continuous values of the model output map were divided into 5 risk categories, using the Jenks algorithm (*Natural breaks* function, ArcGIS Pro, ESRI 2019). This algorithm divides the histogram of relative risk probability in a way that emphasizes the natural gaps that exist in the data (De-Smith et al. 2018). After setting risk levels, the products of the second and third stages were used to designate high-risk areas and high-risk power line sections and to quantify the number of pylons that need to be retrofitted.

Model Validation

The models were validated using the area under the curve (AUC) index, which is statistically interpreted as the probability of correctly discriminating between the positive and negative values of a randomly chosen pair (Phillips et al. 2006, Merow et al. 2013). Mean AUC values of 0.8 or higher were considered as good predictive ability of the model (Remya et al. 2015). The default settings and 5-fold replicates (jackknife cross-validation) were used to test the performance of the model. Random test percentage was set to 20%; hence using 80% of the electrocution data points to train the model, and the rest 20% for testing it (Philips et al. 2006, Merow et al. 2013).

Except for the evaluation of the model with 20% of the previously documented electrocution records as described above, the model was also tested against independent electrocution events that occurred while working on the model (9 Bonelli's Eagle electrocutions were recorded from 28 June 2020 through 14 January 2021). A 2 × 2 Fisher's exact test was used to evaluate whether these new mortality events were randomly distributed in the power network according to the number of pylons in each risk category. To do that, the pylons in the risk categories were clumped into 2 groups: the 3 lower risk categories were regarded as low risk pylons (group 1) and the high and very high-risk categories as high-risk pylons (group 2).

Evaluating the Potential Effects of Insulating the Power Grid According to the Model on Other Bird Species

The potential effects of insulating the most hazardous pylons according to the Bonelli's Eagle model on other species of birds was inferred by using a dataset of documented electrocution records ($n = 658$) containing events pertaining to 12 raptor and 2 stork species. The potential impact of full implementation of the insulation of the grid according to model outputs on each species was calculated as the relative percentage of each species' electrocution records that fall within each of the model's risk levels. The percentage of electrocution events that fall within the two highest risk categories (that were nominated for retrofitting) was considered as the relative remedy for that species.

RESULTS

Distribution Maps

The 3 stages of the model yielded different predicted distribution maps and corresponding sets of explanatory variables with their relative weights.

Stage 1 product: The distribution of non-adult eagles

The map of predicted Bonelli's Eagle dispersal distribution (Figure 2) was produced at the first stage of the analysis. The AUC value of the MaxEnt model was 0.899 (SD = 0.006).

Stage 2: The spatial distribution of electrocution risk

The map produced at this stage (Figure 3A) was generated using the same set of explanatory variables, plus the additional distribution layer that was produced in the first stage (Figure 2). The recorded electrocutions served as observations ($n = 39$). The mean AUC for the training and the test data was 0.976 (SD = 0.003) and 0.935 (SD = 0.028), respectively. Dividing the risk histogram into 5 categories using Jenks algorithm yielded highly selective thresholds, where the highest two levels covered about 1.5% of Israel, while accounting for ~69% of the electrocutions (Supplementary Material Table S2).

According to the model, the riskiest areas for eagle electrocution were within the higher probability dispersal areas (as delineated by the model in the previous stage), and within them it has explicitly highlighted all the water bodies and their surrounding (reservoirs, fish ponds, etc.) producing a very selective map.

Stage 3: Identifying high-risk power lines

The map produced at this stage is shown in Figure 3B. The mean AUC for the training and the test data was 0.990

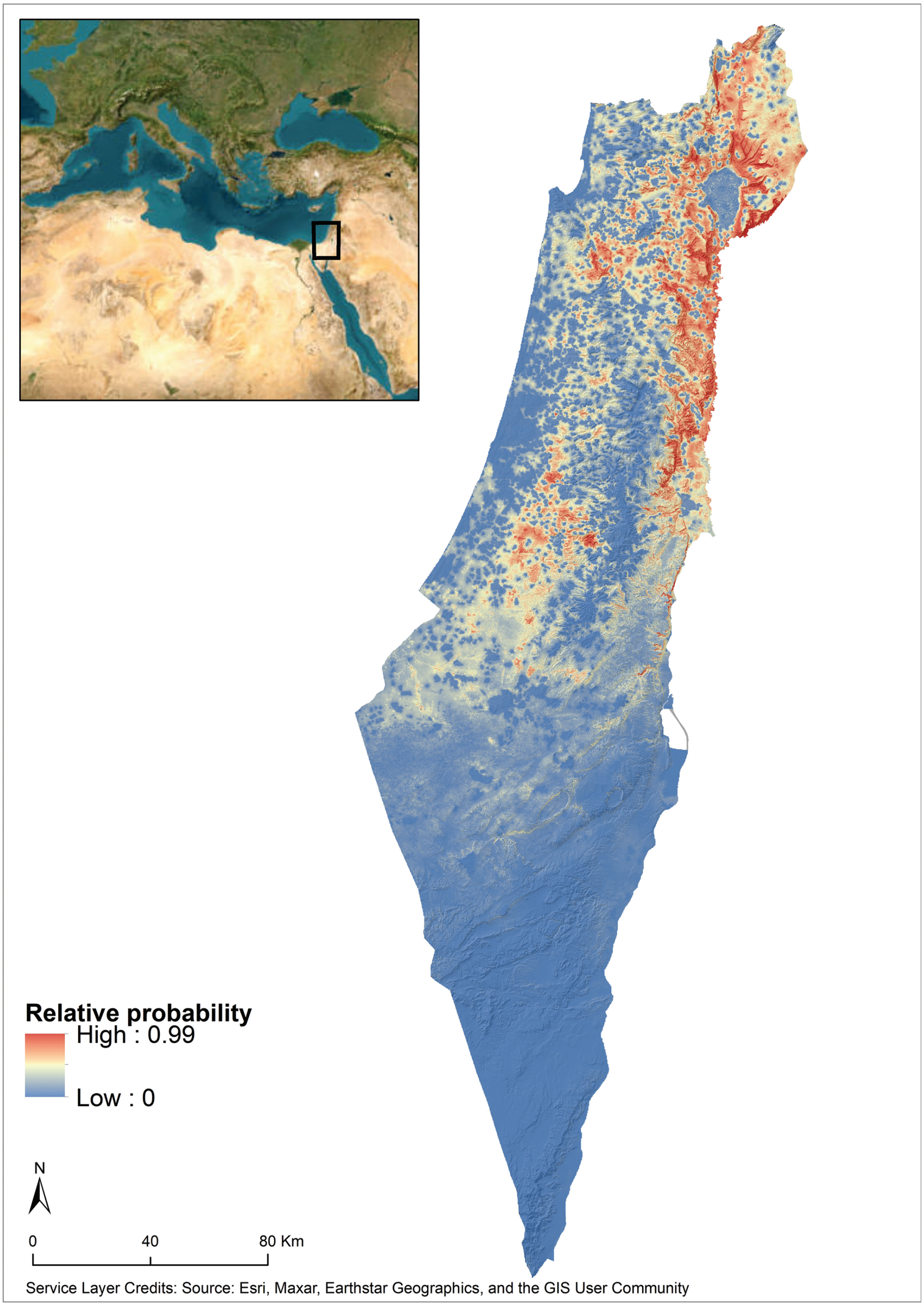

FIGURE 2. Predicted dispersal distribution of non-adult Bonelli's Eagles in Israel as generated by the MaxEnt model (in stage 1). The high probability areas of the maps cover mostly low-lying, irrigated agricultural areas that are known to be favored by Bonelli's Eagles during their dispersal period.

(SD = 0.002) and 0.969 (SD = 0.021), respectively. The addition of the pylon density layer was significant, accounting for ~36.1% of the calibration of the MaxEnt model (Table 1), as expected by the fact that electrocution events can only happen in areas with power lines. Hence, the addition of this layer yielded a model that was much more spatially restricted and limited to pixels with any density of pylons, where all the risk categories, except for the lowest risk (as divided by Jenks algorithm), spanned much smaller areas, without losing their prediction accuracy.

Explanatory Environmental Variables

There were marked differences in the relative contribution of each environmental variable to the three distribution models,

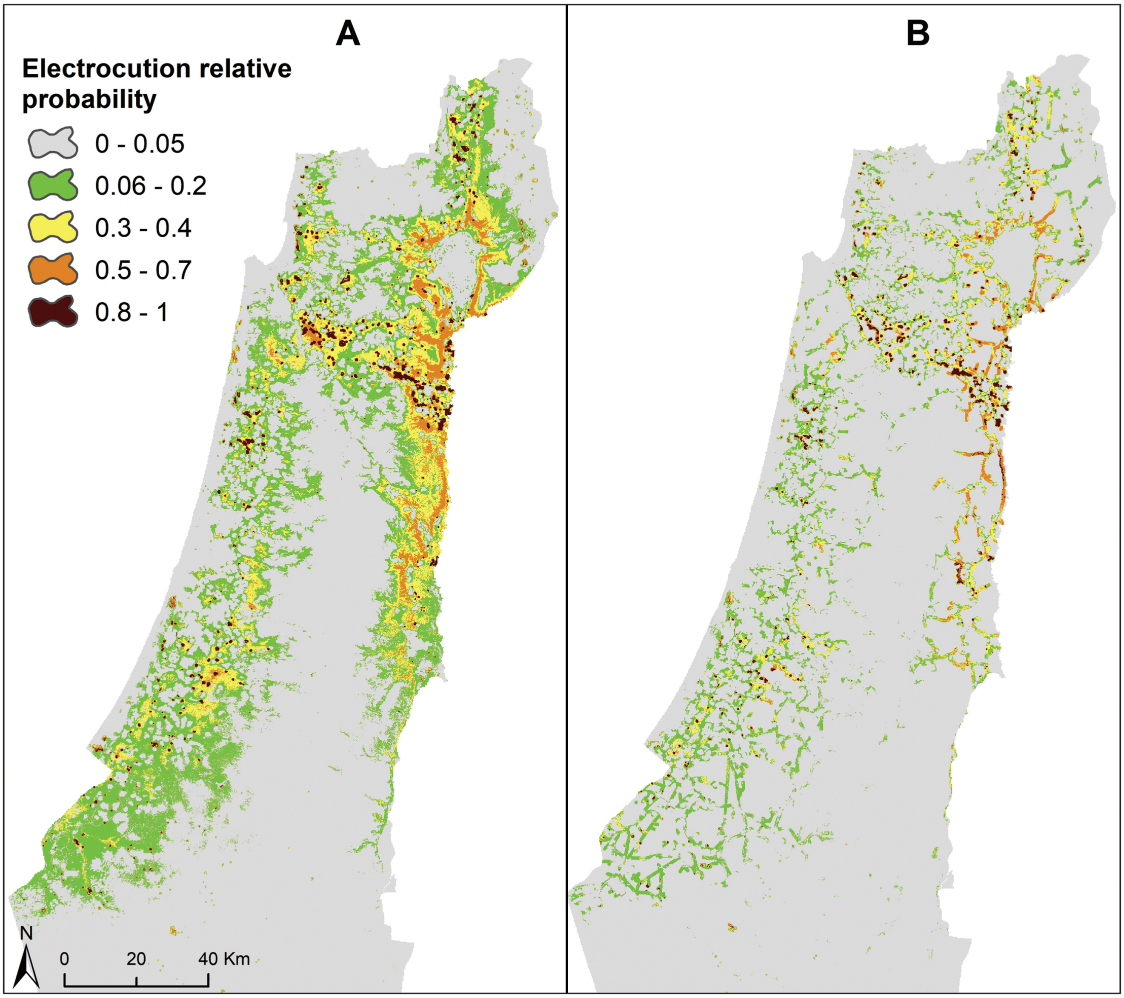

FIGURE 3. Sensitivity maps that were produced by the model (southern Israel is not shown as it contains only the lowest risk level). (**A**) Second-stage model (predicting the spatial distribution of electrocution risk, regardless of existing infrastructures). (**B**) Third-stage model (predicting the distribution of risk along existing power lines).

TABLE 1. Contribution of the environmental variable layers to the calibration of the predicted distribution maps (averaged over 5 replicate runs).

		Relative contribution (%)		
Layer code	Description	Stage 1: Predict Bonelli's Eagle dispersal distribution	Stage 2: Predict electrocution sensitive areas	Stage 3: Predict sensitive power line sections
DEM	Height a.s.l (elevation)	10.0	4.1	0.8
Slope	Topographical aspect ratio	10.0	2.3	1.0
Precip	Annual mean precipitation	32.3	0.2	0
Forest	Natural/planted forest cover	0.8	1.1	1.1
Settlement	Distance to human settlement	25.3	0.1	0.3
Reservoir	Distance from water reservoirs and ponds	5.0	54.2	26.6
MedSea	Distance from Mediterranean Sea shoreline	10.0	2.8	1.7
NDVI	NDVI vegetation index	5.9	0.3	0.6
Predictor Layers that were used for predicting electrocution sensitive areas (Stage 2)				
PredictBon	Product of the MaxEnt model in stage 1	NA	34.7	31.8
Predictor Layer used for predicting electrocution sensitive power line sections (Stage 3)				
PylonDens	The number of medium voltage pylons in 500 m radius of each pixel	NA	NA	36.1

related to the different sets of observational data and the addition of explanatory variables (Table 1, Figure 5).

Stage 1 model

The variables with the highest percentage contribution to the model were precipitation (32.3%) and distance to human settlements (25.3%). Specifically, the areas with the highest predicted eagle density were regions with moderate (200–500 mm) annual precipitation and 1,000–5,000 m away from any building or settlement.

Stage 2 model

The variables with the highest contribution to the model were distance from reservoirs (54.2%) and the predicted distribution of non-adult eagles (34.7%). Specifically, areas with the highest risk of electrocution were within short distances of reservoirs (reaching maximum risk within few tens of meters from them and dropping sharply with increasing distance) and in the higher probabilities of the birds' distribution ranges. This was also indicated by the jackknife test (Supplementary Material Figure S1), with distance from reservoirs producing the greatest gain when used in isolation and the substantial decrease of the gain when omitted.

Stage 3 model

The variables with the highest contribution to the model were pylon density (36.1%) and distance to reservoirs (26.6%). Specifically, highest risk areas for electrocution were located near water bodies and within a pylon density of 3 to 16 pylons per 500-m radius circle (3.8 to 20.4 pylons km^{-2}).

The variables with the greatest gain in the jackknife test (Supplementary Material Figure S1) were distance from reservoirs, predicted eagle distribution, and pylon density. Pylon density was the second variable in its relative gain, while it showed the largest decrease in the model's gain when omitted.

The distribution of electrocution records versus pylon density (Supplementary Material Figure S3) revealed a positive linear relationship between electrocution probability and pylon density in the lower values of pylon density, reaching the maximal risk at a density of 11–15 pylons per 500-m circle, and decreasing in the higher density values. The mean density of pylons in the vicinity of electrocutions was 8.58 (range: 1–21, SD = 4.51), while the mean density of the entire network was 11.67 (range: 1–120, SD = 11.56).

Determining Which Pylons Should Be Retrofitted

As shown in Supplementary Material Figure S4, 62% of the electrocutions fall within the very-high risk level, which represents ~1.4% of the pylons in the national medium-voltage network, and ~77% of the events fall within the 2 highest risk levels. Overall, the electrocutions in these 2 highest risk levels correspond to ~3.6% of the total number of pylons in the medium-voltage electricity grid (4,976 out of ~139,000 pylons). These pylons are consequently recommended for retrofitting.

Model Evaluation with Independent Data

During the period the models were constructed, 9 more Bonelli's Eagle electrocutions were recorded, all of them within the 2 high-risk pylon categories (8 at the very high-risk category and 1 at the high-risk category). This is a significant ($p < 0.0001$) circumstantial evidence for the potential risk imposed by the pylons of these categories.

Potential Effects of Mitigation According to the Model on Other Bird Populations

The effect of retrofitting the pylons in each category of the risk map on other avian species was evaluated by calculating the proportion of documented electrocutions of each species ($n = 658$ in total for all species) in each risk category (Table 2). According to this examination, the species that are

TABLE 2. Percentage of electrocution events recorded for each species ($n = 658$, individuals collected during 2009–2020) in each category of the Bonelli's Eagle risk map (ordered by their total frequency of electrocution).

	Percentage of events in each risk category					
	Very high	High	Medium	Low	Very low	Number of electrocution records
Species	5	4	3	2	1	
White stork	12%	16%	24%	14%	33%	251
Black kite	21%	5%	8%	9%	57%	219
Bonelli's eagle	**62%**	**15%**	**10%**	**13%**	**0%**	**39**
Eagle owl	6%	13%	10%	26%	45%	31
Short-toed eagle	8%	13%	4%	54%	21%	24
Common buzzard	4%	21%	8%	33%	33%	24
Black stork	32%	9%	14%	5%	41%	22
Long-legged buzzard	8%	15%	23%	23%	31%	13
Eastern Imperial eagle	70%	20%	0%	10%	0%	10
Griffon vulture	0%	0%	13%	25%	63%	8
Golden eagle	20%	0%	20%	0%	60%	5
Egyptian vulture	0%	0%	20%	40%	40%	5
Osprey	40%	0%	0%	0%	60%	5
White-tailed eagle	50%	0%	50%	0%	0%	2
Average	24%	9%	15%	18%	35%	

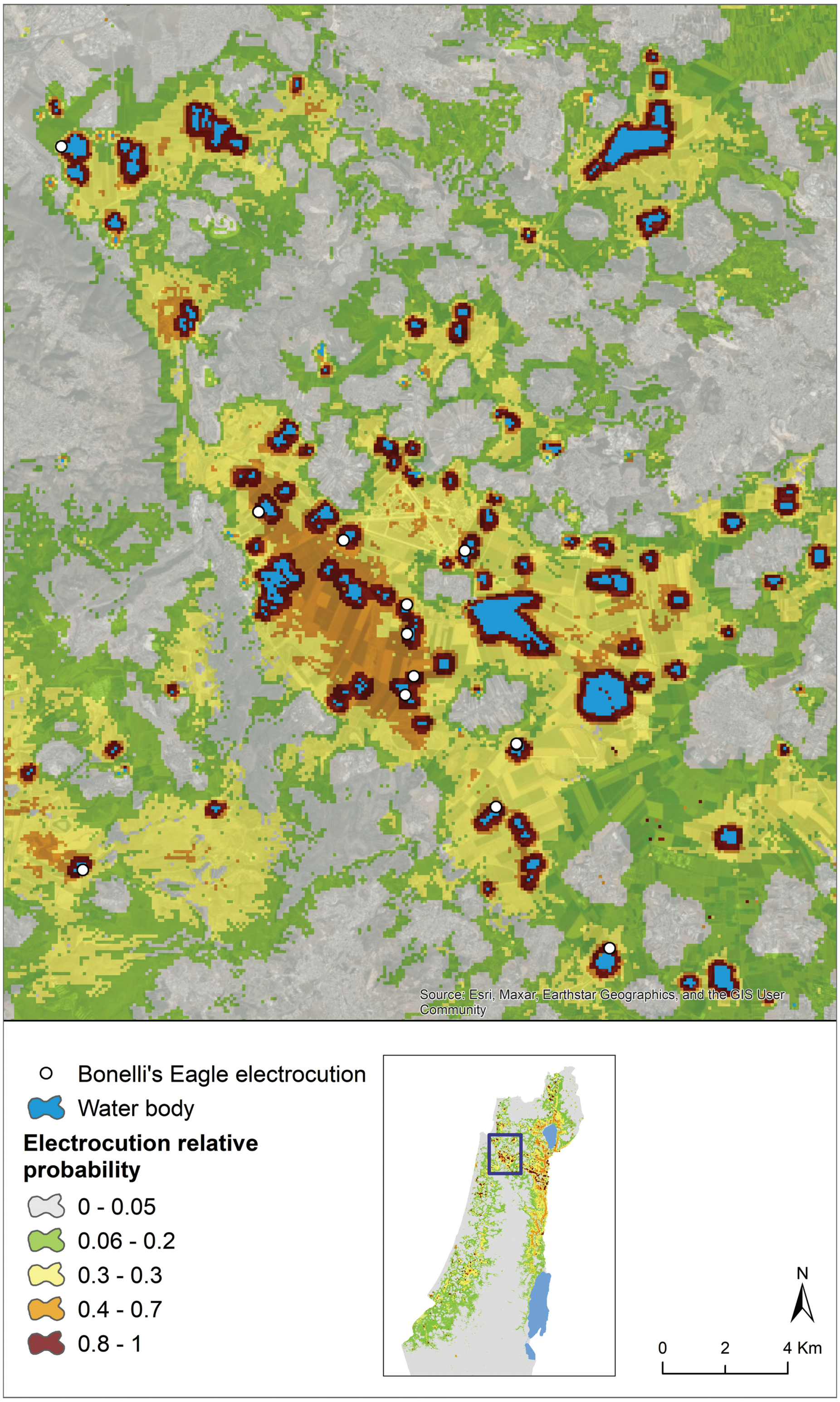

FIGURE 4. The second-stage model sensitivity map, focused on Jezreel Valley in Northern Israel. Enlarged view emphasizes the correlation of the predicted electrocution risk to the agricultural fields and water bodies. Recorded Bonelli's Eagle electrocutions are indicated by white dots.

expected to benefit the most from pylon retrofitting of the highest risk levels are Eastern Imperial Eagle (*Aquila heliaca*), White-tailed Eagle (*Haliaeetus albicilla*), Osprey (*Pandion haliaetus*), and Black Stork (*Ciconia nigra*), and to a lesser extent, a variety of other electrocution-prone species in Israel.

DISCUSSION

We found that the variable with the highest contribution to the predicted electrocution distribution (second-stage model) was the proximity to reservoirs (51.7%). The much higher contribution of this layer to the risk distribution, as

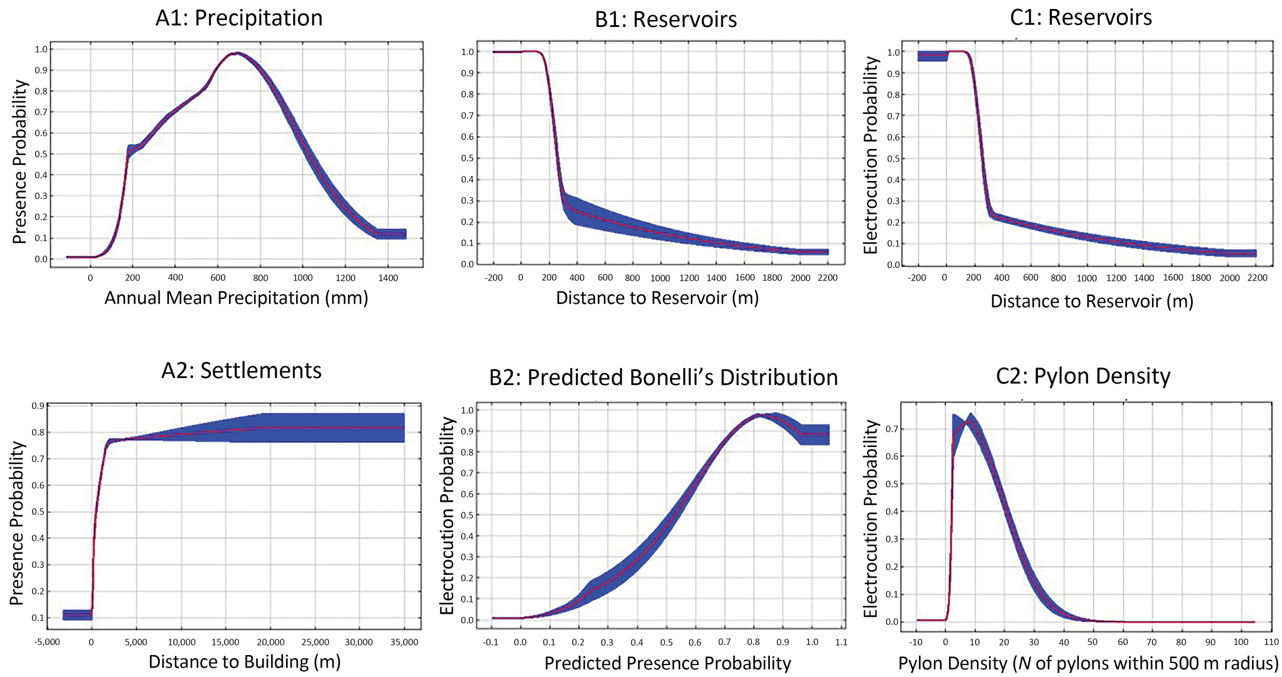

FIGURE 5. Response curves for the two most important environmental variables in each of the three models (each curve was produced by generating a model using only the corresponding variable). (A1, A2) Stage 1 model (predicting general Bonelli's Eagle distribution). (B1, B2) Stage 2 model (predicting the spatial distribution of electrocution risk). (C1, C2) Stage 3 model (predicting the spatial risk of existing power line segments). (A1) Eagle presence probability is highest with intermediate levels of precipitation. (A2) Eagle presence probability is highest at distances larger than 1,000 m from any settlement. (B1) Eagle electrocution probability as highest up to 200 m from a reservoir. (B2) Eagle electrocution probability is highest at the higher levels of eagle predicted distribution. (C1) Eagle electrocution probability is highest up to 200 m from a reservoir. (C2) Eagle electrocution probability is higher at pylon density of 3–16 pylons per 500 m radius.

compared to its marginal contribution to the predicated eagle dispersal distribution (5.0%), may indicate an exceptional high-risk potential around reservoirs, which is proportional neither to their relative area within the distribution ranges, nor to the time that the eagles spend near them, compared to other habitats or environments. This is best indicated by the accumulation of electrocutions near reservoirs (Figure 4, Supplementary Material Figure S2), as ~64.1% of the events occur within 200 m from a reservoir.

The variables with the highest contribution to the final model were pylon density (36.1%), the predicted eagle distribution (31.8%) and distance to reservoirs (26.6%). Distance to reservoir was even more dominant and showed the greatest gain in the jackknife test, whereas pylon density showed the largest decrease in the model's gain when omitted, which therefore appears to have the most information that is not present in the other variables. Hence, it is likely that this large contribution of the pylon layer to the model was through the exclusion of pixels where no electricity pylons were found, but the prediction of risky segments within the network was based mostly on other variables such as the presence of reservoirs and the predicted eagle distribution.

The distribution of Bonelli's Eagles' electrocution records in relation to pylon density shows a positive linear relationship between electrocution probability and pylon density in the lower density range, and a weaker relationship in the higher density range (Supplementary Material Figure S3). These results are in partial agreement with other studies that have shown a positive correlation between pylon density and the risk of bird electrocution (Tintó et al. 2010, Pérez-García et al. 2011, Dwyer et al. 2016, Bedrosian et al. 2020). This partial agreement can be explained by the Bonelli's Eagles' tendency to occupy rural agricultural areas that have a low density of infrastructures compared to urban and more heavily populated areas of the country. This relationship between electrocutions and network density might be species-specific, although the examination of other species' electrocution records in relation to the risk areas of the model (Table 2) reveals high correlations for several species, among them the endangered Eastern Imperial and White-tailed eagles, Black stork, and others.

Our work highlights the importance of applying predictive models to direct an effective mitigation of raptor electrocution. Past studies suggested that retrofitting ~20% of the most high-risk pylons (Tintó et al. 2010), or 16% of the area (Pérez-García et al. 2017), could reduce bird mortality by up to 80%. Hence, the results of the model presented here, proposing that retrofitting only 3.6% of the pylons would achieve ~77% reduction in electrocution cases, are striking. This is especially intriguing given that the technical features of the pylons (such as the presence of transformers, disconnectors or other energized equipment) were not available, while these features were found to be one of the most important parameters determining electrocution risk elsewhere (Mañosa 2001, Tintó et al. 2010, Guil et al. 2011, Hernández-Lambraño et al. 2018). This can be explained by the importance of the environmental features that impact the risk of electrocutions of Bonelli's Eagles in Israel. As shown in Supplementary Material Figure S2, most of the electrocutions occurred near reservoirs located in low-laying areas of Northern and Central Israel. The reservoirs are hotspots for birds and biodiversity in general, typically hosting waterfowl like coots and ducks that are taken as prey by the eagles.

To hunt in these artificial reservoirs, the eagles look for high perching observation points, which will allow them to scan the water and the banks from a high viewing point. In many cases the only tall perches in the vicinity of the reservoirs are the pylons that lead the power lines to the reservoirs' control and pumping facilities, as all the trees were removed when the reservoirs were initially constructed. Another parameter that may contribute to the risk in these focal points is the structure of the pylons that are closer to reservoir. It is worth mentioning that the last pylon in the distribution line is typically carrying equipment such as transformers and disconnectors, interconnected through multiple wires, forming a highly dangerous structure (Lehman et al. 2007, López-López et al. 2011, Hatzofe 2013, Hernández-Lambraño et al. 2018). Apparently, this combination of environmental circumstances has created a detrimental ecological trap (Schlaepfer et al. 2002, Dwyer 2009, Hale and Swearer 2016).

However, in 2 other studies that have demonstrated a decrease in eagle mortality resulting from electrocution mitigation programs (López-López et al. 2011, Chevallier et al. 2015), the number of retrofitted pylons was quite similar to the proposed number in our study. Retrofitting of 6,560 pylons in Andalucía has resulted in 62% reduction in Spanish Imperial Eagle electrocution frequency and a subsequent increase of its population (López-López et al. 2011). Retrofitting of ~500 pylons in 15 breeding home ranges of Bonelli's Eagles had a dramatic effect on their survival (Chevallier et al. 2015). Hence, we believe that insulation of 6,000 pylons suggested by our study (over the area of Israel, about one third of that of Andalucía), including ~1,000 pylons that are nominated for correction in 13 breeding home ranges, is very likely to achieve a highly significant outcome.

It should be noted that models produce only a theoretic prediction, while the true impact of the mitigation actions on the target population may not be simple or linear. A decrease in mortality from electrocution might be compensated by other mortality causes such that the mitigation effort would not be fully translated into the ultimate survival of non-adult birds (Chevallier et al. 2015). In the same way, we should also expect that as pylons in the higher risk categories of the model would be retrofitted, more eagles would be lost from electrocution on pylons in the lower risk categories. These processes might reduce, to some extent, the efficiency of the mitigation and its positive effect on the Bonelli's Eagle population.

Examination of the potential service of the Bonelli's Eagle as an "umbrella" species revealed that the species that are expected to benefit the most from the retrofitting of pylons according to the model are species that share similar habitats and spatial distribution with the Bonelli's Eagle as well as the tendency to perch on electricity pylons. Bonelli's Eagles are especially prone to electrocute in low-laying areas and near reservoirs and these habitats are also occupied by wintering Greater-spotted Eagles (*Clanga clanga*), Eastern Imperial Eagles, and White-tailed Eagles, as well as migrating Lesser-spotted Eagles (*C. pomarine*), that pass through the region in many tens of thousands (Shirihai 1996). Yet, Greater-spotted and Lesser-spotted eagles were never found electrocuted in Israel. This finding reflects the fact that these species usually perch on trees and only rarely on artificial structures such as pylons. The other two eagle species (Eastern Imperial and White-tailed) use the power pylons for perching and are indeed electrocuted quite often. However, since the model presented here yielded a mitigation program that is already being implemented, it would hopefully be possible in a few years to assess the true service of the Bonelli's Eagle as an umbrella species for electrocution.

Although our modelling approach appears promising and the models were performed at very high spatial resolution (enabling the identification of the contribution of environmental features such as reservoirs and ponds to electrocution risk), the small sample size of electrocution events may bias the assessment of the relative risk of different areas and power line sections. In addition, the model includes no information on the pylon types and their designs, which are most likely important factors affecting electrocution risk. Consequently, the maps produced by the model should be treated as a masterplan for mitigation, and a more detailed planning is required before retrofitting can actually be performed. Yet, this masterplan was found very efficient for understanding the extent of urgent insulation requirements, prioritizing areas for pylon correction, estimating the required budget and mobilizing a proactive mitigation process. The plan was approved and budgeted by the Israeli Electricity Authority, and pylon correction works have begun in 2022. This achievement is unprecedented in Israeli terms, as the electrical authority does not usually budget environmentally oriented projects, but it was made possible through the formal and evidence-based prioritization process, the well-defined number of pylons selected for correction and the unambiguous estimation of the retrofitting budget that was derived from it.

The work presented here aims to prioritize raptor electrocution mitigation in an arid and semi-arid environment. As far as we know, most of the bird electrocution studies were so far done in the more temperate zones of Europe and North America (Prinsen et al. 2011, Guil and Pérez-García 2022). Nevertheless, electrocution in arid areas is of a particular concern in many developing countries, where networks of poorly designed distribution lines are rapidly growing and many raptors, both of resident and migratory populations, are spending significant parts of their life cycle (Angelov et al. 2013, Dixon et al. 2013, Galmes et al. 2018, Mwacharo 2021). In particular, eagle electrocution rate was found to be the highest in Africa, where very few studies and mitigation projects were done so far (Guil and Pérez-García 2022). The modeling approach that was used in this study might be highly appropriate for these arid developing countries, where detailed data and GIS layers of the power network are likely to be missing or inaccessible, but good and precise data of the distribution of the species of concern can be acquired through telemetry and observations.

Supplementary material

Supplementary material is available at *Ornithological Applications* online.

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Ethics statement

This study was done under general ethics protocol. It does not include any experiments involving the use of animals.

Conflict of interest statement

There were no conflicts of interest related to this study.

Author contribution

AM, EH, OH and NS conceived the ideas and designed methodology; AM, ME and OH collected the data; EH and DT analyzed the data; AM and NS led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Data availability

Data and code are available at https://doi.org/10.6084/m9.figshare.25183823.v1.

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