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Assessing the susceptibility of raptor species to electrocution: A framework for Kenya

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ABSTRACT

Developing countries are witnessing rapid expansion of electrical infrastructure to meet increasing energy demands, prompting a critical need to assess the potential impact on avian biodiversity. Leveraging open access data, our study conducted a comprehensive assessment to detect electrocution and collision risk hotspots in Kenya while identifying raptor species highly susceptible to these risks. Through an integrated approach that considers morphological and behavioral traits of the species, environmental factors at the site, and technical parameters of the power lines, we developed risk maps and categorized raptors' susceptibility into high, medium, and low-risk levels. Applying this framework, we identified three raptor species at high risk of electrocution; the long-crested eagle, the augur buzzard, and the steppe eagle. Meru and Kiambu counties emerged as high-risk areas due to substantial overlap between high-risk buffer zones and areas with high raptor species distribution. It is worth noting that this framework only accounts for thirteen raptor species, and there is scope to expand it in the future to include other avian species, such as storks, bustards, pelicans and flamingos, which are also susceptible to electrocution and collision incidents and measures to mitigate electrocution of raptors may not be sufficient for these other group of birds.

1. Introduction

Globally, thousands of kilometers of power lines transport generated energy from both traditional (e.g. coal and gas) and renewable sources (e.g. wind, solar, hydropower) to the end user (Kettel et al., 2022). Global demand for energy is projected to increase by over 25% from 2018 to 2040 (International Energy Agency, 2019), and with it there is a growing shift towards renewable energy sources due to mounting energy and climate change concerns. While this transition promises economic advancement for countries (Chaurey et al., 2004), it also presents significant environmental challenges (Sánchez-Zapata et al., 2016). Balancing economic progress with environmental sustainability becomes imperative, especially for rapidly developing nations like those in Africa.

Global avian mortality is significantly influenced by interactions with overhead electrical power lines, (Avian Power Line Interaction Committee, 2006; Bevanger, 1994, 1998; Loss et al., 2014, 2015; Prinsen et al., 2011). While elevated power lines can confer certain advantages to specific bird species (Ferrer et al., 2020; Karyakin, 2008; Tryjanowski et al., 2014), such as serving as perches for hunting, marking territory, regulating body temperature, resting, or building nests (Dwyer and Dalla Rosa, 2015; Kolnegari et al., 2022; Moreira et al., 2018; Restani and Lueck, 2020), the overall impact on avian populations leans more towards harm. Electrocution and collision risks associated with electrical infrastructure pose greater threat to avian populations than any potential benefits (Dwyer et al., 2022). Furthermore, power lines, as man-made structures, can induce avoidance behaviors in birds, potentially leading to habitat loss and fragmentation (Marques et al., 2022).

The configuration of power lines and their associated risks for bird

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electrocution and collisions vary depending on the voltage they carry. High voltage lines (115–500 kV), often referred to as "transmission lines", are responsible for transmitting electricity from transmission substations to distribution substations. In distribution substations, the voltage is 'stepped down' to levels ranging from 12 to 35 kV while low voltage power lines (120–480 V) are commonly utilized to connect residential or small commercial customers to utility services (Avian Power Line Interaction Committee APLIC, 2018). Bird electrocution incidents are predominantly associated with distribution lines (Bevanger, 1994; Haas et al., 2005). On these lines, the distances between electrical conductors, such as cables, poles, and transformers, are often close enough for larger birds to simultaneously contact two conductors, or a conductor and a ground component resulting in electrocution.

Instances of raptor electrocutions date back to the 1920s with the introduction of electric utility systems (Hallinan, 1922; Lano, 1927). Concerns over electrocutions, especially of Golden Eagles (*Aquila chrysaetos*) in the United States, emerged in the 1970s as a conservation issue (Miller et al., 1975; Olendorff et al., 1981). Even today, nearly five decades later, electrocutions remain a threat to Golden Eagles and various raptor species worldwide (Demeter et al., 2018; Dixon et al., 2017; Harness et al., 2013; Mojica et al., 2018; US Fish and Wildlife Service (USFWS), 2016). The construction practices of pylons in many developing countries pose an escalating risk, as grounded steel or concrete configurations endanger even small raptors and other birds (Demeter et al., 2018; Pérez-García et al., 2016).

Kenya, a lower-middle-income country with a population of 53.1 million as of 2021 (World Bank, 2021) has experienced significant growth in recent years. The Kenyan government is actively striving to improve the supply and accessibility of reliable, affordable and sustainable energy, with the goal of achieving universal access by 2022. This endeavor is bolstered by a robust private sector, a well-established national power company, and an abundance of energy resources, including geothermal, wind, and solar energy. As a result, Kenya boasts one of the most developed power sectors in Sub-Saharan Africa (Republic of Kenya, 2018). Furthermore, the Kenya Electricity Transmission Company (KETRACO) has progressive plans to extend the electrical grid by an additional 4200 km, building upon existing infrastructure and doubling the number of electricity lines across the nation (Development of Kenya's Power Sector, 2015–2020, 2016). While this significant development holds immense promise for Kenya's energy infrastructure, the potential implications to wildlife conservation have been insufficiently addressed (Ngila et al., 2023a), and little is known about avian electrocution and collision incidents associated with power lines in Kenya (Birdlife International, 2021).

Studies show that there are extrinsic and intrinsic factors contributing to increased electrocution and/or collision risk. These factors can be categorized into three main groups (Bernardino et al., 2018): i) the environmental conditions at the site; (e.g. absence of natural perches, frequency of fogs, and location on migratory routes (Dixon et al., 2018; R. Harness et al., 2008)); ii) the morphology and ecology of the bird species involved; (e.g. size and wingspan of the birds, low maneuverability, narrow visual field, hunting behavior (Guil et al., 2015; Janss, 2000; Lehman et al., 2007a; Martin and Shaw, 2010)), and iii) the technical parameters of the power lines which can be pole and cross arm configuration or the wire arrangement; (e.g. grounded steel and concrete poles and crossarms, or the increase of jumper wires (Guil et al., 2011; Tintó et al., 2010)). These factors are interconnected, and they collectively influence the risk level associated with electrocution and collision (Šmídt et al., 2019).

This study adopts a conceptual framework outlined by Biasotto et al. (2022) and (Smeraldo et al., 2020). We integrate Species Distribution Models (SDMs), raptor behavioral ecology, and technical aspects of power lines. SDMs are valuable tools for assessing and mitigating risks by generating risk maps and identifying species that are highly vulnerable to electrocution (e.g. Smeraldo et al., 2020; Biasotto et al., 2022). These maps are critical for identifying areas where wind farm or power line development pose significant threats to wildlife and where additional surveys are needed to evaluate potential impacts (Hernández-Lambraño et al., 2018; Heuck et al., 2019; Maiorano et al., 2019). We hypothesize that raptors' susceptibility to electrocution incidents is influenced by a combination of environmental factors, raptor behavioral ecology, and technical parameters of power lines. Specifically, areas with high raptor density, proximity to power line infrastructure, and environmental characteristics conducive to raptor foraging and nesting are anticipated to exhibit elevated risks of electrocution and collision incidents. Certain raptor species, characterized by larger wingspans and flight patterns that bring them into close proximity with power lines, are predicted to face higher risks, while species with behaviors that keep them at lower altitudes or away from power line corridors may exhibit lower susceptibility. Additionally, open grasslands, lacking natural perches, may coincide with high-risk zones. Furthermore, power line proximity in suitable niche areas for raptors is expected to play a crucial role in determining the likelihood of electrocution incidents. Our study aims to assess species highly susceptible to electrocution, pinpoint risk hotspots in Kenya for these incidents, and evaluate potential areas for such incidents based on the distribution of selected raptors.

2. Methods

2.1. Study area

Kenya is situated between latitudes 5°N and 5°S and longitudes 34°E and 42°E, encompassing a land area of approximately 584,000 km^2. The country experiences a tropical climate characterized by two distinct rainy seasons: one from October to December and another from late March through May. Approximately 17% of Kenya's land is suitable for rain-fed agriculture, while arid and semi-arid savannas and grasslands dominate approximately 82% of the nation's landscape.

Kenya is in the process of development, moving from lower to middle-income status. The distribution of both human population growth and urbanization rates within the country is uneven, necessitating the establishment and expansion of a comprehensive energy infrastructure to meet increasing demands. As of June 2017, the country's transmission network extended over 4766 circuit km at voltage levels of 132 kV. This network included 585 km of 400 kV lines, 375 km of 220 kV lines, and 839 km of 132 kV lines (Republic of Kenya, 2018). Presently, KETRACO is in the process of constructing an additional 4500 km of new lines, effectively doubling the transmission network. This expansion includes the introduction of high voltage 400 kV and 500 kV direct current (DC) lines and plans to connect with three major adjacent countries: Ethiopia, Uganda, and Tanzania (Republic of Kenya, 2018).

2.2. Raptor species included in the study

The selection of raptor species for this study was based on multiple guidelines. Initially, we referred to the findings of a 2009 study conducted by Smallie & Virani which provided a preliminary assessment of species vulnerability to direct interaction with electrical infrastructure, including electrocution, collision, and electrical faulting. This assessment drew insights from the South African experience and considered conservation importance as determined by classifications such as the IUCN Red List. In addition to the species identified in Smallie & Virani's study, we included two "sit and wait" raptors (Muhia and Waiganjo, 2023), and species known to be threatened by electrocution and collision based on their IUCN status.

2.3. Raptor data from GBIF

The following thirteen raptors were therefore included in the study; the Egyptian vulture (*Neophron percnopterus*), White-headed vulture (*Trigonoceps occipitalis*), Lappet-faced vulture (*Torgos tracheliotos*), White-backed vulture (*Gyps africanus*), Rüppell's vulture (*Gyps rueppellii*), Bateleur (*Terathopius ecaudatus*), Martial eagle (*Polemaetus bellicosus*), Secretarybird (*Sagittarius serpentarius*), Hooded vulture (*Necrosyrtes monachus*), Steppe eagle (*Aquila nipalensis*), Tawny eagle (*Aquila rapax*), Long Crested Eagle (*Lophaetus occipitalis*), and Augur buzzard (*Buteo augur*).

We retrieved occurrence records for the thirteen raptor species from the Global Biodiversity Information Facility (GBIF, www.gbif.org) - (The species' doi is available at the bottom of the manuscript). To ensure data quality and integrity, we applied the *clean_coordinates* wrapper function from the CoordinateCleaner package in R (Zizka et al., 2019), as detailed in (Ngila et al., 2023). To address concerns of spatial autocorrelation and sampling bias, we implemented spatial filtering techniques on the records. Following precedent set by Ngila et al., 2023 and Sutton et al. (2020), we applied a spatial filter of 40 km for each species.

2.4. Predictor variables for modeling

The bioclimatic variables and elevation data were obtained from Worldclim database (Version 2.1, Fick and Hijmans, 2017, https://www.worldclim.org/data/worldclim21.html). In consideration of the prevalent instances of electrocution and collisions among raptors, particularly during periods of impaired visibility or when their plumage is damp, the chosen bioclimatic predictors for modeling exclusively confined factors associated with precipitation. These include; annual precipitation (Bio 12), precipitation during the wettest month (Bio 13), precipitation during the driest month (Bio 14), precipitation seasonality (Bio 15), precipitation during the wettest quarter (Bio 16), precipitation during the driest quarter (Bio 17), precipitation during the warmest quarter (Bio 18), and precipitation during the coldest quarter (Bio 19). In addition to these bioclimatic variables, we included elevation as this is often associated with changes in habitat types and vegetation. Raptors may exhibit different behavior and risk profiles based on the elevation they inhabit e.g. the type of prey available, nesting sites, and overall environmental conditions that vary with elevation. Additionally, human activities and infrastructure can vary with elevation. Higher elevations might be less populated or developed, potentially affecting the frequency of power lines and human related risks to raptors.

2.5. Species distribution modeling and model evaluation

We utilized an ensemble approach for our SDMs, employing three algorithms: Generalized linear model (GLM), Random Forest (RF) and MAXENT models within the *biomod2* package in R (Thuiller et al., 2009). The generalized linear model (GLM) algorithm employs a regression method with polynomial terms, utilizing a stepwise procedure to select the most significant variables (Jiguet et al., 2010). Generalized linear models (GLMs) were adjusted using a quadratic distribution and a logistic link function. Random forest (RF) is a machine-learning method that combines tree predictors, with each tree dependent on values of a random vector sampled independently and with the same distribution for all trees in the forest. Random forest (RF) was fitted by growing 750 trees. MAXENT models were fitted with the default settings with a maximum value of 1000 iterations.

We added a background set of 10,000 randomly chosen background points to the study area because our dataset consisted of presence data for model calibration. This inclusion was necessary because all models require information on both presence and absence to accurately determine suitable species conditions. Following established practices in species distribution modeling, the occurrence dataset was randomly partitioned into a 70% sample for model calibration and a 30% sample for model evaluation (Buonincontri et al., 2023; Overly and Lecours, 2024; Smeraldo et al., 2020). To evaluate the predictive performance of the models, we utilized the Area under the receiver operating characteristic curve (AUC) (Hanley and McNeil, 1982) and the True Skill Statistic (TSS) (Allouche et al., 2006).

2.6. Identifying the risk hotspots

Risk Hotspots for electrocution and collision were identified using data on distribution lines for Kenya from World Bank updated through June 2021 (https://energydata.info/dataset/kenya-kenya-electricity-network). We first created an overall exposure map. Since avian electrocution primarily occurs on distribution lines, we focused our selection on medium-voltage power lines, which typically operate within the range of 11–33 kV. This specific voltage range was chosen because it aligns with the spacing between electrical components (wire-wire and pole-wire) and the wingspans of several bird species, as highlighted in prior research (Avian Power Line Interaction Committee, 2006; Eccleston and Harness, 2018; Lehman et al., 2007b). We merged the 11 kV voltage and 33 kV voltage for Kenya using the merge function in ArcGis (Version 10.5).

To assess the exposure of raptors to electrocution and collision, we created buffer areas around each electric power line using the buffer function in ArcGIs (Version 10.5). In this study, exposure is characterized as the likelihood for individuals of a target species to encounter an electric power line. It is presumed to escalate proportionally with proximity to a power line; thus, species inhabiting areas closer to power lines are considered highly exposed. As such, these species exhibit a greater likelihood of encountering power lines and consequently face a heightened risk of electrocution (see Smeraldo et al., 2020). We did this by calculating the probability of distances we deemed probable for posing major threats to electrocution and collision of raptors to power lines. These distances were 100 m (high risk), 500 m (medium risk) and 1000 m (low risk). Binary maps derived from SDMs for the 13 raptor species were stacked to create an overall distribution of all the thirteen species of raptors. These maps were binarized into presence and absence values using a threshold that maximized both sensitivity (the percentage of correctly predicted presence) and specificity (the percentage of correctly predicted absence (Liu et al., 2005).

To generate the risk maps, we clipped the binary stacked maps for the thirteen raptor species with the distribution of power lines within three buffer zones: 100 m, 500 m, and 1000 m from power lines, representing distances posing significant collision risk to the species. Utilizing ArcGIS (Version 10.5), we employed the Spatial Analyst tools for weighted overlay. This process involved converting power line shapefiles into raster format since weighted overlay exclusively employs raster files. The weighted overlay tool then reclassified raster input values based on a common evaluation scale of suitability or preference, considering their relative contributions to the central theme (Iqbal and Khan, 2014). Subsequently, the final map was categorized into five risk classes: high, medium-high, medium, medium-low, and low (e.g. in Giné and Faria, 2018; Bosso et al., 2023).

2.7. Identifying raptor species susceptible to electrocution

We incorporated the behavioral ecology of raptors, focusing on their behavior, feeding patterns, and susceptibility to electrocution. Species susceptibility to electrocution are mainly influenced by intrinsic and extrinsic factors (Bevanger, 1998; Janss, 2000). Birds using power line structures such as poles and wires for perching (Prather et al., 2010) and nesting (Moreira et al., 2018; Morelli et al., 2014) are likely more susceptible. Susceptibility also increases with body size (Dwyer et al., 2015). Recognizing that different raptor species exhibit distinct foraging behaviors and may vary in their susceptibility to electrocution, we conducted an exhaustive literature review. Utilizing databases such as ISI Web of Knowledge, Scopus, and Google Scholar, we searched for information on behavior and feeding patterns to identify the susceptibility of each bird species. To ensure a comprehensive approach, we employed specific search terms for each species, namely (1) 'electrocution', (2) 'electrocution threat', (3) 'species', and (4) 'Foraging Behavior'. For 'species' we replaced this with the name of each of the thirteen species. This method allowed us to identify both peer-reviewed publications and grey literature, including reports. Subsequently, we assessed and classified the vulnerability of the thirteen raptor species into categories of high risk, intermediate risk, and low risk concerning electrocution, as outlined in Table 1. Our literature review was based on extensive examination of 24 scholarly articles, 3 reports, 3 books, and 2 databases. There was no restriction regarding the scope of the papers in terms of region or the year of publication.

Wingspan is often selected as an indicator of susceptibility to electrocution and collision (Bevanger, 1998). The average wingspan was obtained for each species from both iNaturalist (www.inaturalist.org) and Peregrine fund (https://peregrinefund.org) and compiled into the analysis within the buffer zones. Areas within the buffer zones (100 m, 500 m and 1000 m) were adjusted based on the wingspan of each species (see Table 2). To evaluate the risk of electrocution, we multiplied susceptibility ratings from Table 1 with exposure areas for each species across various buffer zones, as detailed in Table 2. This approach mirrors previous frameworks that assess risk by combining exposure and susceptibility, which have been utilized to address other impacts associated with linear infrastructures, such as road kills (Morelli et al., 2020; Visintin et al., 2016) and collisions with power lines (Biasotto et al., 2022; D'Amico et al., 2019). Through this process, we identified species showing the highest susceptibility to electrocution, based on factors including behavior, power line parameters, and environmental variables.

3. Results

3.1. Habitat suitability

Our species distribution models (SDMs) have demonstrated strong performance for each species, indicated by the AUC and TSS scores (supplementary material 2). Elevation, precipitation of the warmest quarter, and precipitation of the coldest quarter were the most influential variables for raptor species, as seen in the variable importance graphs (see supplementary section). The ensemble model predicts a high probability of raptor presence in central Kenya, with scattered areas in the southeast and southwest regions of Kenya. On the other hand, raptor presence is less likely in the eastern and northern regions of the country. The estimated suitable habitat area for the raptor species included in the study was 90,729.75 km^2, roughly 15.5% of Kenya's total land area.

3.2. Raptor species susceptibility

Among the raptor species studied, the Augur Buzzard, Long-crested Eagle, and Steppe Eagle exhibited the highest distribution within high-risk areas, covering 6790 km^2, 6777 km^2, and 5646 km^2, respectively. In contrast, the White-backed Vulture, Hooded Vulture, and Lappet-faced Vulture had the lowest distribution in high-risk areas, spanning 272 km^2, 282 km^2, and 288 km^2, respectively (Table 2). Of these species, the Long-crested Eagle, Augur Buzzard, and Steppe Eagle were found to be highly susceptible to electrocution, while the White-headed Vulture, Hooded Vulture, and Lappet-faced Vulture exhibited the least susceptibility to electrocution (Fig. 2).

3.3. Risk hotspots in Kenya

Total Area for the power line in the three buffer zones (100 m, 500 m and 1000 m) accounting for wingspan were 11,879 km^2, 50,556 km^2 and 81,710 km^2 respectively. These areas represent 2.0%, 8.7% and 14.0% of suitable raptors' habitat (Table 2). Regions in Kenya that have the highest density of power lines as expected are in major towns especially in the central part of Kenya, some parts of Western Kenya and a few areas in the coastal regions. Counties that had high power line densities include; Nairobi, Kiambu, Nyeri, Mombasa, Kakamega, Meru, Bomet, Kisii, Nandi, Uasin Gishu, Trans-Nzoia, Bungoma, Busia, Nyandarua, Nakuru, and Migori. The counties where raptors face the highest

Table 1
Species susceptibility rating to electrocution and collision, classified as either high, intermediate or low based on the intrinsic behaviors of the thirteen raptor species.

Species name and IUCN status	Foraging behavior & Electrocution threat	Species susceptibility rating to electrocution (High risk, Intermediate risk or Low risk)
Steppe eagle [EN]	Soaring flight with short stoops and ground ambushes (Ferguson-Lees and Christie, 2001; Tingay et al., 2008) highly migratory making it susceptible to power lines electrocution (Meyburg et al., 2016; STRIX, 2012)	**High risk** e.g. (Shobrak et al., 2022) in Saudi Arabia; (Dwyer et al., 2022) in Kazakhstan and Russia; (Dixon et al., 2019).
Martial eagle [EN]	Hunt on the wing attacking on a low slanting stoop. Due to habitat loss, many of the large trees martial eagles use to nest are being cut and their habitat converted to agricultural lands. They have also been reports of collision and electrocution with power lines (Global Raptor Information Network, 2009) Due to habitat loss, the species has been reported to use pylons as nesting sites which can lead to power outage (Jenkins et al., 2013)	**High risk** e.g. (Van Eeden et al., 2017) in South Africa; (Smallie and Virani, 2010) in Kenya; (Cloete, 2013) in South Africa
White-headed vulture [CR]	Feeds on carrion and threats is indirect poisoning. Deliberate poisoning to prevent vultures drawing attention to poaching activities has also been documented (Ogada et al., 2016; Roxburgh and Mcdougall, 2012). Low flying raptor, often the first to arrive at a carcass. It is also prone to electrocution by power lines (Smallie and Virani, 2010)	**Low risk** e.g. (Ives et al., 2022)
Lappet-faced vulture [EN]	Soaring flight relying mostly on its eyesight to find its next meal. It ranges widely when foraging and is mainly a scavenger feeding predominantly on carcasses or their remains (Birdlife International, 2024b; Mundy et al., 1992; Mundy, 1982). It is also known to hunt, taking a variety of small reptiles, fish, birds and mammals and has been observed hunting flamingo chicks (McCulloch, 2006). There have been incidences of electrocution (Birdlife International, 2024b; Smallie and Virani, 2010)	**Intermediate risk** e.g. (Kruger et al., 2004) in South Africa; (Smallie and Virani, 2010) In Kenya
Bateleur [EN]	They hunt while soaring at low altitude. It consumes both live and dead food, mostly mammals and birds but also some reptiles, carrion, insects and occasionally birds' eggs and crabs, foraging over a huge range (55–200 km^2) (Ferguson-Lees and Christie, 2001) There have been reports of Bateleur being electrocuted (Smallie and Virani, 2010).	**Low risk** e.g. (Smallie and Virani, 2010) in Kenya

(continued on next page)

Table 1 (*continued*)

Species name and IUCN status	Foraging behavior & Electrocution threat	Species susceptibility rating to electrocution (High risk, Intermediate risk or Low risk)
Secretarybird [EN]	A grassland species that spends most of its time on open plains and grasslands. It is susceptible to electrocution (Whitecross et al., 2019)	**Intermediate risk** e.g. (Smallie and Virani, 2010) in Kenya; (Whitecross et al., 2019) in South Africa
Egyptian vulture [EN]	They spend a lot of their time soaring on thermals with other species while searching for food or from a strategic perch, usually on rocky outcroppings. It is susceptible to electrocution by power lines (Angelov et al., 2013). It is an indiscriminate and opportunistic feeder (Snow, 1978).	**High risk** (e.g. (Angelov et al., 2013) in East Africa; (McGrady et al., 2024) in Oman; (García-Alfonso et al., 2021) in Canary Islands
Hooded vulture [CR]	It is often seen soaring or also in small groups in a dumpsite. It hunts by soaring low over open areas (Ogada and Buij, 2011) It is also susceptible to electrocution (Smallie and Virani, 2010)	**Intermediate risk** e.g. (Smallie and Virani, 2010) in Kenya; (Bakari et al., 2020) in Ethiopia
Long-crested eagle [LC]	Classified as Least concern, it is a sit and wait raptor; it may perch on a power line when searching for prey. It faces threats of electrocution and habitat degradation. It is also facing severe declines that could be attributed to electrocution (Ogada et al., 2022)	**High risk** (e.g. (Smallie and Virani, 2010) in Kenya)
Rüppell's vulture [CR]	A soaring bird spending most of its time soaring up to 7 h in the sky searching for food. Electrocution with power lines may also pose a significant threat to the species (Garrido et al., 2020; Ogada et al., 2016)	**Low risk** e.g. (Garrido et al., 2020; Ogada et al., 2016)
White-backed vulture [EN]	Electrocution can pose significant threats to the white backed vulture (Bamford et al., 2009). It has been recorded to nest on electricity pylons (Birdlife International, 2024a)	**High risk** e.g. (Anderson and Hohne, 2007; Bamford et al., 2009; Howard et al., 2020) in South Africa;
Augur buzzard [LC]	In as much as it is classified as Least concern at the moment, the species has been undergoing major declines just as the Long-crested eagle (Ogada et al., 2022). It hunts from perches or on the wing, soaring or hovering over long periods, then descending slowly on potential prey.	**High risk** e.g. (Eichenwald et al., 2021; Ogada et al., 2022) in Kenya
Tawny eagle [VU]	It has been shown to be killed by electrocution (BirdLife International, 2024; Global Raptor Information Network, 2024)	**High risk** e.g. (BirdLife International, 2024; Global Raptor Information Network, 2024)

potential risk of electrocution and/or collision with power lines are in Kiambu, Meru, Narok, Nairobi, Machakos, Nakuru, Nyandarua, Nyeri (Fig. 1).

4. Discussion

The leading environmental challenges of our time include addressing climate change and curbing global biodiversity loss (IPCC, 2014; Secretariat of the Convention on Biological Diversity, 2014). To confront climate change, the global energy sector is steadily transitioning from fossil fuels to renewable energy sources (REN21, 2014). This shift is expected to continue in the years ahead, given the growing capacity of clean and renewable energy sources to mitigate climate change and assist nations in achieving greenhouse gas emission reduction goals (IPCC, 2014). Similar to other energy sources, the expansion of electrical energy infrastructure may lead to certain adverse environmental effects, including impacts on wildlife that are not always fully understood (Janss and Ferrer, 1999; Marques et al., 2014; Smeraldo et al., 2020). Numerous studies have highlighted electrocution as a prominent cause of human-induced avian fatalities (Loss et al., 2015; Slater et al., 2020). Additionally, it can affect species by modifying their behavior, displacing populations from their habitats, and diminishing fecundity and breeding success (Northrup and Wittemyer, 2013; Sansom et al., 2016). Moreover, in remote and less accessible regions, the development of electrical energy infrastructure may accelerate the loss and fragmentation of once continuous habitats due to the construction of road networks and electric grids (Northrup and Wittemyer, 2013). However, in many parts of the world, a comprehensive evaluation of this impact is still lacking (Biasotto et al., 2022).

The framework proposed in this paper enables a preliminary assessment of the spatial distribution of raptor exposure and

Table 2
Linear buffers around the power lines were traced at a distance of 100 m (high risk), 500 m (medium risk) and 1000 m (low risk); integrating wingspan for each raptor species. The percentages represent areas within each buffer zone in relation to the area of the species.

		Buffer (m)		
Total Area (km^2)		**100m**	**500m**	**1000m**
Species name	**Wingspan in m**	11,879	50,556	81,710
Steppe eagle	1.895			
Surface (km^2)		5646	22,948	35,418
Percentage (%)		47.5	45.4	43.3
Martial eagle	2.080			
Surface (km^2)		968	4260	6940
Percentage (%)		8.1	8.4	8.5
White-headed vulture	2.185			
Surface (km^2)		464	1951	3373
Percentage (%)		3.9	3.9	4.1
Lappet-faced vulture	2.700			
Surface (km^2)		288	1286	2153
Percentage (%)		2.4	2.5	2.6
Bateleur	1.790			
Surface (km^2)		647	2879	4892
Percentage (%)		5.4	5.6	6.0
Secretarybird	2.000			
Surface (km^2)		1949	8496	13,285
Percentage (%)		16.4	17.0	16.3
Egyptian vulture	1.605			
Surface (km^2)		337	1530	2579
Percentage (%)		2.8	3.0	3.2
Hooded vulture	1.675			
Surface (km^2)		283	1084	1863
Percentage (%)		2.3	2.1	2.3
Long-crested eagle	1.205			
Surface (km^2)		6777	28,025	42,391
Percentage (%)		57.1	55.4	51.9
Rüppell's vulture	2.430			
Surface (km^2)		2380	9267	14,745
Percentage (%)		20.0	18.3	18.0
White-backed vulture	1.900			
Surface (km^2)		272	1162	1944
Percentage (%)		2.3	2.3	2.4
Augur buzzard	1.350			
Surface (km^2)		6790	28,058	42,261
Percentage (%)		57.2	55.5	51.7
Tawny eagle	1.710			
Surface (km^2)		542	2292	3866
Percentage (%)		4.6	4.5	4.7

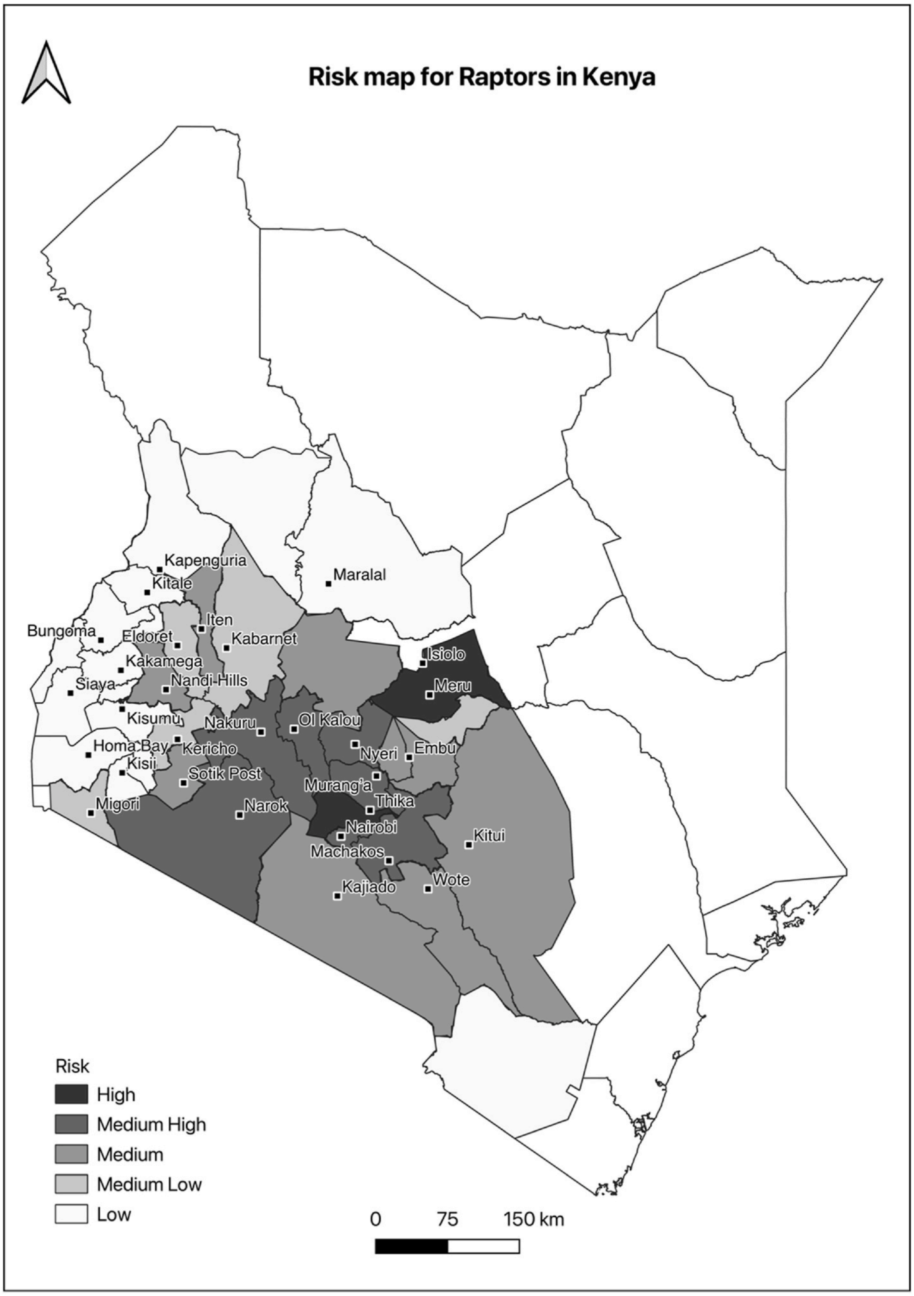

Fig. 1. Electrocution risk map for all the raptor species in Kenya shown for counties in Kenya. The map shows electrocution risk classified from low to high with high risk in Kiambu and Meru counties.

susceptibility, which collectively determine the potential risk of raptor electrocution. Moreover, this framework integrates three key factors; environmental/climatic factors, raptor behavior/ecology, and technical parameters of the power lines to evaluate the risk hotspots for electrocution and collision of raptors in Kenya. The framework has helped identify three raptor species at the highest risk of electrocution based on their distribution and behavior.

Overall, the results of this study provide an initial evidence across different raptor species and spatial range of raptors that may be at highest exposure to electrical energy infrastructure. The proposed risk maps have the potential to assist conservationists and policymakers in the energy sector by identifying the most vulnerable areas where mitigation efforts should be focused to protect raptors. Additionally, these maps highlight potential areas where electrocution and collisions of raptors may occur. For instance, Samburu and Laikipia counties are currently not classified as high-risk areas for such incidents. However, future development in these regions would likely increase the risk of electrocution and collisions based on the distribution of raptors. It is worth noting that this framework only accounts for thirteen raptor species, and there is scope to expand it in the future to include other avian species, such as storks, bustards, and flamingos, which are also susceptible to electrocution and collision incidents and measures to mitigate electrocution of raptors may not be sufficient to extend to these other group of birds.

4.1. Implications for conservation and recommendations

Our study builds on the initial work of Smallie and Virani (2010) who conducted the first research on bird collision and electrocution incidents in Kenya. The findings from their research identified the risks posed by

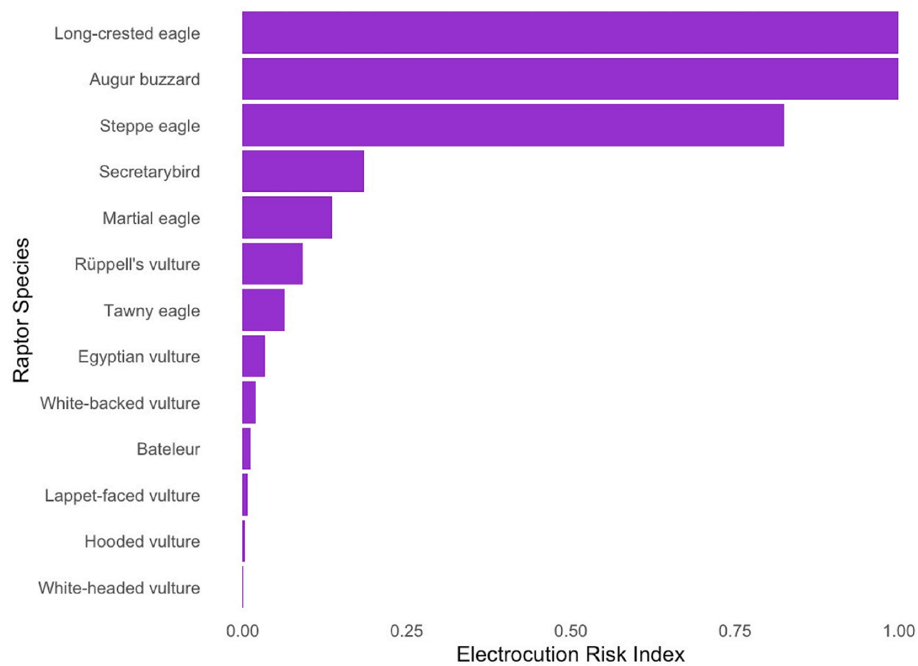

Fig. 2. Electrocution risk index for the thirteen raptor species in Kenya. The Long-crested eagle, Augur buzzard, and Steppe eagle face the highest risk of electrocution due to their suitable niche distribution in high-risk areas and behavior that makes them highly vulnerable.

electrical infrastructure to avian species, particularly to raptors, with 86% of examined bird species identified to be susceptible to electrocution. Leveraging their insights, we applied a comprehensive framework to assess the risk of electrocution and collision across Kenya.

Our analysis identified two counties in Kenya – Meru and Kiambu as high-risk areas for raptor mortality associated with power line infrastructure. These regions are characterized by a semi-urban landscape with extensive forest cover. Kiambu county, for example, encompasses eight major forest areas and Meru county features a National park surrounded by Kora National park, Bisanadi National reserve and Mwingi National reserve. These four protected areas are highly interconnected and could tentatively be included as a World Heritage Site (Kenya News Agency, 2022; UNESCO- World Heritage Convention, 2023). In areas classified medium- or medium high risk such as Nairobi, Narok, Machakos, Murangá, Nyeri, Nyandarua, and Nakuru counties, we recommend targeted investigations to gather data on electrocution events and power system failures. Such data can provide valuable insights into the relationship between landscape composition and raptor mortality, guiding the selection of appropriate mitigation strategies. For instance, previous research has highlighted the role of pole location and configuration in influencing electrocution risk for raptors, emphasizing the importance of tailored interventions (Mojica et al., 2018).

Our study identified three raptor species—Steppe eagle, Long-crested eagle, and Augur buzzard—as particularly vulnerable to electrocution. Given their behavioral ecology and conservation status, specific guidelines can be developed to mitigate the risk of electrocution and collision for these species. Considering the potential implications of electrocution events on raptor populations, proactive measures are essential to safeguard their long-term survival and ecological integrity (De Pascalis et al., 2020; Eccleston and Harness, 2018; Slater et al., 2020). However, it is important to acknowledge that the apparent low electrocution risk observed in species such as the hooded vulture, lappet-faced vulture, and white-headed vulture may be influenced by their limited distribution. This could be due to low vulture populations in Kenya resulting from poisoning incidents (see Ogada, 2014; Ogada et al., 2012; Ogada and Buij, 2011) potentially impacting the study's outcomes.

Mitigation strategies such as modifying crossarms to safer designs and insulating conductors have been shown to be effective, with extended lifetimes and lower rates of maintenance and installation failures (Avian Power Line Interaction Committee, 2006; Guil et al., 2011). These methods offer promising alternatives to older strategies like perch deterrents, which have faced scrutiny for their effectiveness and maintenance challenges (Slater et al., 2020). Despite some regions still utilizing perch deterrents due to their cost-effectiveness (Janss and Ferrer, 1999; Prather et al., 2010), the adoption of newer, more efficient methods holds potential for reducing avian mortality associated with power line collisions and electrocutions.

Efforts to expand renewable energy development must prioritize biodiversity conservation. Achieving this goal requires extensive collaboration among academics, conservationists, engineers, government agencies, and civil society. By working together across disciplines and national borders, stakeholders can develop innovative solutions that promote sustainable energy production while mitigating its adverse effects on wildlife.

4.2. Study limitations

Our study has some limitations especially when interpreting the results. The resolution of the spatial data used in the study may not capture fine-scale variations in habitat suitability or risk exposure. This could result in oversimplified representations of raptor habitat preferences and vulnerability to power line collisions and electrocutions. There are also no data presented on actual electrocution or collision mortalities. Nonetheless, our findings offer preliminary evidence across raptor species and spatial coverage, shedding light on areas where raptors may face heightened exposure to electrical energy and infrastructure.

Looking ahead, we recommend that future studies consider incorporating other avian species that were not covered in our analysis. Wetland bird species such as flamingoes (especially lesser flamingoes) and pelicans are particularly susceptible to electrocution and collision, while species like bustards and cranes may also warrant inclusion due to their behavioral traits. Furthermore, in high-risk areas identified by our study, continuous data collection efforts could help identify species most affected by electrocution events. Additionally, marking power lines in these areas may potentially mitigate the impact of power lines on a broader range of species (e.g. (Janss and Ferrer, 1998; Morkill and Anderson, 1991).

5. Species downloaded information

1. Hooded vulture (*Necrosyrtes monachus*) - GBIF. org (December 1, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.tm9dmp
2. Tawny eagle (*Aquila rapax*) - GBIF. org (December 1, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.v5kj6b
3. Augur buzzard (*Buteo augur*) - GBIF. org (December 1, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.mmz4d7
4. Long-crested eagle (Lophaetus occipitalis) - GBIF. org (December 1, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.uh2u2p
5. Lappet-faced vulture (*Torgos tracheliotus*) - GBIF. org (December 1, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.6jpabr
6. Steppe eagle (*Aquila nipalensis*) **-** GBIF. org (June 9, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.2v9353
7. Secretarybird (*Sagittarius serpentarius*) - GBIF. org (June 9, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.nu3s3z
8. Martial eagle (*Polemaetus bellicosus*) - GBIF. org (April 12, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.utpbre
9. Bateleur (*Terathopius ecaudatus*) - GBIF. org (April 12, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.ufdwfy

10 White-backed vulture (*Gyps africanus*) - GBIF. org (April 12, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.69fvka

11. Ruppell's vulture (*Gyps rueppellii*) - GBIF. org (April 6, 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.c2jgxp

12 Egyptian vulture (*Neophron percnopterus*) - GBIF. org (April 6, 2023) GBIF Occurrence Downloadhttps://doi.org/10.15468/dl.9ry3gt

13 White-headed vulture (*Trigonoceps occipitalis*) - GBIF. org (April 6, 2023) GBIF Occurrence Downloadhttps://doi.org/10.15468/dl.x74bd8

CRediT authorship contribution statement

Peggy Mutheu Ngila: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **David Chiawo:** Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization. **Margaret Awuor Owuor:** Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization. **Vivian Oliver Wasonga:** Writing – original draft, Supervision, Investigation, Conceptualization. **Elizabeth Ellwood:** Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Dominic Mugo:** Writing – original draft, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2024.100400.

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