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MAJOR THREATS TO A MIGRATORY RAPTOR VARY GEOGRAPHICALLY ALONG THE EASTERN MEDITERRANEAN FLYWAY

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Major threats to a migratory raptor vary geographically along the eastern Mediterranean flyway

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A B S T R A C T

The Convention of Migratory Species aims to protect migratory animals throughout their range, but efficient mitigation of threats facing migratory birds is hindered by poor knowledge about the magnitude and geographic range of threats. We used an expert assessment to prioritise which threats to mitigate in 13 countries along the eastern Mediterranean flyway to protect globally threatened Egyptian Vultures *Neophron percnopterus*. We informed this assessment by satellite tracking 71 birds to quantify where and how mortalities occurred, surveying 4216 km of powerlines to detect carcasses, conducting 910 interviews to quantify poison use, and by surveying markets and hunters to assess direct persecution. Mortality of 50 birds occurred in Europe and the Mediterranean Sea (44%), the Middle East (18%), and Africa (38%), and mortality causes varied geographically. Inadvertent poisoning resulting from rural stakeholders targeting predators occurred along most of the flyway. On the breeding grounds in eastern Europe and in Saudi-Arabia, poisoning and collision and electrocution are the priority threats to mitigate. Electrocution on small and poorly designed electricity pylons was the priority threat in Turkey, Jordan, Egypt and Ethiopia. Direct persecution for belief-based use of vulture products was the priority threat in Nigeria and Niger, while other illegal killing was the priority threat in Lebanon and Syria. Our work cannot quantify which threat has the greatest demographic impact on Egyptian Vultures. Nonetheless, because all threats we assessed are relevant for many other migratory birds, our assessment highlights the priority threats that range states need to address to protect migratory birds.

1. Introduction

Migratory animals connect countries and continents, and pose a particular conservation challenge, because threats to migratory animals that occur in one geographic region may limit their population size at distant breeding or wintering regions. The global network of protected areas, established to conserve biodiversity and habitats, is however largely inadequate to protect migratory animals along their flyways (Runge et al., 2015). Countries through which migratory animals pass have therefore committed to internationally coordinated conservation measures to protect migratory animals throughout their range under the Convention of Migratory Species (CMS), an environmental treaty of the United Nations.

Every year millions of large soaring birds migrate from European breeding grounds to wintering areas in Africa (Porter and Beaman, 1985). Because most soaring birds are reluctant to cross large water bodies such as the Mediterranean Sea (Agostini et al., 2015), major flyways follow routes around either the western or eastern periphery of the Mediterranean Sea (Finlayson, 1992; Leshem and Yom-Tov, 1996; Porter and Willis, 1968). One major flyway around the eastern Mediterranean funnels birds from Central and Eastern Europe and western Asia around the Black Sea and via the Bosporus into Turkey. Birds along this flyway travel through the Middle East towards the Red Sea, which they follow on either the western or eastern shoreline (Bijlsma, 1983; Phipps et al., 2019; Welch and Welch, 1988).

Counts of migrating raptors along this flyway indicate that >1 million raptors of >25 species regularly migrate along this route (Alon et al., 2004; Jobson et al., 2021; Verhelst et al., 2011). Among these species are 12 globally threatened species, and several whose populations appear to be declining on breeding grounds. Understanding the threats to these species along the flyway is important to inform effective conservation. Although many of the threats that exist along the flyway are broadly known in general terms (Brochet et al., 2016; Kirby et al., 2008; Ogada et al., 2015), there is so far no guidance which threats pose the greatest risk in which geographic region – information that is needed to efficiently target conservation efforts (Efrat et al., 2020; Vickery et al., 2014).

One of the globally threatened species using the eastern Mediterranean flyway is the Egyptian Vulture *Neophron percnopterus*, a soaring migrant with a broadly dispersed wintering range (Buechley et al., 2018; Oppel et al., 2022; Phipps et al., 2019). The Egyptian Vulture breeding population in the Balkans in eastern Europe has declined dramatically over the past 30 years, and while threats on breeding grounds have been studied and partially mitigated, the magnitude and distribution of threats along the flyway is so far poorly understood (Arkumarev et al., 2018; Velevski et al., 2015). Providing conservation management guidelines to rapidly halt current population declines of the Egyptian Vulture and 14 other vulture species is the goal of a multi-species action plan adopted by CMS parties in October 2017 (Botha et al., 2017). However, a detailed understanding of the most important threats in each country is required to achieve the goals of this plan.

Here we examine the relative mortality risk posed by different known major threats to Egyptian Vultures in 13 countries along the eastern Mediterranean flyway. Our goal was to facilitate the effective conservation envisioned in the multi-species action plan by providing an evidence-based ranking of the most relevant threats in each country. We used an expert consultation to qualitatively assess the relative importance of threats by geographic region. This expert assessment was informed by quantitative evidence of bird mortality which we collected through satellite tracking, powerline surveys and interviews with local people to understand the poisoning and persecution risk. The resulting country-specific threat ranking can therefore be used by range states to prioritise conservation work to meet their obligations under the Convention of Migratory Species (Botha et al., 2017).

2. Methods

2.1. Study species and study region

The Balkan population of Egyptian Vultures breeds in Albania, North Macedonia, Bulgaria, Greece and Turkey (Velevski et al., 2015), and migrates to wintering areas in Africa and the southern Arabian peninsula (Buechley et al., 2018; Oppel et al., 2015; Phipps et al., 2019). We focussed our study on the five breeding countries, and important countries along the flyway and wintering areas where work was practically feasible. Specifically, we conducted work in Albania, North Macedonia, Bulgaria, Greece, Turkey, Syria, Lebanon, Jordan, Egypt, Saudi Arabia, Ethiopia, Niger and Nigeria. All these countries, except Turkey, are parties to the Convention of Migratory Species, and have therefore committed to protecting migratory animals. Study areas within countries were selected based on knowledge about the distribution of birds from surveys (Arkumarev et al., 2014; Hilgerloh et al., 2011; Oppel et al., 2014) or from satellite telemetry (Buechley et al., 2018; Oppel et al., 2015).

2.2. Expert assessment to rank priority threats for each country

The major threats to Egyptian Vultures are broadly known in general terms for the flyway, but given the limited capacity to address all threats in all countries, a ranked assessment of the relative importance is needed to prioritise conservation action in each country (Botha et al., 2017). Threats are typically measured on different scales and in different units, and it is therefore logistically impractical to quantitatively estimate which threat has the greatest demographic impact on Egyptian Vultures. To facilitate decision making in each country with regard to prioritizing threat mitigation, we therefore convened regional experts and ranked threats based on quantitative evidence and expert's knowledge about their respective countries (Hugé and Mukherjee, 2018; Martin et al., 2012). We convened experts at regional scales for Europe (North Macedonia, Albania, Bulgaria, Greece), the Middle East (Turkey, Lebanon, Syria, Jordan, Saudi Arabia), and Africa (Ethiopia, Egypt, Niger, Nigeria) to ensure regional consistency in the ranking of threats. For each threat, a country-specific ranking was obtained by considering two dimensions, namely how widespread each threat is in a respective country, and how severe each threat is in terms of causing mortality (both informed by quantitative evidence described in Section 2.3). Priority of threat mitigation was then scored qualitatively from 0 (very low priority – when a threat was absent or negligible) to 5 (very high priority – when a threat was ubiquitous and severe), and consensus among regional experts was sought through discussions and available evidence.

Due to the qualitative nature of the ranking of threats, we emphasize that this ranking is intended to allow governments and conservation organisations to prioritise efforts to reduce the most important threats in each country, but does not allow a quantitative comparison of the threats across countries and continents.

2.3. Quantitative evidence to inform expert assessment

2.3.1. Telemetry to assess causes of mortality

From August 2010 to June 2021 we tracked 71 individually marked Egyptian Vultures (46 juveniles, 16 immatures of 1–5 years of age, 9 adults) with solar-powered GPS transmitters (Microwave or Ornitela, 30-45 g, all <3% of body mass) from capture locations in the Balkans, Ethiopia, and Jordan at high spatial and temporal resolution (one GPS position every 10 min – 1 h; for more details see Buechley et al., 2018; Oppel et al., 2015; Phipps et al., 2019). Some (n = 23) of the tracked juveniles were of captive origin, but a comprehensive analysis indicated that captive origin had no major effect on their survival (Buechley et al., 2021a), and for the purpose of our assessment we assumed that anthropogenic threats would affect birds of wild and captive origin equally. Transmitters were attached with a backpack or leg-loop harness configuration that is unlikely to affect survival probability in vultures (Anderson et al., 2020; Sergio et al., 2015). For those birds whose transmissions ended, we attempted to identify the cause of signal loss through inspection of the last signals (Sergio et al., 2019) and ground searches. When carcasses were found or the cause of signal loss could be reliably ascertained from the sequence of transmissions, we classified mortality as either 'natural mortality' (e.g. drowning, predation, exhaustion, starvation), 'direct persecution', 'poisoning' or 'electrocution'; all remaining cases were classified as 'unknown'. We caution that in most cases no detailed necropsy was performed, and that the true cause of death could have been masked by the more visually apparent cause of death. We present proportions of the number of tracked animals and of identifiable mortalities that were due to different causes.

2.3.2. Collision risk with wind turbines

Collision with wind turbines is a potential mortality cause for Egyptian Vultures (Carrete et al., 2009; Thaxter et al., 2017), but we did not observe mortality from wind turbine collision in our tracking data. We therefore used our tracking data to assess the potential exposure of birds to wind turbines along the flyway. We used data hosted on Open Street Map that summarised the location and size of wind power generation facilities (hereafter 'windfarms') (Dunnett et al., 2020), supplemented by a proprietary data set provided by The WindPower.net (obtained in June 2020). Given the spatial and temporal resolution of our tracking data, and the poor precision of turbine locations across the cross-continental scale of our study, it was impossible to assess how often a bird flew within the rotor-swept area of an existing turbine. We therefore assessed the 'potential exposure' to windfarm mortality by quantifying the frequency of locations within a 10 km radius around the central point of each windfarm location. A 15 km radius around wind turbines was previously found to predict mortality in Egyptian Vultures (Carrete et al., 2009), but we truncated this radius to 10 km given that a tracked bird flying at 40 km/h (Mellone et al., 2012) would register at least one GPS location every 15 min within that radius. If the windfarm area exceeded 100 km^2, we used the actual area of the windfarm rather than the 10 km radius.

We interpolated our tracking data to regular 15 min intervals, and summarised the total amount of time our tracked birds spent within the 10 km buffers of known windfarms. We then related the amount of time spent in the vicinity of windfarms to the total amount of time our tracked birds spent in each country to assess the relative exposure to windfarm collision risk. We acknowledge that this coarse assessment of potential exposure cannot quantify the immediate mortality risk at every single turbine, which would be affected by the turbine height, the flight altitude of the bird, and the exact flight trajectory (Marques et al., 2014). However, the relative exposure risk was adequate to inform the expert assessment regarding the relative importance of collision risk.

2.3.3. Surveys to detect electrocution and collision victims

Electrocution and powerline collision mortality is a recognised major threat along the flyway (AEWA, 2012; Angelov et al., 2013). We therefore conducted surveys under power distribution lines in areas that were frequented by Egyptian Vultures during breeding, migration, or wintering (Fig. 1). These surveys were designed to ensure broad spatial coverage and provide minimum estimates of mortality, and we caution that our surveys do not account for various factors that influence detection and persistence probability of carcasses (Bellan et al., 2013; Etterson, 2013; Korner-Nievergelt et al., 2015). However, despite potentially missing carcasses, these surveys are nonetheless valuable to prioritise whether electrocution and collision are a relevant threat in a specific region and can therefore be used for prioritisation of conservation actions (Bernardino et al., 2018; D'Amico et al., 2019).

Power lines were selected as those that were perceived to pose a high risk due to location and design of the support structure (Bernardino et al., 2018; D'Amico et al., 2019; Lehman et al., 2007). We selected small- to medium-voltage distribution lines that were supported by single poles with a cross-bar and conducting wires propped up above the support structure, as these powerlines are the most dangerous for electrocution (Eccleston and Harness, 2018; Lehman et al., 2007). We spatially selected lines that were within 10 km of breeding or feeding areas such as vulture restaurants, abattoirs or rubbish dumps, or major concentration areas on migratory routes where birds may be vulnerable when entering or departing from overnight roosts. Due to the non-random selection of searched powerlines and the heterogenous distribution of mortality (see Results), we are unable to extrapolate the total number of electrocution or collision victims per country based on the size of the power distribution network.

Surveys were conducted in 2012 and 2013 (Bulgaria, Greece), and between 2018 and 2021 (remaining countries) in seasons when Egyptian Vultures were present in the survey areas. We searched carcasses by slowly walking under each power line and searching the ground and any adjacent vegetation where scavengers may have dragged collision or electrocution victims (Costantini et al., 2017; Demerdzhiev, 2014). Any carcass or remnants of a carcass were identified to species, and species that could not be identified were recorded as 'unknown'. We re-surveyed two lines in Ethiopia and six lines in Egypt repeatedly to determine whether the mortality found under those lines during the first survey had occurred solely by chance. Carcasses found during a survey were removed or labelled to avoid counting the same carcass again on a

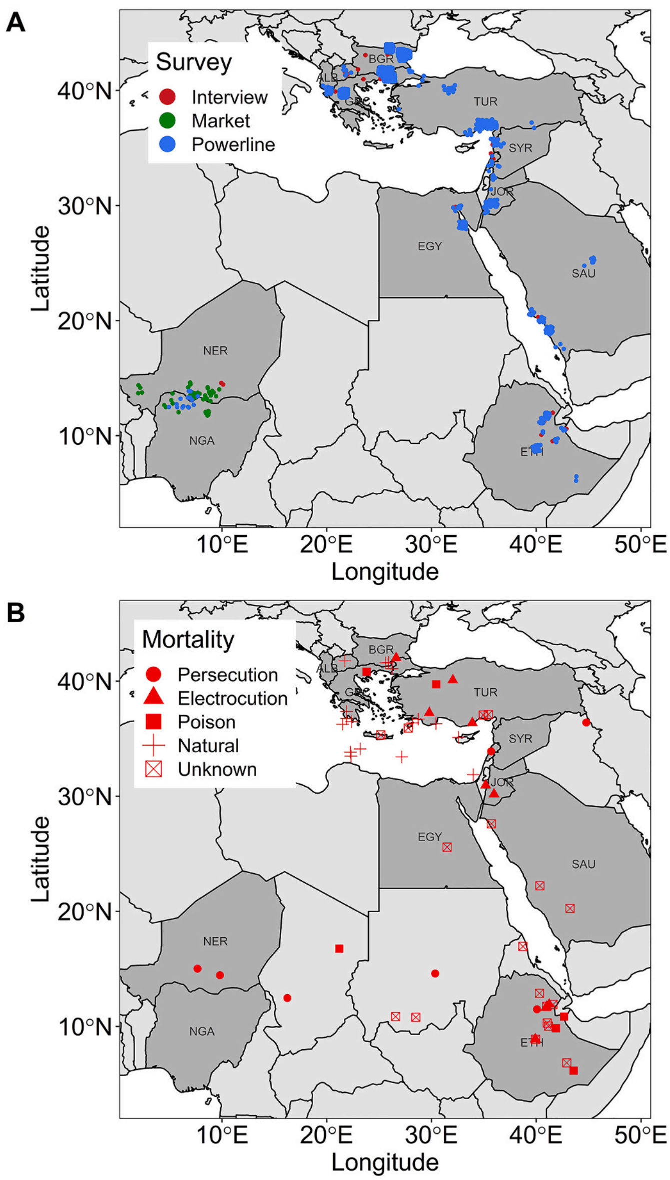

Fig. 1. Spatial distribution of (A) field survey effort and (B) mortality of Egyptian Vultures in 13 focal countries (dark grey) along the Eastern Mediterranean flyway between 2010 and 2021. Red symbols in (B) indicate locations where Egyptian Vulture mortality was recorded from either satellite-tracked individuals or from surveys. Country abbreviations are ALB – Albania, BGR – Bulgaria, GRC – Greece, TUR – Turkey, SYR – Syria, JOR – Jordan, SAU – Saudi Arabia, EGY – Egypt, NER – Niger, NGA – Nigeria, ETH – Ethiopia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

subsequent survey. We summarise and present results as the relative number of victims per km of powerline surveyed in each country.

2.3.4. *Interviews to assess risk of poisoning*

The inadvertent poisoning of vultures as a consequence of human-wildlife and human-human conflicts is a major threat on breeding (Margalida et al., 2014; Ntemiri et al., 2018; Parvanov et al., 2018; Sanz-Aguilar et al., 2015) and on wintering grounds (Monadjem et al., 2018; Murn and Botha, 2018; Ogada et al., 2015). To assess the prevalence of poison use by people using rural habitat in vulture breeding or wintering areas, we conducted interviews with rural stakeholders such as livestock owners, farmers, hunters, or other people who may have conflicts with wildlife or other land users that could conceivably be resolved with poison (Craig et al., 2018; Santangeli et al., 2016). We conducted interviews in all our focal study countries except Jordan and Nigeria, where poisoning by rural people was considered unlikely to affect birds from our target population because our telemetry data did not indicate foraging congregations of Egyptian Vultures in these countries (Oppel et al., 2015).

Interviews were conducted in a semi-structured conversation (Torkar et al., 2011; Young et al., 2018), and in each interview rural people were asked only two general questions: (1) what are your main problems in raising livestock or growing crops?; and (2) what solutions do you routinely employ to overcome these problems? We did not ask specifically about the use of poison, and thus avoided directly asking about illegitimate behaviour that would have required sophisticated elicitation techniques (Hinsley et al., 2019; Jones et al., 2021; Nuno and St. John, 2015). Answers were categorised into six different themes to portray problems (habitat availability, climate, invasive species, disease, predation, other), and into eight different types of solutions (re-location, guarding/chasing, fencing, shooting, trapping, poisoning, medicine, and other solutions). Depending on the social structure of rural communities, questionnaires were conducted either with individuals or with focus groups consisting of 2–12 people. We summarised the frequency of answers per interview regardless of the number of people participating in a given interview, because group interview participants provided a single collective answer and not independent answers.

All interviews were conducted anonymously (no identity-revealing information was requested from or provided by participants) in the local language of rural stakeholders by a local associate who then translated responses back to researchers (for general locations see Fig. 1). All participants were informed of the research prior to the interview, and all participants were given the opportunity to discontinue the conversation at any time (St John et al., 2014).

Besides the intentional use of poisonous substances to resolve human-wildlife conflicts, the poisoning of vultures can also occur indirectly through the use of certain veterinary medical products (non-steroidal anti-inflammatory drugs) that can cause kidney failure in vultures (Green et al., 2006; Oaks et al., 2004; Shultz et al., 2004), or through the use of highly toxic substances to control agricultural pests or feral animals near human settlements (Abebe, 2013; Ogada, 2014; Parvanov et al., 2018; Plaza et al., 2019). We therefore interviewed officials from local authorities to understand what veterinary medical products were authorised for use in each country, and interviewed public health authorities to discover whether public health issues were controlled in ways that could put scavengers at risk of poisoning (Tschopp et al., 2016; Zewdu et al., 2010).

2.3.5. *Assessment of direct persecution*

Many migratory birds are directly persecuted and illegally killed or taken on migration along the entire flyway (Brochet et al., 2016). In addition, direct illegal persecution of vultures occurs in many African countries due to demands for vulture products in belief-based uses (Buij et al., 2016; Ogada et al., 2015; Saidu and Buij, 2013). We assessed the magnitude of these two processes on Egyptian Vultures by extrapolating the number of birds illegally killed through direct persecution (Brochet et al., 2019a; Brochet et al., 2016; Brochet et al., 2019b), and by conducting surveys of markets in Africa to assess the magnitude of demand for vultures. We assume that our surveys are indicative of general patterns in the countries we surveyed, but acknowledge that due to the illegal nature of direct persecution our surveys could potentially underestimate the true scale of this threat.

To assess illegal killing of migratory birds along the flyway, we used data collected in regional assessments (Brochet et al., 2019a; Brochet et al., 2016; Brochet et al., 2019b). Briefly, national experts and organisations were consulted between 2014 and 2018 to assess if wild birds were known or likely to be illegally killed in non-trivial numbers in their country. Sites where hunting and shooting occurred were surveyed to obtain information from hunters and other informants about the species being hunted and to estimate the approximate number of birds being killed at focal hunting areas. Simultaneously, literature and unpublished reports were consulted to gauge the extent of illegal killing, and data were extrapolated and rounded to the nearest thousand to avoid spurious precision (Brochet et al., 2019a; Brochet et al., 2016; Brochet et al., 2019b). We extracted the minimum and maximum of these estimates for all birds, and for Egyptian Vultures specifically.

The available regional assessments did not include our focal countries in sub-Saharan Africa (Ethiopia, Niger, Nigeria). In Africa, the illegal killing and taking of vultures occurs to satisfy demands primarily in Nigeria. Following the death of a tracked individual Egyptian Vulture that was shot in Niger to supply a market in Nigeria (Kret et al., 2018), we conducted surveys at several markets in Nigeria and Niger (Fig. 1) in 2018 and 2019 to determine the magnitude of the vulture trade with a particular focus on Egyptian Vultures. During the surveys, a local collaborator first assessed how many stalls at each market sold any vulture parts, and then quantified the number of stalls that either have in the past or would sell Egyptian Vulture parts in the future. Sellers were asked about the origin of vulture parts on sale. Vulture products are not routinely sold at markets in Europe, the Middle East, Egypt or Ethiopia, hence we did not conduct market surveys in those regions.

3. Results

3.1. Quantitative evidence for the severity of threats

3.1.1. Evidence for mortality from telemetry data

We lost 50 (70%; 27 died as juveniles, 15 as immatures, 8 as adults) of the 71 individual Egyptian Vultures tracked with satellite telemetry by the end of June 2021, and for 16 (32%) of these birds the cause of loss could not be ascertained. Of the 50 lost birds, 22 (44%) perished on or near the breeding grounds in eastern Europe (including 12 juveniles drowning in the Mediterranean Sea during their first autumn migration), nine (18%) in the Middle East and Arabian Peninsula, and 19 (38%) in Africa. Of the 34 individuals whose cause of mortality could be ascertained, seven (20%) were shot, five (15%) were poisoned, and three (9%) were electrocuted, while the remaining 19 (56%) died from natural causes (Fig. 1).

3.1.2. Collision risk with wind turbines

We tracked individual birds since 2010 for up to 9 years per individual (total 19,468 bird tracking days), resulting in 30–7230 tracking days per country in our focal study countries along the flyway (Table S2). In two countries, Greece and Turkey, the tracked birds spent >16% of their time within 10 km of existing windfarms, and in three further countries (Jordan, Bulgaria and Lebanon) the tracked birds spent >3.5% of their time near windfarms (Table S2). In Ethiopia, our tracked Egyptian Vultures did not spend any time near existing windfarms because windfarms occurred in the highlands and tracked birds occurred in lowlands.

3.1.3. Evidence for electrocution and collision

We conducted 682 surveys in 13 countries to search for electrocution and collision victims under powerlines, covering a total of 4216 km. During these surveys we found a total of 708 bird carcasses of 54 species, of which 17 were Egyptian Vultures. The highest encounter rates of bird carcasses per km of powerline occurred in Turkey, Ethiopia, and Saudi Arabia. The most Egyptian Vulture carcasses were found in Ethiopia (Table S1), where the largest known congregations of this species occur (Arkumarev et al., 2014), and the most bird victims (197) were found in Egypt (Table S1).

3.1.4. Evidence for poisoning

We interviewed a total of 1135 rural stakeholders during 910 distinct interviews in ten countries along the flyway where Egyptian Vultures occur regularly (Tables S3, S4). Our interviews revealed that most livestock herders experienced problems with carnivores that occasionally attacked their livestock. The threat of carnivores to livestock was highlighted in >65% of interviews in Albania, Niger, Syria, Turkey and Ethiopia, but only in 14% of interviews in Bulgaria and 23% in Lebanon (Table S3).

Given that predation by carnivores was the most frequently stated problem, many of the solutions provided revolved around the topic how livestock could be protected from predators, except in Turkey, where rural stakeholders accepted the loss of livestock to natural predators. Between 0 and 93% of respondents mentioned that they use guarding dogs, fenced enclosures or other non-lethal protection measures to keep their livestock safe. The most common alternative solutions to control the problem of predators were shooting all predators (in Syria, Saudi Arabia, and Ethiopia), or the use of poison, which occurred in every country where we interviewed people except in Turkey. The highest prevalence of poison use occurred in Syria and Greece, followed by Saudi Arabia, Egypt, North Macedonia, and Ethiopia (Table S3).

Chemicals (e.g. strychnine, methomyl) were used to control feral dogs by local authorities in Ethiopia, Egypt, Lebanon, Syria, and Saudi Arabia. Mass poisoning campaigns were conducted for public health purposes in the vicinity of human settlements and at rubbish dumps. Feral dogs poisoned with strychnine or other toxins were mostly buried, but sometimes also disposed in open fields or landfills, which allowed scavenging birds to access and feed on poisoned carcasses.

We found that veterinary medical products that are known to cause fatal liver failure in vultures (Diclofenac, Ketoprofen) were widely available in veterinary pharmacies in Egypt, Saudi Arabia, Syria, Jordan, and Lebanon, and available to authorised users in Nigeria. Carcasses of animals treated with such products were not buried or removed. On breeding grounds in Greece, veterinarians and livestock owners relied primarily on Meloxicam (which is safe for vultures) and Flunixin (which is toxic to vultures; Cuthbert et al., 2007; Eleni et al., 2019) to treat moribund livestock, and also disposed of carcasses of treated animals openly in fields. In Bulgaria, Diclofenac destined for human use (e.g. standard painkillers) or imported from neighbouring countries was used by small-scale livestock holders without veterinary guidance.

3.1.5. Evidence for direct persecution

Illegal killing of birds in the nine countries we assessed exceeded 6 million birds every year, and may have been as high as >20 million birds in these focal countries alone (Table S5). Because Egyptian Vultures are relatively rare, and do not appear to be targeted specifically even in countries where raptor persecution is common (e.g. Saudi Arabia), illegal killing may remove 10–90 individuals per year (Table S5).

One particular aspect of the illegal taking of birds is the trade of vulture products in parts of Africa. We surveyed 12 markets with 25,980 stalls or sellers in Nigeria, and 33 markets with 26,955 stalls or sellers in Niger. In Nigeria, 397 sellers (1.5%) offered vulture products for sale, while in Niger only 63 sellers (0.23%) offered vulture products. Although no Egyptian Vultures were available at the time of the surveys in Nigeria, all sellers (100%) stated that they would sell Egyptian Vultures if their suppliers would deliver them. In Niger, 12 sellers (19% of those offering any vulture product) offered Egyptian Vulture parts (Table S6).

Egyptian Vulture parts were unavailable on markets in Nigeria because sellers stated in interviews that the species had disappeared due to direct persecution for trade. Because of the absence of vultures in Nigeria, sellers in Nigeria obtained only a fraction of vultures they sold from within Nigeria, but sourced their products from Niger, Chad, Cameroon, Burkina Faso, Mali, Senegal, and the Central African Republic.

3.2. Synthesis and ranking of threats

Using the evidence from satellite telemetry, surveys, and interviews, and the regional knowledge of conservation experts working in each country, we ranked the known threats to prioritise them for mitigation in each of our focal countries (Table 1). In Europe, poisoning was the most highly ranked threat affecting Egyptian Vultures, while in the Middle East direct persecution (Syria, Lebanon), electrocution (Turkey, Jordan), and poisoning (Saudi Arabia) were the threats requiring most urgent mitigation (Table 1). In Africa, persecution for the vulture trade was the primary threat in Niger and Nigeria, while electrocution was the most highly ranked threat in Egypt and Ethiopia (Table 1).

4. Discussion

The key threats to Egyptian Vultures along the Eastern Mediterranean flyway vary among the 13 countries that we included in our assessment, with poisoning and electrocution occurring in every country along the flyway. Collision and electrocution are major problems in Turkey, Ethiopia, Saudi Arabia, Egypt, Jordan and Greece, and direct persecution was a key threat in Syria, Lebanon, Egypt, Niger and Nigeria. These threats will affect Egyptian Vultures, but also hundreds of thousands of storks, buzzards, kites and eagles that use the same flyway (Fülöp et al., 2014; Leshem and Yom-Tov, 1996; Megalli and Hilgerloh, 2013; Oppel et al., 2014), and resident raptors, storks and vultures that share the same habitats in Africa or the Middle East (Buechley et al., 2021b; Santangeli et al., 2019; Shobrak et al., 2021). Although our work cannot estimate which of the threats has the greatest demographic impact on Egyptian Vultures, our overview allows governments and conservation organisations to prioritise efforts to reduce threats in each country. Rapid action to mitigate threats can protect Egyptian Vultures and many other migratory birds and thus honour each country's commitments under the Convention of Migratory Species.

A fully quantitative assessment of the relative demographic impact of each threat would require an impractical amount of data and therefore delay urgently needed conservation action. The main weakness of our study is that we cannot quantify the impact of any of the threats we identified on vulture populations, and we cannot quantitatively compare the impact of the different threats on populations. For example, while we found evidence for electrocution of vultures in Ethiopia, it is impossible to translate the number of victims found per km of powerline into a typical demographic parameter such as annual survival probability that would allow a quantitative extrapolation of the impact on populations, especially since our surveys did not account for detection probability and may therefore underestimate the true scale of mortality (Bellan et al., 2013; Etterson, 2013; Korner-Nievergelt et al., 2015). Likewise, while we also found evidence that poisoning occurs in Ethiopia, the risks of poisoning and electrocution are measured on different scales in our approach, and cannot be objectively compared. To overcome this issue, we assembled vulture and conservation experts from each country, and discussed the relative importance of each threat based on our evidence and existing detailed country-level information (Table 1). Nonetheless, there is no guarantee that mitigating the highest priority threats we identified will immediately revert population declines, especially since other threats such as habitat loss or food shortage may impose further diffuse effects on populations.

The threats we evaluated cause bird mortality, particularly vulture mortality, and occur across broad spatial extents (Kirby et al., 2008; Ogada et al., 2015; Botha et al., 2017). Our work was not designed to identify previously unknown threats. However, given the number and diversity of threats along the flyway, we provide important guidance about which threats should be addressed first in which geographic region (Table 1). Our approach therefore complements the information in the multi-species action plan (Botha et al., 2017) by providing refined country-specific recommendations. Together with work that has identified the geographic areas where vultures reach highest density and diversity (Buechley et al., 2018; Santangeli et al., 2019), there is now sufficient information for governments and international funding agencies to work towards reducing threats to vultures (Efrat et al., 2020; Safford et al., 2019; Oppel et al., 2021) and migratory birds in general.

The highest priority for immediate action and the highest potential for immediate benefit is to avoid increasing the level of threat posed by electrocution and collision along the flyway. We found that electrocution and collision risk occurs in every country, and this risk is potentially increasing in many countries due to the expansion of electricity distribution and power generation networks (Flade, 2012; Kiesecker et al., 2019; Oppel et al., 2021; Serrano et al., 2020). Numerous guidelines exist on how to design and deploy bird-safe electricity infrastructure (AEWA, 2012; BirdLife International, 2015; Martín et al., 2019), and our assessments indicate that in some countries such infrastructure is in fact well designed: for example, in Syria most of the low-voltage power distribution networks use a safe pylon design, which resulted in low rates of electrocution and collision (Table S1), while in Jordan all wind power installations require a shut-down on demand system that considerably reduces the collision risk to migratory birds (Khoury, 2017; Tomé et al., 2017). Temporary shut-downs of wind turbines, as well as bird electrocution that causes power disruptions, incur substantial economic costs (D'Amico et al., 2018; Moreira et al., 2018). Safer location of large scale power infrastructure developments based on existing knowledge about bird sensitivities (Loss, 2016; Smith and Dwyer, 2016; Thaxter et al., 2017), and safer designs of transport infrastructure will therefore result in both biodiversity and economic benefits and improved quality of power supply. We urge funders and policy makers to revise the design requirements for power infrastructure and develop infrastructural standards that eliminate the electrocution and collision risk to large migratory birds.

Existing infrastructure that poses high electrocution and collision risk needs to be safeguarded with insulation, visual markers, or other effective mitigation devices to reduce bird mortality (AEWA, 2012; Badia-Boher et al., 2019; López-López et al., 2011; Sánchez et al., 2020).

Table 1
Expert assessment of the priority to mitigate three major anthropogenic threats to Egyptian Vultures along the Eastern Mediterranean flyway. Priority to mitigate threats was scored qualitatively from 0 (very low - if threat was absent or irrelevant) to 5 (very high - if threat was ubiquitous and severe), with colour coding for visual emphasis. Note that the threat mitigation priority is intended for work at a country-level, and we do not recommend comparing the priority between continents.

	Country	Poisoning	Electrocution/collision	Direct persecution
Europe	Albania	4	3	1
	North Macedonia	4	2	1
	Bulgaria	4	3	2
	Greece	5	3	1
Middle East	Turkey	2	5	2
	Syria	3	2	4
	Lebanon	3	2	4
	Jordan	2	4	1
	Saudi Arabia	5	4	2
Africa	Egypt	3	4	2
	Ethiopia	4	5	0
	Nigeria	2	1	5
	Niger	2	1	4

Such action is exceptionally urgent in Turkey, Ethiopia, and Saudi Arabia, where we found high levels of bird mortality (Table 1), and where major concentrations occur during migration (Buechley et al., 2018; Oppel et al., 2014) and in winter (Arkumarev et al., 2014; Keijmel et al., 2020; Shobrak et al., 2020). For example, in Sudan a hazardous powerline (Angelov et al., 2013) was replaced with bird-safe infrastructure in 2014 to reduce bird electrocution. We therefore believe that safeguarding of existing energy infrastructure will be technologically and financially feasible in other countries along the flyway if policy makers and funders honour their commitments under the Convention of Migratory Species.

Besides electrocution and collision, poisoning was the most widespread threat along the flyway. None of our interviews revealed any intention of people or authorities to deliberately poison vultures or other large birds, and poisoning was therefore invariably an inadvertent consequence of securing personal interests, or attempts to improve public health by controlling the number of feral animals. Public health campaigns aimed at reducing rabies transmission by eliminating free-ranging dogs can have major impacts on vulture populations, because free-ranging dogs often congregate and are targeted at rubbish dumps where vultures also congregate (Angelov et al., 2020; Arkumarev et al., 2019). Public health officials aiming to control rabies should therefore consider the inadvertent risks to wildlife and human health when using non-selective methods such as toxic chemicals that can affect non-target species (WHO, 2018). Alternative approaches to improve public health by controlling or vaccinating feral animals could combine fertility control and more humane and more targeted removal methods (Massei et al., 2010; Sillero-Zubiri and Switzer, 2004). Similar bans should be considered for the veterinary use of drugs that are known to be harmful for raptors, such as Diclofenac and Ketoprofen. Following catastrophic declines of vulture populations, India, Nepal and Pakistan banned the veterinary use of Diclofenac in 2006, and we recommend that all countries along flyways used by vultures and other large raptors implement a similar ban to prevent avoidable mortality.

Solutions to reduce the incidence of poisoning by individual stakeholders are complicated and require an increase of awareness and law enforcement (Ogada, 2014; Richards et al., 2018), as well as a diversification of household income sources to reduce total dependency on livestock (Davies and Bennett, 2007; Romañach et al., 2007; Tsegaye et al., 2013). Potential improvements to protect livestock from wild predators are enclosures (Lichtenfeld et al., 2015), protective collars (Khorozyan et al., 2020), distraction displays (Radford et al., 2020), or guarding dogs (Khorozyan and Waltert, 2019; McManus et al., 2015; van Bommel and Johnson, 2012), and helping rural livestock holders to improve their protection measures may reduce the propensity to use poison. Alternatively, improvements to veterinary care and access to water and food resources may increase the health of livestock populations and could either directly reduce predation risk (Khorozyan et al., 2015), or reduce the economic impact of livestock predation if predation losses are offset by other sources of income (Jackson and Wangchuk, 2004; Romañach et al., 2007).

Illegal killing of birds may cause the death of >20 million individuals along the Eastern Mediterranean flyway every year (Brochet et al., 2016), but our assessment revealed that the indiscriminate killing of all migratory birds in the Middle East may not cause many Egyptian Vulture deaths every year in our focal countries. There is, however, considerable uncertainty in assessments that rely on interviews and extrapolations, and the true extent of Egyptian Vulture mortality is unknown. More effective legislation and more robust enforcement of existing hunting laws are urgently required in several countries along the flyway.

The direct persecution for the market trade in Nigeria is highly targeted and has the potential to affect all vulture populations in the central Sahel region (Buij et al., 2016; Ogada et al., 2015; Saidu and Buij, 2013), especially neighbouring countries such as Niger. We found hundreds of market sellers willing to sell vulture products, including Egyptian Vultures, and these products may be sourced from other countries (Kret et al., 2018), and possibly as a by-product of poisoning incidents (Mateo-Tomás and López-Bao, 2020). The trade in vulture parts also exists in Niger, but at a smaller scale, and with much of the demand driven by Nigeria. Vultures are legally protected in Nigeria, with both the killing and trade of vulture species being illegal. However, this law is not enforced and without a reduction in demand in Nigeria, it is unlikely that the persecution in the Sahel region will cease.

In conclusion, our detailed examination of Egyptian Vultures highlights that governments along the Eastern Mediterranean flyway face considerable challenges to protect migratory birds under the Convention of Migratory Species, and the most important actions to reduce mortality will vary by country. While governments in eastern European breeding range countries urgently need to address the problem of wildlife poisoning, the governments in Turkey, Saudi Arabia, Jordan and Ethiopia should focus on reducing threats to migratory birds from energy infrastructure while not neglecting the threat of poisoning. Enforcement of existing laws to reduce the illegal killing of birds should be a priority in Syria, Lebanon, Egypt, Nigeria and Niger.

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Declaration of competing interest

We have declared our funding sources and have no conflict of interest to declare.

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