Received: 6 May 2021 | Accepted: 12 February 2022

DOI: 10.1111/1365-2664.14160

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa

Jethro G. Gauld[1] | João P. Silva[2,3] | Philip W. Atkinson[4] | Paul Record[5] | Marta Acácio[1] | Volen Arkumarev[6] | Julio Blas[7] | Willem Bouten[8] | Niall Burton[4] | Inês Catry[2,3] | Jocelyn Champagnon[9] | Gary D. Clewley[10] | Mindaugas Dagys[11] | Olivier Duriez[12] | Klaus-Michael Exo[13] | Wolfgang Fiedler[14] | Andrea Flack[14,15] | Guilad Friedemann[16] | Johannes Fritz[17] | Clara Garcia-Ripolles[18] | Stefan Garthe[19] | Dimitri Giunchi[20] | Atanas Grozdanov[21,22] | Roi Harel[23] | Elizabeth M. Humphreys[10] | René Janssen[24] | Andrea Kölzsch[14] | Olga Kulikova[25] | Thomas K. Lameris[26] | Pascual López-López[27] | Elizabeth A. Masden[28] | Flavio Monti[29] | Ran Nathan[23] | Stoyan Nikolov[6] | Steffen Oppel[30] | Hristo Peshev[22,31] | Louis Phipps[32] | Ivan Pokrovsky[14,33,34] | Viola H. Ross-Smith[4] | Victoria Saravia[35] | Emily S. Scragg[4] | Andrea Sforzi[36] | Emilian Stoynov[22] | Chris Thaxter[4] | Wouter Van Steelant[8] | Mariëlle van Toor[37] | Bernd Vorneweg[14] | Jonas Waldenström[37] | Martin Wikelski[14] | Ramūnas Žydelis[38] | Aldina M. A. Franco[1]

[1]School of Environmental Sciences, University of East Anglia, Norwich, UK; [2]CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Vairão, Portugal; [3]CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade de Lisboa, Lisbon, Portugal; [4]British Trust for Ornithology, The Nunnery, Thetford, UK; [5]Heriot Watt University, Edinburgh, UK; [6]Bulgarian Society for the Protection of Birds, BirdLife Bulgaria, Sofia, Bulgaria; [7]Department of Applied Biology, Estación Biológica de Doñana, Seville, Spain; [8]Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands; [9]Tour du Valat Research institute for conservation of Mediterranean wetlands, Arles, France; [10]British Trust for Ornithology Scotland, Stirling University Innovation Park, Stirling, UK; [11]Nature Research Centre, Vilnius, Lithuania; [12]Centre of Evolutionary and Functional Ecology, CNRS Campus, Montpellier, France; [13]Institute of Avian Research, Vogelwarte, Helgoland, Germany; [14]Max Planck Institute of Animal Behavior, Radolfzell am Bodensee, Germany; [15]Centre for the Advanced Study of Collective Behaviour, University of Konstanz, Constance, Germany; [16]Department of Zoology, Tel Aviv University, Tel Aviv, Israel; [17]Waldrappteam Conservation and Research, Austria; [18]Environment Science and Solutions S.L., Valencia, Spain; [19]Research and Technology Centre (FTZ), Kiel University, Kiel, Germany; [20]Department of Biology, University of Pisa, Pisa, Italy; [21]Department of Zoology and Anthropology, Sofia University St. Kliment Ohridski, Sofia, Bulgaria; [22]Fund for wild Flora and Fauna, Bulgaria; [23]Department of Ecology, Evolution and Behavior, The Hebrew University of Jerusalem, Jerusalem, Israel; [24]Bionet Natuuronderzoek, EL Stein (Lb), The Netherlands; [25]Institute of Biological Problems of the North, FEB RAS, Magadan, Russia; [26]Netherlands, Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands; [27]Movement Ecology Lab, Environmental Research, Cavanilles Institute of Biodiversity and Evolutionary Biology, University of Valencia, Valencia, Spain; [28]Institute, North Highland College – UHI, University of the Highlands and Islands, Thurso, UK; [29]Department of Physical Sciences, Earth and Environment, University of Siena, Siena, Italy; [30]Centre for Conservation Science Research, Royal Society for the Protection of Birds, Cambridge, UK; [31]Department of Geography, Ecology and Environmental Protection, South-West University Neofit Rilski, Blagoevgrad, Bulgaria; [32]The Vulture Conservation Foundation, Zürich, Switzerland; [33]Institute of Plant & Animal Ecology, UB RAS, Ekaterinburg, Russia; [34]Institute of Biological Problems of the North, FEB RAS, Magadan, Russia; [35]Hellenic Ornithological Society (BirdLife Greece), Athens, Greece; [36]Maremma Natural History Museum, Grosseto, Italy; [37]Department of Biology and Environmental Science, Linnaeus University, Kalmar, Sweden and [38]DHI, Hørsholm, Denmark

Correspondence
Jethro G. Gauld
Email: j.gauld@uea.ac.uk; jethro.g.gauld@gmail.com

Aldina M. A. Franco
Email: a.franco@uea.ac.uk

Present address
Jethro G. Gauld, University of East Anglia, Norwich, UK

Funding information
Recovery of the Populations of Large European Vultures in Bulgaria and Vultures back to LIFE - Bright Future for Black Vulture in Bulgaria LIFE projects, Grant/Award Number: LIFE08 NAT/BG/000278 and LIFE14 NAT/BG/000649; BAE Systems; FCT - Foundation for Science and Technology within the scope of the project, Grant/Award Number: POCI-01-0145-FEDER-006821, POCI-01-0145-FEDER-028176 and UID/BIA/50027/2013; FEDER Funds through the Operational Competitiveness Factors Program - COMPETE; FlySafe; German Aerospace Centre (DLR), Grant/Award Number: ICARUS; German Air and Space Administration (DLR); Horizon 2020 Framework Programme, Grant/Award Number: No 727922 (Delta-Flu); LIFE+ project "Reason for Hope", Grant/Award Number: LIFE+12-BIO_AT_000143; Marine Renewable Energy and the Environment (MaREE) project; Max-Planck Institute of Animal Behavior; Natural England; NERC Env-East DPT; NEXUSS CDT, Grant/Award Number: BSF 255/2008 and DIP-DFG NA 846/1-1; Niedersächsische Wattenmeerstiftung, Grant/Award Number: NWS 04/09; NWO (Netherlands Organisation for Scientific Research), Grant/Award Number: NPP 866.13.010; The Return of the Neophron and Egyptian Vulture New LIFE, Grant/Award Number: LIFE10 NAT/BG/000152 and LIFE16 NAT/BG/000874; Tuscan Archipelago National Park, Grant/Award Number: BSF 255/2008 and DIP-DFG NA 846/1-1; UK Department for Business, Energy and Industrial Strategy (BEIS) Offshore Energy Strategic Environmental Assessment (OESEA) research programme; Whitley Fund for Nature, Project: Saving the Balkans' last vultures: introducing Vulture Safe Areas as a model for scavenger conservation in the Anthropocene, Grant/Award Number: LIFE14 NAT/BG/000649

Handling Editor: Marc-André Villard

Abstract

1. Wind turbines and power lines can cause bird mortality due to collision or electrocution. The biodiversity impacts of energy infrastructure (EI) can be minimised through effective landscape-scale planning and mitigation. The identification of high-vulnerability areas is urgently needed to assess potential cumulative impacts of EI while supporting the transition to zero carbon energy.
2. We collected GPS location data from 1,454 birds from 27 species susceptible to collision within Europe and North Africa and identified areas where tracked birds are most at risk of colliding with existing EI. Sensitivity to EI development was estimated for wind turbines and power lines by calculating the proportion of GPS flight locations at heights where birds were at risk of collision and accounting for species' specific susceptibility to collision. We mapped the maximum collision sensitivity value obtained across all species, in each 5 × 5 km grid cell, across Europe and North Africa. Vulnerability to collision was obtained by overlaying the sensitivity surfaces with density of wind turbines and transmission power lines.
3. Results: Exposure to risk varied across the 27 species, with some species flying consistently at heights where they risk collision. For areas with sufficient tracking data within Europe and North Africa, 13.6% of the area was classified as high sensitivity to wind turbines and 9.4% was classified as high sensitivity to transmission power lines. Sensitive areas were concentrated within important migratory corridors and along coastlines. Hotspots of vulnerability to collision with wind turbines and transmission power lines (2018 data) were scattered across the study region with highest concentrations occurring in central Europe, near the strait of Gibraltar and the Bosporus in Turkey.
4. *Synthesis and applications*. We identify the areas of Europe and North Africa that are most sensitive for the specific populations of birds for which sufficient GPS tracking data at high spatial resolution were available. We also map vulnerability hotspots where mitigation at existing EI should be prioritised to reduce collision risks. As tracking data availability improves our method could be applied to more species and areas to help reduce bird-EI conflicts.

KEYWORDS
animal movement, bird conservation, collision risk, environmental impact assessment, GPS, renewable energy, spatial planning, telemetry

1 | INTRODUCTION

The transition to zero carbon energy is essential to avoid runaway climate change (IPCC, 2018). However, the expansion of renewable energy infrastructure (EI) required to achieve this poses a challenge to wildlife conservation due to collision and electrocution risks, particularly for birds and other aerial taxa (Bernardino et al., 2018a; Kiesecker et al., 2019; Marques et al., 2014). European, onshore wind energy capacity is projected to grow from approximately 169 GW in 2018 to between 262 GW and 760 GW by 2050 with enough economically viable wind turbine locations (approximately 3.4 million) for up to 13.4 TW of capacity (Ryberg et al., 2019). Countries in the Middle East and North Africa also have targets to increase the share of electricity supply from onshore wind with Morocco and Tunisia aiming for 100% renewable electricity by 2050 (Timmerberg et al., 2019). Huge investment in the electricity transmission network will accompany this expansion of renewables, with an estimated fivefold increase in transmission capacity required between 2010 and 2050 (Mckinsey & Company, 2010). However, when poorly designed or situated, wind farms and power lines can result in increased mortality of susceptible birds such as large water birds, gulls, ibis, storks, owls, vultures and other raptors (Janss, 2000; Oppel et al., 2021; Thaxter et al., 2017).

Organisations, such as energy companies, charged with supporting the rollout of renewable energy generation are obliged by national, European legal (2009/147/EC, 2010) and pan-flyway voluntary (Horns & Şekercioğlu, 2018) frameworks to mitigate risks to birds (Gyimesi & Prinsen, 2015). Methods to evaluate and mitigate these impacts are relatively well understood at project-specific and local scales (Schaub et al., 2020; Serrano et al., 2020). However, such assessments often occur after a development site has already been selected because the initial feasibility studies for energy projects tend to focus on the economic viability of the development over other factors. The scale and pace of new development requires greater integration of high-level assessments of the potential cumulative impact at regional and flyway scales into these feasibility studies to highlight areas where additional EI development is likely to significantly increase the risk to bird populations (Eichhorn et al., 2017; Loss et al., 2019; Thaxter et al., 2019). This is particularly important for migratory bird species who may experience the impact of multiple developments in operation within key migration routes, stopover sites, wintering grounds and breeding sites (Bernardino et al., 2018a; Gove et al., 2013).

Bird sensitivity maps can be developed to illustrate the relative risk associated with EI development for sensitive bird species (Vasilakis et al., 2016; Warwick-Evans et al., 2017). The distribution and behaviour of birds inferred from GPS tracking of individuals can be used to create a spatio-temporal measure of the potential impact of new EI developments, by identifying where and when birds would be most exposed to potential collision risks from EI developments (Ross-Smith et al., 2016; Thaxter et al., 2019; Warwick-Evans et al., 2017). For areas with sufficient tracking data, combining sensitivity maps with other inputs, such as the available wind resources, can help planners optimise new wind farm and power line locations by avoiding high sensitivity areas during the site selection stage of the development process (Kiesecker et al., 2019). This, in turn, can reduce mitigation costs and produce better wildlife outcomes compared with site-based assessments alone (Bradbury et al., 2014; Bright et al., 2008).

Sensitivity mapping is particularly useful for assessing the potential for negative interactions between birds and energy infrastructure at the level of migratory flyways. For example, a wind farm sensitivity map created for the Red Sea flyway estimates the potential collision risks for soaring migratory birds at the flyway scale (BirdLife International, 2015). This tool enables preliminary impact assessment of wind farms by viewing protected areas and raw GPS tracks of susceptible bird species. However, it does not account for all dimensions related with collision risk, such as the height at which birds fly, which in turn may vary depending on landscape, meteorological, seasonal and species-specific factors (Kleyheeg-hartman et al., 2018; Marques et al., 2020). In the terrestrial context, other sensitivity mapping studies largely rely on trait-based analysis in relation to population densities of susceptible bird species (D'Amico et al., 2019; Thaxter et al., 2017).

In this context sensitivity is a measure of potential collision risk identifying areas where the tracked birds could collide if wind turbines or powerlines are present (Thaxter et al., 2019). We calculated this by combining susceptibility traits with GPS location and altitude data for individuals from 27 species, including resident and migratory birds in Europe and Northern Africa, to describe where and when the tracked birds are most sensitive to collision risks from terrestrial EI. Within the areas for which we obtained sufficient high spatial resolution GPS tracking data; this allows us to identify sensitivity hotspots where future onshore EI development should be discouraged. However, our work cannot reveal 'safe' areas where EI development could be encouraged. We then overlay this sensitivity surface onto the density of existing EI to identify vulnerability hotspots where the tracked individuals are most exposed to collision risks due to the presence of wind turbines and powerlines. Similar approaches using GPS tracking data have been applied to assess the impacts of proposed offshore windfarm developments where survey logistics are more challenging (Bradbury et al., 2014; Cleasby et al., 2015; Lees et al., 2016; Ross-Smith et al., 2016; Thaxter et al., 2019). Our work also highlights the spatial variation in GPS tagging effort and data availability which helps identify priority areas for future tracking studies and the need to increase data sharing via online platforms such as Movebank to help fill in the gaps in the existing tracking data where sensitivity assessment is not currently feasible using publicly available GPS tracking data.

2 | MATERIALS AND METHODS

2.1 | Data acquisition

An overview diagram of the methods is presented in Supporting Information S1, section 1. We sourced bird movement data via the Movebank data repository, a web-based online platform for sharing data from animal tracking studies (Movebank, 2019), with a view to maximising coverage of Europe and North Africa. In November of 2018, we identified 254 bird GPS tracking studies on Movebank within Europe, the Mediterranean and North Africa. A literature search undertaken between October 2018 and March 2019 was used to assess whether the species in these GPS tracking studies were susceptible to mortality associated with EI. This literature search is summarised in Supporting Information S1, section 2. We did not request data from tracking studies with less than five individuals unless multiple individuals of the same species were tracked in other Movebank studies. Data managers were contacted between October 2018 and January 2019 to request access to their datasets with a response deadline of the end of April 2019. Studies using ARGOS Doppler tags (insufficient spatial accuracy; Thomson et al., 2017), captive birds, laboratory-based tests of GPS devices, lacking altitude data or tracking predominantly pelagic species were not included. In total, we obtained permission to use data from 65 suitable GPS tracking studies (Figure 1), representing 27 species and 1,454 individual birds. This included some data hosted on the University of Amsterdam Bird-tracking system database (UvA-BiTS, Bouten, 2018), offered for inclusion in this analysis by managers of some of the requested Movebank datasets. To our knowledge, all fieldwork associated with the movement datasets included in this study was undertaken with permission from the relevant licensing authority, further details of each dataset are provided in the Data References section of this paper and Supporting Information 1, section 3. The earliest tag deployment within any of the datasets was 2006, while the latest deployment date is 2018; the mean deployment duration was 2.7 ± 1.8 *SD* years.

Infrastructure and terrain data were processed in QGIS and ArcGIS (ESRI, 2019; QGIS Development Team, 2019). We sourced transmission power line data from the open infrastructure project (Garret, 2018; OpenStreetMap, 2018). OpenStreetMap defines transmission lines as >50 kV (OpenStreetMap, 2019a). Flights between 10 and 60 m aboveground were here taken as being within the danger height for transmission power lines (Figure 2) where birds risk collision (Harker, 2018;

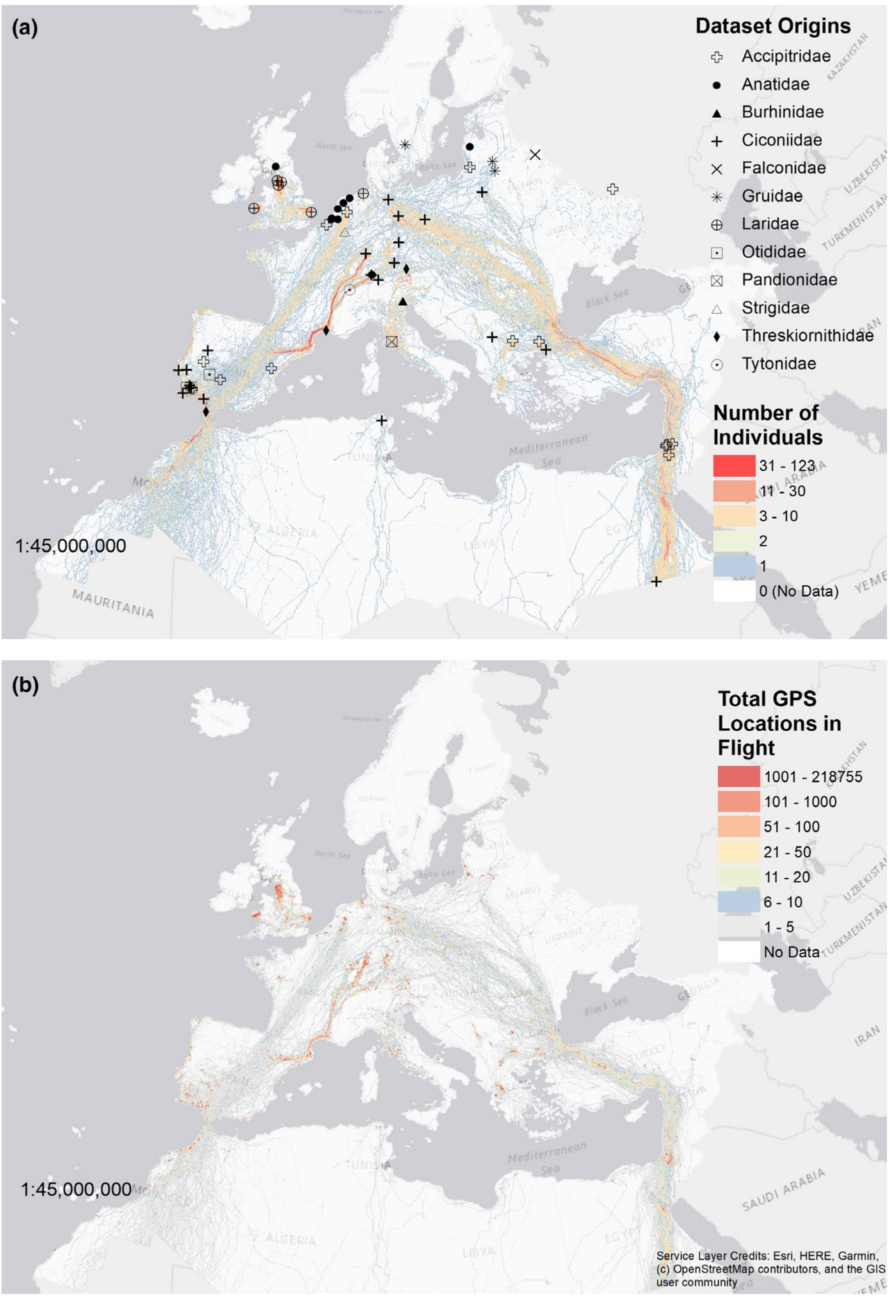

FIGURE 1 (a) The location of the first GPS location of each dataset included in the analysis and the flux of individual birds through each 5 × 5 km grid cell (not controlled for year) for all areas for which we could source GPS tracking data. (b) The density of GPS locations in flight per 5 × 5 km grid cell for all GPS tracking studies included in this study

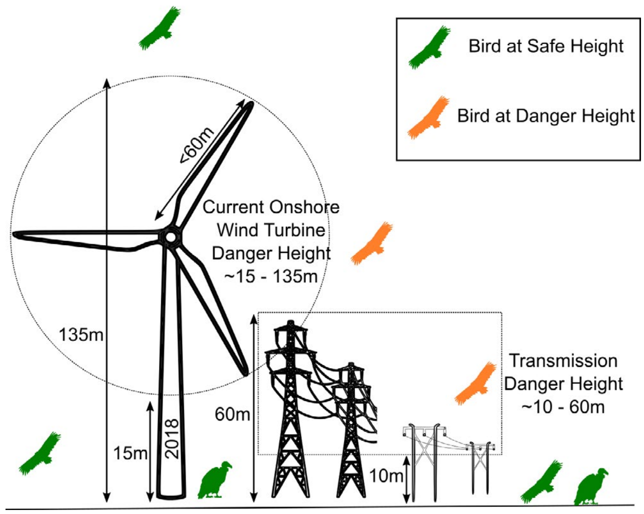

FIGURE 2 Danger height band definitions for energy infrastructure within which birds could be vulnerable to collision. The majority of transmission power lines (66 kV and over) range from 10 to 60 m in height (National Grid, 2014). For current onshore wind turbines, we derive a rotor swept zone ranging from 15 to 135 m above-ground (Pierrot, 2018; Thaxter et al., 2019)

Infante & Peris, 2003). We intersected the data with a fishnet grid consisting of 554,993 individual 5 × 5 km grid cells representing a total area of 13.9 million square kilometres. Power line density is the total length in kilometres per grid cell, normalised onto a 0–100 scale.

Data on the location and size of onshore wind farms were downloaded from windpower.net (Pierrot, 2018). This dataset contained centroid coordinates and information for 18,681 wind farms within Europe and North Africa. We used this to map the relative density of turbines on a 0–100 scale for each 5 × 5 km grid cell. Density was highest towards the North and West of Europe. From the hub heights and blade lengths in this dataset, we derived a danger height (sometimes known as the rotor swept zone) of 15–135 m for wind turbines (Figure 2), further details in Supporting Information S1 section 4. To our knowledge, all tracking datasets used were collected in line with relevant guidance and licensing requirements of national ethical committees.

2.2 | Movement data analysis

Measures of GPS accuracy were not uniformly indicated across all studies. Where the number of satellites was provided, only GPS locations associated with ≥5 visible satellites were included (Morris & Conner, 2017). Duplicate GPS locations were removed. We used the RASTER package (R version 4.0.5, Hijmans, 2019) to append elevation data from two 30 m horizontal and 5 m vertical accuracy digital surface models (DSMs), STRM-GL1 and STRM-GL1-Ellipsoidal from the OpenTopography Portal (National Science Foundation, 2019; NGA and NASA, 2000) to each GPS location. For the small number of GPS locations at latitudes greater than 60° latitude an ALOS 30 m DSM was used instead (JAXA, 2016). Further details of these DSM surfaces are in Supporting Information S1 section 5. Height above-ground in metres was calculated by subtracting the elevation of the ground from the altitude of the bird. Where bird altitude is in height above ellipsoid, ellipsoidal height of the land surface is used. Where altitude is relative to sea level, orthometric height of the land surface is used (Péron et al., 2020). In some datasets, such as some Lesser Black-backed Gull studies, bespoke correction to obtain orthometric height had already been estimated in the database (Thaxter et al., 2019). GPS locations for each study were classified as breeding or non-breeding (including the migratory period) season by plotting week against latitude, (Supporting Information S1 section 6).

Because instantaneous speed was not available across all datasets we estimated speed in metres per second (m/s) using the time and distance between subsequent GPS locations derived with the anytime and GEOSPHERE R packages (Hijmans et al., 2015; Eddelbuettel, 2018). All GPS locations within the 95% confidence interval for heights relative to ground level and greater than 10 m above-ground or associated with speeds greater than or equal to 1.39 m/s (~5 km/hr) were classified as in flight. This approach accounts for the vertical error given by many GPS devices and excludes locations where the bird is likely to be stationary on the ground. The vertical position error associated with GPS tracking devices is typically in the range of 1.5 m but can be as large as 31 m due to the combined error of the GPS device and the DSM surface (Marques et al., 2020). We categorised each flying GPS location as within each danger height band or not (Figure 2).

Some datasets contained bursts of high frequency GPS measurements (up to 1hz). Because the heights recorded in these bursts are not likely to be independent, the data were filtered to remove this potential source of bias by ensuring a minimum of 1 min between subsequent GPS locations resulting in a total sample size of 18.0 million GPS locations. We then summarised the proportion of GPS locations in flight (6.6 million) observed at each danger height within each grid cell for each species in the dataset.

Due to the nature of data obtained from tracking studies, the distribution of studies and individuals was heterogeneous across the study region (Figure 1), hence we considered cells with more tracking data to have more reliable estimates of the proportion of GPS locations in flight (Péron et al., 2017; Silva et al., 2017). We accounted for this at the species level using the Wilson's score (Reichensdörfer et al., 2017) whereby the lower bound of the Wilson confidence interval (WCI), calculated using the binconf function in the HMISC R package (Harrell, 2018), was used in place of the percentage (Lewis & Sauro, 2006; Lott & Reiter, 2020). Compared to a raw proportion, at low sample sizes, this has the effect of reducing the value assigned to grid cells where uncertainty is higher. For example, if a grid cell contained only three GPS locations, the Wilson score (WS) tended towards zero due to the large WCI around the central point estimate of the proportion of GPS locations at danger height, as sample size increased (n > 50) and the WCI converged towards zero, the WS became comparable to a percentage (Cao, 2018). See further information in Supporting Information S1, section 7.

We weighed this proportion of flying GPS locations to account for the collision susceptibility of different species using a morpho-behavioural risk index (MBRI) based on the method utilised in D'Amico et al., 2019 and morphology data provided by Storchová & Hořák, 2018. Wing area and aspect in relation to weight is an important factor in avoidance ability as species with higher wing load are less able to take evasive action (Bevanger, 1998; Janss, 2000; May, 2015). Because wing area values were not available for all species, we simplified the shape of a bird as a rhombus and calculated a simplified area using the wingspan (WS) and body length (BL) in metres using data from Svensson et al., 2016 or Storchová & Hořák, 2018. Comparing this with wing area data available for 17 of the 27 species (Hedenström & Strandberg, 1993) using linear regression ($R^2 = 0.61$, $F_{1,15} = 23.44$, $p < 0.001$) suggests that it is a good proxy for assessing relative differences between species and an improvement on using wingspan alone ($R^2 = 0.46$, $F_{1,15} = 14.38$, $p < 0.001$), further details are provided in Supporting Information S1, section 8. We then estimated a wing load proxy by dividing this area (m^2) by body mass (BM) in kilograms as per Equation 2:

$$\mathrm{WBMR} = \frac{(\mathrm{WS} * \mathrm{BL}) \div 2}{\mathrm{BM}}. \tag{1}$$

We combined this wing–body mass ratio (WBMR) with several other factors scored as either 1 or 2 associated with avoidance ability (D'Amico et al., 2019). These factors include flight style (FS), flapping (1) versus soaring (2) because soaring species are less capable of making sudden changes in trajectory to avoid collision compared to flapping species (May, 2015); whether the species has binocular vision (BV) (1) or peripheral vision (2) (D'Amico et al., 2019; Martin & Shaw, 2010); whether the species is a flocking species (FL) (2) or not (1) and whether the species flies frequently at night (ND) (2) or not (1). This definition of MBRI is the similar to D'Amico et al., 2019 apart from the flight style because D'Amico et al., 2019 use flight style as a proxy for flight height whereas we use flight style to help infer manoeuvrability (May, 2015). To account for the impact of mortality on the population of each species, this MBRI was then combined with European conservation status (Least Concern = 1, Other categories = 2) to produce a morpho-behavioural risk conservation status index (MBRCI) as per Equation 2:

$$\mathrm{MBRCI} = \mathrm{CI} * \frac{(\mathrm{WBMR} * \mathrm{FS} * \mathrm{BV} * \mathrm{FL} * \mathrm{ND})}{5}. \tag{2}$$

MBRCI was then normalised onto a scale between zero and one by calculating the ratio between the MBRCI for each species and the maximum value across all species. MBRCI for each species is detailed in the table in Supporting Information 1, section 8. Sensitivity at the species level for each grid cell was then calculated as the proportion of tracking locations at danger height (quantified by the Wilson Score WS) multiplied by the MBRCI to produce a value between 0 and 1. The final sensitivity across all species is then defined as the maximum sensitivity of any species present in each grid cell. For example, if two species were present and species A was associated with a sensitivity score of 0.2 and species B was associated with a score of 0.4 the sensitivity for species B would be used for that grid cell. Alternative approaches using the raw proportion of flight locations at danger height, the Wilson score proportion or weighting the Wilson score proportion by conservation status did not alter our conclusions significantly and are provided in (Supporting Information 1, section 9).

2.3 | Vulnerability to collision for GPS tracked birds

Vulnerability is a measure of how exposed individuals are to the presence of EI in horizontal and vertical space and how sensitive they are to the collision risks posed by this infrastructure (Thaxter et al., 2019). We calculated vulnerability associated with existing infrastructure, for each grid cell, by multiplying the relative density of each EI type (0–100 scale) by the sensitivity value at the relevant height band for each 5x5km grid cell at the species level resulting in a value between 0 and 100. As per Equation 3:

$$\text{vulnerability} = \text{sensitivity} * \text{EI density}. \tag{3}$$

A score of zero indicates that either no EI is present or sensitivity is zero whereas vulnerability of 100 would require relative density of EI to equal 100 and sensitivity to equal 1. Combined vulnerability is the sum of vulnerability for each height band. The final vulnerability across all species for each infrastructure is then defined as the maximum value of any species present in each grid cell.

2.4 | Defining sensitivity and vulnerability categories

To ensure classification of sensitivity and risk was driven by the data (Gouhier & Pillai, 2020), we defined categories using the 25th, 75th and 97.5th percentiles for all grid cells where the sensitivity (or vulnerability) for a given height band was greater than zero. Grid cells scoring greater than zero but less than the 25th percentile are 'Low', scores between the 25th and 75th percentile are 'Moderate', scores greater than the 75th percentile are 'High' and cells in the top 2.5% of observations are 'Very High'. All other cells are classified as 'Very Low' if there are GPS locations but none at danger height resulting in a score of zero or 'No Data' if data were lacking. We emphasise, therefore, that our method can only identify areas where a high risk of EI exists, but that the absence of a high-vulnerability score in our analysis cannot be interpreted as indicative of low impact of EI due to the potential for other bird or bat populations (for which no data were available in our study) to be affected.

3 | RESULTS

3.1 | Bird sensitivity to wind farm and power line development

We mapped movements of 1,454 individual birds of 27 species (Figure 1). The study species travel across the continent and converge along key migratory routes. As expected, we observed a high flux of individuals through the bottlenecks of the European–African Flyway, such as Southern Iberia, Sinai, the Gulf of Iskenderun and the Bosporus in Turkey. Important gaps existed in the tracking data in North Spain, Scotland, Scandinavia, Italy, Eastern Europe and central North Africa (Figure 1). The median number of individuals tracked per species was 21, the species with the most tracked individuals was the White Stork *Ciconia ciconia* ($n = 491$; Supporting Information S1, section 3).

In total, 99,641 of the 554,993 5x5km grid cells in the study area (18%) contained at least one GPS location in flight. Sensitivity to wind turbines was greater than zero in 54.9% ($n = 54{,}703$) of these grid cells (Figure 3a). 13.57% ($n = 13{,}516$, 337,900 km^2) of these cells were classified as high sensitivity, that is, they were in the upper quartile of sensitivity scores (>0.11). There was significant variability in sensitivity between species (ANOVA $F_{26,59,592} = 432.4$, $p < 0.001$) with Eurasian eagle owl *Bubo bubo*, whooper swan *Cygnus cygnus*, eurasian spoonbill *Platalea leucorodia*, common crane *Grus grus* and white-fronted goose *Anser albifrons* exhibiting the greatest sensitivity to wind turbines across the grid cells where data are available for these species (Table 1). Sensitivity to transmission power lines (10–60 m height band) was greater than zero in 37.64% ($n = 37{,}509$) of grid cells (Figure 3b). Across Europe and North Africa 9.41% ($n = 9375$, 234,375 km^2) of these cells are classified as high sensitivity, that is, they are in the upper quartile of sensitivity scores (>0.14). Eurasian spoonbill *Platalea leucorodia*, European eagle owl *Bubo bubo*, whooper swan *Cygnus cygnus*, Iberian imperial eagle *Aquila adalberti* and white stork *Ciconia ciconia* are the five species which exhibited the greatest sensitivity at the transmission power line danger height band (Table 1).

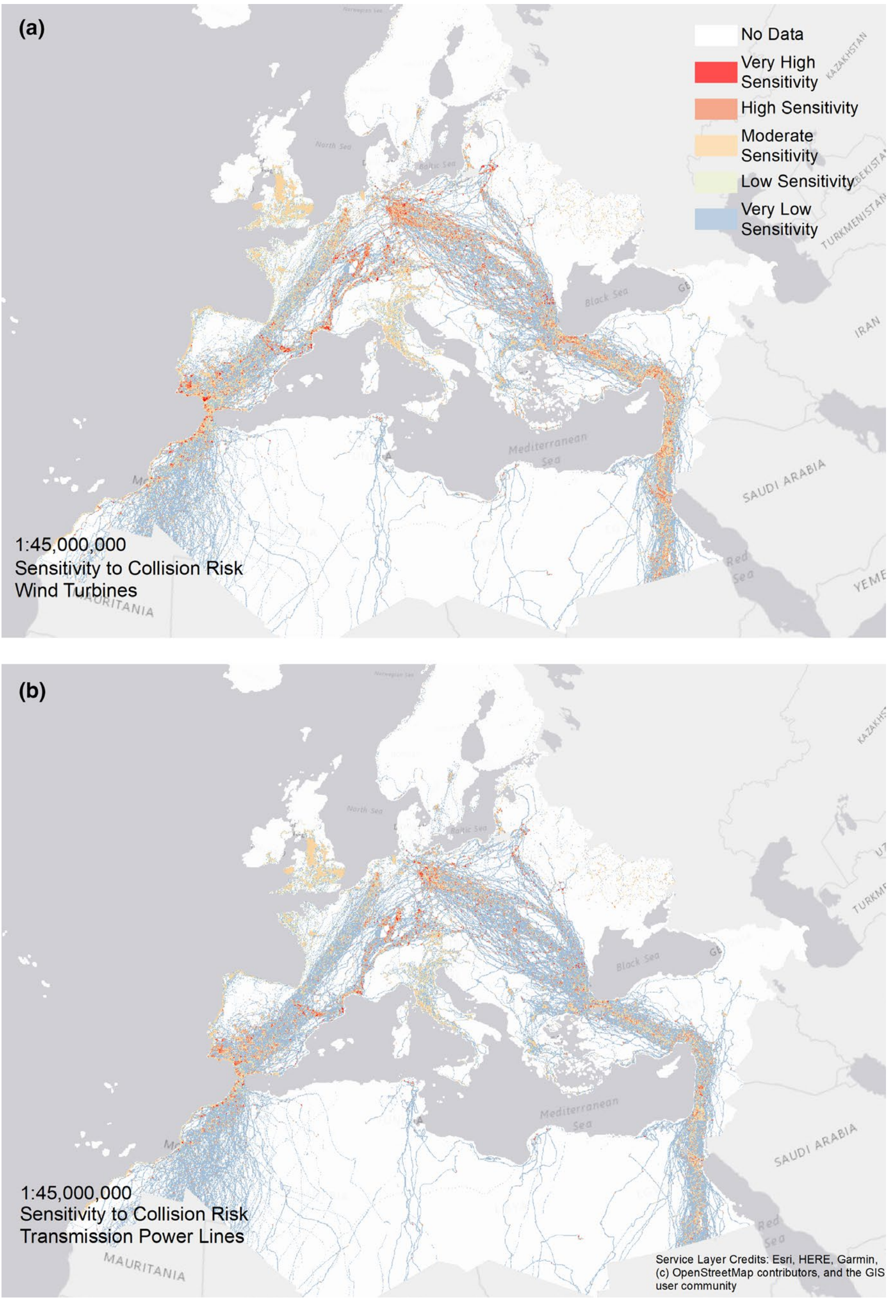

FIGURE 3 (a) Year-round sensitivity to wind turbines across all species ($n = 27$) and areas for which we could obtain suitable GPS tracking data, (b) year-round sensitivity to transmission power lines across all species using GPS tracking data ($n = 27$) and areas for which we could obtain suitable GPS tracking data. Sensitivity at the species level for each grid cell was then calculated as the proportion of tracking locations at danger height (quantified by the Wilson score WS) multiplied by the MBRCI to produce a value between 0 and 1. The final sensitivity across all species is then defined as the maximum sensitivity of any species present in each grid cell. Maps for breeding and non-breeding seasons are provided in Supporting Information 2. Basemap from (OpenStreetMap, 2019b)

TABLE 1 Sensitivity and vulnerability across all seasons and grid cells for which sufficient GPS data were obtained: Summarised by species and infrastructure type, sorted according to species name in alphabetical order. Vulnerability hotspots are defined as the upper quartile of the vulnerability scores obtained separately for vulnerability to collision with wind turbines and power lines. Mean combined vulnerability across all grid cells with sufficient data for that species is also described here

Species	Common name	Number of grid cells where sensitivity > 0 for wind turbines	Number of grid cells where grid cells sensitivity > 0 for power lines	Number of high-vulnerability grid cells (vulnerability hotspots) associated with wind turbines	Number of high-vulnerability grid cells (vulnerability hotspots) associated with power lines	Mean combined vulnerability $\pm$ *SD*
Anas platyrhynchos	Mallard	176	132	0	5	0.22 ± 0.28
Anser albifrons	White-fronted goose	20	27	0	5	0.74 ± 0.85
Aquila adalberti	Iberian imperial eagle	1,734	1,530	9	270	0.83 ± 1.05
Branta leucopsis	Barnacle goose	291	208	1	4	0.12 ± 0.29
Bubo bubo	Eurasian eagle owl	10	11	0	6	1.44 ± 1.32
Burhinus oedicnemus	Eurasian stone curlew	11	12	0	0	0.21 ± 0.26
Buteo lagopus	Rough-legged buzzard	815	766	0	88	0.49 ± 0.72
Buteo rufinus	Long-legged buzzard	455	296	0	8	0.23 ± 0.35
Ciconia ciconia	White stork	27,401	17,772	323	5,361	2.14 ± 3.62
Ciconia nigra	Black stork	226	136	1	11	0.37 ± 0.9
Circaetus gallicus	Short-toed snake eagle	553	285	0	0	0.20 ± 0.25
Circus aeruginosus	Western marsh harrier	1,063	780	0	1	0.10 ± 0.147
Circus pygargus	Montagu's harrier	555	303	0	0	0.04 ± 0.08
Clanga clanga × pomarina	Hybrid spotted eagle	2,711	1,425	17	127	0.43 ± 0.68
Cygnus cygnus	Whooper swan	90	97	3	29	1.63 ± 1.98
Falco peregrinus	Peregrine falcon	347	300	0	0	0.09 ± 0.15
Geronticus eremita	Northern bald ibis	3,830	2,695	7	217	0.34 ± 0.57
Grus grus	Common crane	2,794	1,482	85	362	1.30 ± 2.56
Gyps fulvus	Griffon vulture	2,019	1,407	3	71	0.38 ± 0.63
Larus fuscus	Lesser black-backed gull	7,227	5,955	26	122	0.22 ± 0.31
Mareca penelope	Eurasian wigeon	276	232	0	0	0.09 ± 0.11
Neophron percnopterus	Egyptian vulture	792	477	4	81	1.01 ± 1.36
Pandion haliaetus	Osprey	524	325	0	48	0.59 ± 0.99
Pernis apivorus	European honey buzzard	5,384	2,966	53	440	0.62 ± 1.016
Platalea leucorodia	Eurasian spoonbill	19	19	0	5	1.02 ± 1.12
Tetrax tetrax	Little bustard	256	259	0	60	0.78 ± 0.73
Tyto alba	Barn owl	40	41	0	0	0.052 ± 0.04

Sensitivity was determined separately for breeding and non-breeding seasons (Supporting Information 2 section 1). Although the proportions are similar between seasons, during the breeding season we observed fewer overall high sensitivity grid cells at danger height than during the non-breeding season (Supporting Information 2 section 1). This clustered pattern is a product of sampling effort and is also indicative of the smaller scale movements of the tagged birds during the breeding season, which are centred on breeding locations. In the non-breeding season, birds move away from their breeding areas and we observe high sensitivity along coastlines and within major migratory routes. Notable sensitivity hotspots include the Western Mediterranean coast of France and Southern Spain, Eastern Romania, the Moroccan Coast, the Sinai Peninsula and the Baltic coast of Germany. Taxon specific maps of sensitivity are provided in Supporting Information S2 section 2, these can be used to compare with previous studies (see discussion) and highlight taxon specific gaps in the tracking data available on Movebank. For some taxa such as cranes, as represented by common crane *Grus grus* in our dataset, this highlights how individuals may travel long distances at altitudes where they are unlikely to collide with EI resulting in highly localised sensitivity hotspots.

3.2 | Vulnerability of tracked birds to energy infrastructure risks

We plotted the combined vulnerability score as the sum of vulnerability from wind turbines and power lines present in each grid cell (Figure 4a). The tagged birds experience some degree of vulnerability

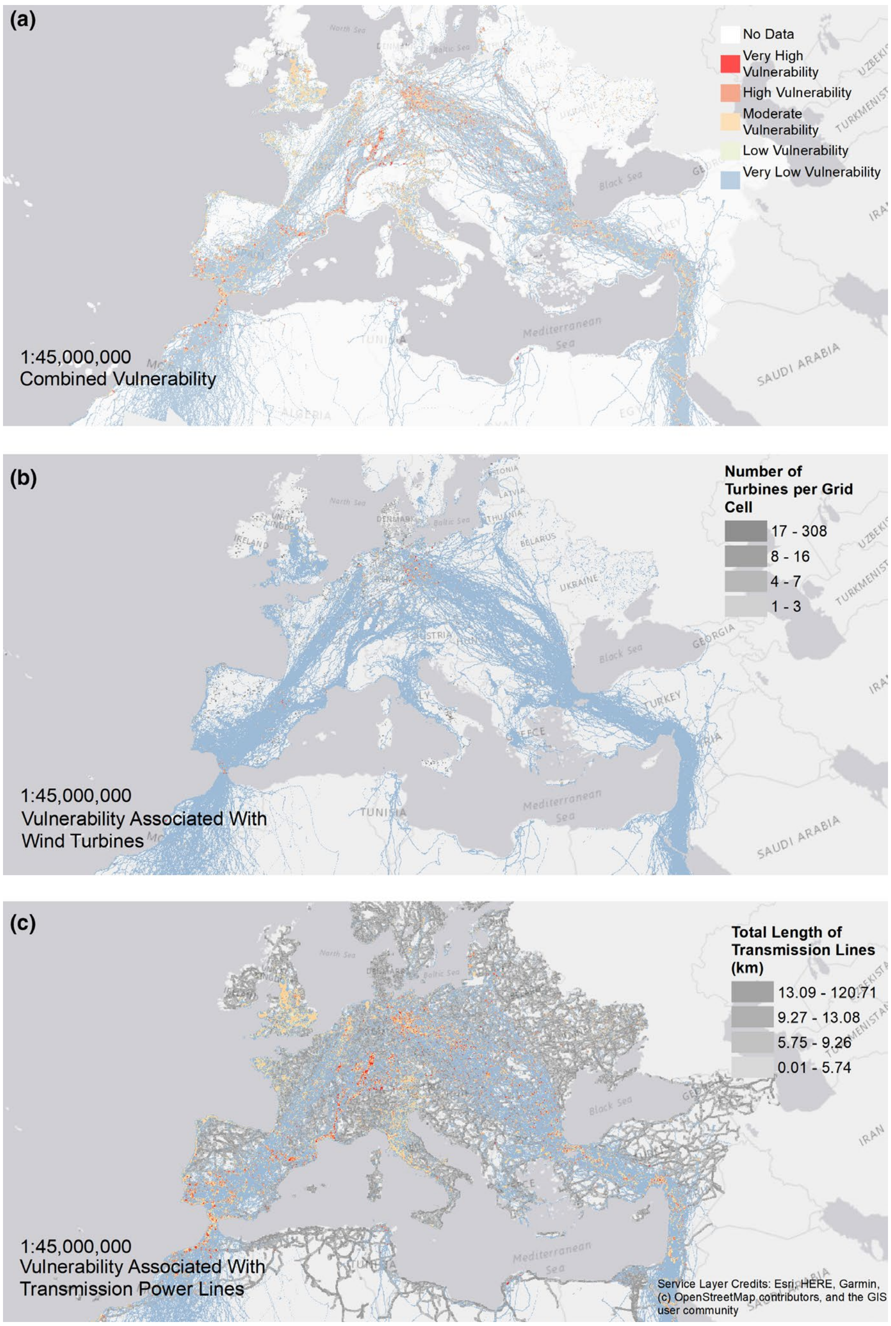

FIGURE 4 (a) Vulnerability hotspots for wind farms where the GPS tracked birds ($N = 1,454$) are most likely to interact with wind turbines at danger height, white grid cells represent areas currently lacking sufficient GPS tracking data to assess vulnerability. (b) Hotspots where the GPS tracked birds ($N = 1,454$) are most vulnerable to risks associated with transmission power lines. Grey grid cells in panels b and c represent the density of EI in grid cells for which we do not have sufficient tracking data and as such represent areas of unknown vulnerability. Vulnerability categories are symbolised as per the legend in panel a. Basemap from (OpenStreetMap, 2019b) in 28.2% ($n = 28,051$) of the grid cells with at least one GPS location in flight. 7.0% of these grid cells (n = 7,013) are high-vulnerability with values in the upper quartile of vulnerability scores (>1.13) and 1.7% (n = 702) are very high-vulnerability as they fall in the upper 2.5 percentile (>9.03). Fewer high-vulnerability grid cells are associated with wind turbines (n = 483, Figure 4b) compared with transmission lines (n = 6,861, Figure 5c). This suggests that transmission power lines are currently a more ubiquitous source of potential collision risks than wind turbines.

High-vulnerability areas were not distributed evenly across the study area (Figure 4a): just five countries (Germany, Spain, France, Turkey and Poland) accounted for 50.5% (n = 3,539) of the high-vulnerability grid cells. Measuring this relative to the percentage area of each country, the five countries with the most high-vulnerability grid cells were Liechtenstein (14.2%, n = 1), Germany (7.2%, n = 1,028), Israel (5.8%, n = 48), Lebanon (5.4%, n = 22) and Portugal (5.0%, n = 176; Supporting Information S2, Section 3). However, it must be noted that this ranking will at least be partly influenced by the distribution of available tracking data. In the case of Turkey, Spain, Israel, Lebanon and Portugal, this indicated high densities of EI within important migratory bottlenecks where there is high flux of tracked birds at danger heights. On the other hand, for Central Europe, this high-vulnerability is likely associated with the high density of wind turbines. Germany alone accounted for 55.2% (n = 267) of the 483 grid cells associated with a high-vulnerability from wind turbines (Figure 4b). There were marked differences in vulnerability between species, with mean combined vulnerability ranging from 0.042 ± 0.081 SD for western marsh harrier *Circus pygargus* to 2.14 ± 3.62 *SD* for white stork (Table 1).

4 | DISCUSSION

For areas with sufficient tracking data (currently 18% of the study area), our sensitivity surface identifies sensitivity hotspots associated with different height bands for wind turbines and transmission power lines (Figure 3). These are the areas where the tracked individuals are most sensitive to collision with EI. While not replacing the need for environmental impact assessment at more local and site-specific scales of relevance to local bird populations, our analysis successfully identified, areas where wind turbine and transmission powerline development should be minimised to protect the integrity of the flyway. As expected, many of these areas coincide with key migratory bottlenecks, such as the coasts of either side of the Strait of Gibraltar (Martín et al., 2018), the Bosporus Strait, Gulf of Iskenderun and the southern Sinai Peninsula (Buechley et al., 2018). This supports the idea that further development of EI within these migratory bottlenecks where species fly at danger height is likely to exacerbate existing anthropogenic mortality risks. Rigorous ecological impact assessment, spatial planning and mitigation at the local scales are needed within these bottleneck areas, as highlighted in other studies (De Pascalis et al., 2020; Martín et al., 2018). Comparing our results for the Laridae species included in our analysis (lesser black-backed gull *Larus fuscus*) with previous work by Thaxter et al., 2019, which differed in methodology but utilised many of the same *L. fuscus* datasets, reveals similar patterns in sensitivity across the region for this species, supporting the validity of our approach (Supplementary information S2, section 2).

Our results also highlighted differences in sensitivity to EI between species and which type of EI poses the most risk to each species (Table 1). It is beyond the scope of this study to provide specific ecological explanations for this observed variation as this is an ongoing topic of research in of itself, however, this is likely a product of ecological and morphological factors such as flight style (flapping vs. soaring), migratory behaviour, habitat preference and how foraging strategy influences flight heights relative to the danger height bands (Bernardino et al., 2018a; Martin & Shaw, 2010; Thaxter et al., 2017).

Despite efforts to obtain as complete coverage of the study region as possible, we acknowledge gaps were present in the available GPS tracking data, particularly within areas such as northern France, northern Spain, Scandinavia, Algeria and Libya. These gaps reflect geographical and seasonal variation in the availability of bird telemetry data (Bouten et al., 2013). As such, our results successfully highlight where sensitivity and vulnerability to collision with EI occurs, but cannot indicate where vulnerability does not occur. Our sample includes only a subset of the most susceptible species, most of which are larger birds with a body mass of 350 g or more, and only a subset of populations of these species, leading to sampling-related bias which is most evident during the breeding season (Supporting Information 2, section 4). These sampling-related biases are a common issue in ecology, and collision risk cannot be inferred for areas where information is not available (Brotons et al., 2004). Despite these limitations, the approach used, based on existing tracking data, accounting for species susceptibility to collision and the proportion of GPS records at danger height, provides a simple way to assess risk in the areas where data are available. As more tracking data become available, this analysis can be updated using the code provided in supplementary material 3 and data from (Movebank, 2019). This study highlights the benefits of data sharing and we expect data availability to increase significantly in the near future as GPS telemetry becomes more affordable and miniaturisation enables tracking devices to be fitted to smaller bird species (Bouten et al., 2013). Advances in sensor technology may also soon allow collision mortality to be detected in real-time (O'Donoghue & Rutz, 2016). One priority to aid future research is to help fill these gaps by improving data sharing via platforms such as Movebank or UvA-BiTS, promotion of new bird tracking studies in under-represented areas and taxonomic groups, improved standardisation of biologging datasets and deployment of loggers outwith the breeding season (Sequeira et al., 2021). Other methods to address these data gaps may include the use of GPS data to model the relationship between flight heights and spatio-temporal factors such as weather, time of year, topography and land cover. However, such an analysis is beyond the scope of this paper.

Overlaying sensitivity with the existing wind farms and transmission lines identified a number of vulnerability hotspots where the tracked birds are vulnerable to collision with EI (Figure 4). While it is beyond the scope of this paper to evaluate the effectiveness of different mitigation options, we suggest that for areas with sufficient GPS tracking data, the vulnerability map can help identify priority areas for mitigation of impacts of EI, to reduce risks to birds. For existing power lines this could include line marking to increase visibility, burying cables or altering routes to avoid high sensitivity areas (Jenkis et al., 2010). For wind turbines, options include repowering with fewer larger turbines (Arnett & May, 2016), marking blades (May et al., 2020), temporary shutdown periods during the peak of the migratory season (de Lucas et al., 2012) which is already a requirement in some countries such as Jordan (Tomé et al., 2017). Another option is to retrofit radar or camera-based systems to monitor bird movements and automatically shut down turbines during periods of high migratory movement (McClure et al., 2018). Future analyses could be improved if official, multi-country, energy network spatial datasets were composed and made available to researchers. This would enable consideration of lower voltage distribution power lines which are under-represented in open-source data and are associated with electrocution, which was not considered in this study, as a major cause of injury and mortality (Garret, 2018; Hernández-Lambraño et al., 2018). In a European study with Northern Bald Ibises 45% of the losses were caused by electrocution (Fritz et al., 2019). As with collision, there are several options such as retrofitting insulators or perches to reduce electrocution risk (Dixon et al., 2019), but the problem could be entirely avoided by constructing safe poles that eliminate electrocution risk in the first place (AEWA, 2012).

5 | IMPLICATIONS FOR MANAGEMENT AND CONSERVATION

To our knowledge, this is the first time that an assessment of this kind has been undertaken at the flyway scale across multiple species. Our methodology provides a readily transferable approach to assess sensitivity and vulnerability for other species and areas as more GPS tracking data become available. The results presented here do not preclude the need for detailed local environmental impact assessment of the potential ecological impacts of EI on birds and other wildlife combined with post-construction monitoring to assess the risks due to disturbance, habitat loss, electrocution as well as collision which was the focus of this paper (Bernardino et al., ; Gove et al., 2013). However, for areas with sufficient GPS tracking data, our sensitivity maps can inform where new wind farms and power lines should not be constructed and help include consideration of these impacts early in the site selection process for developments. Moreover, the vulnerability maps can help more effectively target areas for surveys to identify specific locations where mitigation of existing wind farms and power lines should be implemented. In our race to tackle the climate crisis, it is vital that we do not neglect the biodiversity crisis (Vasilakis et al., 2016), sensitivity and vulnerability maps derived from GPS tracking data will be an important tool to help protect wildlife as our energy system transitions to zero carbon.

ACKNOWLEDGEMENTS

We thank all those who have granted us permission to use the data in our analysis and those who assisted in data collection. A full summary of datasets used in the analysis is available in Supporting Information S1, section 3. We are very grateful to all the people who helped to collect these data in the field. Many thanks to: Carlos Carrapato, Instituto da Conservação da Natureza e das Florestas, Lisbon, Portugal, for permitting the use of Iberian Imperial Eagle data. Movebank study 28407489. Peter Desmet (ORCID 0000-0002-8442-8025), Research Institute for Nature and Forest (INBO), Brussels, Belgium, for granting permission to use the Western Marsh Harrier dataset (Anselin et al., 2019). Vladimir Dobrev, Bulgarian Society for the Protection of Birds (BirdLife Bulgaria), Sofia, Bulgaria, for his assistance with the Neophron percnopterus Bulgaria/Greece Egyptian vulture dataset. Movebank Study ID 15869951. Steffen Hollerbach, Storkenkate Preten (The Stork Foundation), Preten/Amt Neuhaus, Germany, for granting permission to use the Ciconia ciconia Sudewiesen dataset. Movebank study ID 4502577. Elzbieta Kret, WWF Greece, Athens, Greece, for her assistance with the Neophron percnopterus Bulgaria/Greece Egyptian vulture dataset. Movebank Study ID 15869951. Jose Manuel Lopez Vazquez, Ministry of the Environment, Junta de Andalucía, Sevilla, Spain, for granting permission to use the Proyecto Eremita Geronticus eremita Reintroduction in Andalusia (Spain) dataset. Movebank study ID 463673774. Carlos Pacheco for his assistance with the White Stork tracking project in Portugal. Emmanuel Pixner, Waldrappteam, Research and Technology Centre (FTZ), Mutters, Austria for use of the Bald Ibis Waldrappteam dataset. https://doi.org/10.1111/izy.12163. Shay Rotics, Department of Ecology, Evolution and Behaviour, The Hebrew University of Jerusalem, Jerusalem, Israel, for the use of the Eastern flyway spring migration of adult white storks (data from Rotics et al., 2018) dataset. Movebank study ID 560041066. Robin Séchaud, Department of Ecology and Evolution, Universite de Lausanne, Lausanne, Switzerland, for use of the Barn owl *Tyto alba* dataset. Movebank study ID 2001600. Carlos Pacheco and Luís Venâncio for their invaluable help on the 'Black Storks Portugal' project. We also acknowledge: Support and training provided by the NEXUSS CDT. The protected areas of Tuscan Archipelago National Park, Maremma Regional Park, Diaccia Botrona Nature Reserve, WWF Orbetello Lagoon and Orti-Bottagone Nature Reserve in Italy and the rest of the 'Progetto Falco pescatore' team, for their invaluable support in fieldwork activities related to monitoring of Ospreys in Italy. BTO Lesser Black-backed Gull tracking studies were undertaken in collaboration with the University of Amsterdam; data from these studies are held jointly by the BTO, University of Amsterdam and the funders of the project, and can be made available through their agreement. The UvA-BiTS tracking studies are facilitated by infrastructures for e-Science, developed with support of the NLeSC (http://www.esciencecenter.com/) and LifeWatch, carried out on the Dutch national e-infrastructure with support from the SURF Foundation. Barnacle Geese and Honey Buzzards were tracked using UvA-BiTS, facilitated by infrastructures for E-Science, developed with the support of the Netherlands eScience Center (NLeSC) and

LifeWatch, and conducted on the Dutch National e-Infrastructure with support from the SURFfoundation. Jethro G. Gauld receives funding from NERC as part of the NEXUSS CDT (UKRI) including a capital grant to support the ongoing development and deployment of new GPS tracking devices; 'Rough-legged buzzard' and 'Peregrine falcon projects were funded by the Max-Planck Institute of Animal Behaviour, and the German Air and Space Administration (DLR). The GPS data of the Barents Sea flyway geese were provided by FlySafe (https://www.flysafe-birdtam.eu/), a project initiated by the Integrated Applications Promotion (IAP) Programme of the European Space Agency. It was carried out as cooperation between the Institute of Avian Research, the Dutch Centre of Field Ornithology (SOVON) and the University of Amsterdam. Tracking of Lesser Black-backed Gulls in northern Germany was partly funded by the Niedersächsische Wattenmeerstiftung (NWS 04/09); Tracking Northern Bald Ibises was funded in the frame of the LIFE+ project 'Reason for Hope' (LIFE+12-BIO_AT_000143). BTO studies on Lesser Black-backed Gulls were supported by the UK Department for Business, Energy and Industrial Strategy (BEIS) Offshore Energy Strategic Environmental Assessment (OESEA) research programme, the Marine Renewable Energy and the Environment (MaREE) project (funded by Highlands and Islands Enterprise, the European Regional Development Fund, and the Scottish Funding Council), BAE Systems and Natural England. White stork tracking of the Portuguese population was financed by the FEDER Funds through the Operational Competitiveness Factors Program — COMPETE and by National Funds through FCT – Foundation for Science and Technology within the scope of the project 'POCI-01-0145-FEDER-028176', by InBIO (UID/BIA/50027/2013 and POCI-01-0145-FEDER-006821) and FCT/MCTES. The Portuguese white stork tracking was also financed by the NERC Env-East DPT, NERC NEXUSS CDT (grant number NE/N012070/1), the British Ornithologists Union Small Research Grant, Norwich Research Park Translational Fund, University of East Anglia Innovation Funds and Earth and Life Systems Alliance funds. Black stork tracking of the Portuguese population was financed by NERC, via the NEXUSS CDT (grant number NE/N012070/1) and Microwave Telemetry 'Christiane Howey Rising Scholar Award'. The Osprey GPS tracking work in Italy was financially supported by the Tuscan Archipelago National Park (Italy). R.N. acknowledges support from grants BSF 255/2008, DIP-DFG NA 846/1-1, and the Minerva Center for Movement Ecology. Some of the tracking studies were supported by the LIFE projects 'The Return of the Neophron' (LIFE10 NAT/BG/000152) and 'Egyptian Vulture New LIFE' (LIFE16 NAT/BG/000874, www.LifeNeophron.eu) funded by the European Union and co-funded by the A. G. A.G. Leventis Foundation. Vulture tracking in the Balkans is implemented and financed also by LIFE projects 'Recovery of the Populations of Large European Vultures in Bulgaria' (LIFE08 NAT/BG/000278), 'Vultures back to LIFE - Bright Future for Black Vulture in Bulgaria' (LIFE14 NAT/BG/000649) funded by the European Union and project 'Saving the Balkans' last vultures: introducing Vulture Safe Areas as a model for scavenger conservation in the Anthropocene' funded by Whitley Fund for Nature. The Barnacle Geese project was funded by an NWO (Netherlands Organisation for Scientific Research) polar program grant (NPP 866.13.010). Data collection of studies at the Max Planck Institute of Animal Behaviour was done under the ICARUS directive funded by the German Aerospace Centre (DLR). The Eurasian Wigeon data were funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 727922 (Delta-Flu).

CONFLICT OF INTEREST

All authors declare that they have no conflict of interest with the content of this work.

AUTHORS' CONTRIBUTIONS

J.G.G. is the principal author of the work; A.M.A.F. suggested the initial idea for the paper and provided advice throughout the analysis and writing stages of the work along with P.W.A., J.P.S. and P.R.; All authors contributed critically to data collection, drafting the manuscript and gave final approval. Efforts were made to foster collaboration with individuals from across the entire study region. Our study brought together authors and dataset managers from across Europe and the Middle East; however, there is a lack of representation of authors from African Nations. While this is in part a by-product of the current distribution of available GPS bird telemetry datasets it does highlight a need for greater collaboration and engagement with researchers from across the afro-palaearctic flyways.

DATA AVAILABILITY STATEMENT

The raw bird tracking datasets associated with this analysis are available for download on request via https://www.movebank.org/cms/movebank-main (Movebank, 2019), many of these datasets relate to sensitive or protected species and therefore permission from the managers of these datasets may be required prior to download. The processed datasets used to produce the sensitivity and vulnerability maps in this paper, including shapefiles of the final sensitivity surfaces and the density of energy infrastructure, are available via the Dryad Digital Repository: https://doi.org/10.5061/dryad.jm63xsjcw (Gauld et al., 2022).

ORCID

Jethro G. Gauld https://orcid.org/0000-0001-9266-1372
Marta Acácio https://orcid.org/0000-0002-9947-1181
Philip W. Atkinson https://orcid.org/0000-0002-0838-557X
Volen Arkumarev https://orcid.org/0000-0003-1146-5594
Willem Bouten https://orcid.org/0000-0002-5250-8872
Niall Burton https://orcid.org/0000-0001-9675-1834
Jocelyn Champagnon https://orcid.org/0000-0003-4850-8033
Gary D. Clewley https://orcid.org/0000-0002-6068-2221
Mindaugas Dagys https://orcid.org/0000-0001-9342-3464
Klaus-Michael Exo https://orcid.org/0000-0001-9140-1835
Andrea Flack https://orcid.org/0000-0002-9099-2802
Guilad Friedemann https://orcid.org/0000-0003-0715-3272
Johannes Fritz https://orcid.org/0000-0003-4691-2892
Clara Garcia-Ripolles https://orcid.org/0000-0003-3615-6501
Atanas Grozdanov https://orcid.org/0000-0002-3360-2468

Roi Harel https://orcid.org/0000-0002-9733-8643
Elizabeth M. Humphreys https://orcid.org/0000-0002-2570-400X
Andrea Kölzsch https://orcid.org/0000-0003-0193-1563
Olga Kulikova https://orcid.org/0000-0002-4029-9452
Thomas K. Lameris https://orcid.org/0000-0001-7023-3406
Pascual López-López https://orcid.org/0000-0001-5269-652X
Elizabeth A. Masden https://orcid.org/0000-0002-1995-3712
Flavio Monti https://orcid.org/0000-0001-8835-1021
Steffen Oppel https://orcid.org/0000-0002-8220-3789
Hristo Peshev https://orcid.org/0000-0001-8925-053X
Louis Phipps https://orcid.org/0000-0003-0400-2014
Ivan Pokrovsky https://orcid.org/0000-0002-6533-674X
Emilian Stoynov https://orcid.org/0000-0002-5201-8996
Chris Thaxter https://orcid.org/0000-0003-0341-4199
Wouter Van Steelant https://orcid.org/0000-0002-9447-8587
Jonas Waldenström https://orcid.org/0000-0002-1152-4235
Aldina M. A. Franco https://orcid.org/0000-0001-6055-7378

REFERENCES

2009/147/EC, C. D. (2010). Directive 2009/147/EC of the European Parliament and of the council on the conservation of wild birds. *Official Journal of the European Union*, *20*, 7–25. https://doi.org/10.1126/science.aah3404

AEWA. (2012). *Guidelines on how to avoid or mitigate impact of electricity power grids on migratory birds in the African-Eurasian region*. United Nations Environment Programme.

Anselin, A., Desmet, P., Milotic, T., Janssens, K., T'Jollyn, F., De Bruyn, L., & Bouten, W. (2019). MH_WATERLAND – Western marsh harriers (*Circus aeruginosus*, Accipitridae) breeding near the Belgium–Netherlands border. *Zenodo*. https://doi.org/10.5281/zenodo.3826591

Arnett, E., & May, R. (2016). Mitigating wind energy impacts on wildlife: Approaches for multiple taxa. *Human-Wildlife Interactions*, *10*(1), 28–41. https://doi.org/10.26077/1jeg-7r13

Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J. F., Marques, A. T., Martins, R. C., Shaw, J. M., Silva, J. P., & Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, *222*, 1–13. https://doi.org/10.1016/j.biocon.2018.02.029

Bevanger, K. (1998). Biological and conservation aspects of bird mortality caused by electricity power lines: A review. *Biological Conservation*, *86*(1), 67–76. https://doi.org/10.1016/s0006-3207(97)00176-6

BirdLife International. (2015). *Migratory soaring birds project: Soaring bird sensitivity map*. Retrieved from http://migratorysoaringbirds.undp.birdlife.org/en/sensitivity-map

Bouten, W. (2018). *UvA-BiTS bird tracking system*. University of Amsterdam. Retrieved from http://www.uva-bits.nl/

Bouten, W., Baaij, E. W., Shamoun-Baranes, J., & Camphuysen, K. C. J. (2013). A flexible GPS tracking system for studying bird behaviour at multiple scales. *Journal of Ornithology*, *154*(2), 571–580. https://doi.org/10.1007/s10336-012-0908-1

Bradbury, G., Trinder, M., Furness, B., Banks, A. N., Caldow, R. W. G., & Hume, D. (2014). Mapping seabird sensitivity to offshore wind farms. *PLoS ONE*, *9*(9), e106366. https://doi.org/10.1371/journal.pone.0106366

Bright, J., Langston, R., Bullman, R., Evans, R., Gardner, S., & Pearce-Higgins, J. (2008). Map of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. *Biological Conservation*, *141*(9), 2342–2356. https://doi.org/10.1016/j.biocon.2008.06.029

Brotons, L., Thuiller, W., Araújo, M. B., & Hirzel, A. H. (2004). Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. *Ecography*, *27*(4), 437–448. https://doi.org/10.1111/j.0906-7590.2004.03764.x

Buechley, E. R., Oppel, S., Beatty, W. S., Nikolov, S. C., Dobrev, V., Arkumarev, V., Saravia, V., Bougain, C., Bounas, A., Kret, E., Skartsi, T., Aktay, L., Aghababyan, K., Frehner, E., & Şekercioğlu, Ç. H. (2018). Identifying critical migratory bottlenecks and high-use areas for an endangered migratory soaring bird across three continents. *Journal of Avian Biology*, *49*(7), e01629. https://doi.org/10.1111/jav.01629

Cao, X. (2018). *Improved online Wilson score interval method for community answer quality ranking*, (April), pp. 1–8.

Cleasby, I. R., Wakefield, E. D., Bearhop, S., Bodey, T. W., Votier, S. C., & Hamer, K. C. (2015). Three-dimensional tracking of a wide-ranging marine predator: Flight heights and vulnerability to offshore wind farms. *Journal of Applied Ecology*, *52*(6), 1474–1482. https://doi.org/10.1111/1365-2664.12529

D'Amico, M., Martins, R. C., Álvarez-Martínez, J. M., Porto, M., Barrientos, R., & Moreira, F. (2019). Bird collisions with power lines: Prioritizing species and areas by estimating potential population-level impacts. *Diversity and Distributions*, *25*, 975–982. https://doi.org/10.1111/ddi.12903

de Lucas, M., Ferrer, M., Bechard, M. J., & Muñoz, A. R. (2012). Griffon vulture mortality at wind farms in southern Spain: Distribution of fatalities and active mitigation measures. *Biological Conservation*, *147*(1), 184–189. https://doi.org/10.1016/j.biocon.2011.12.029

De Pascalis, F., Panuccio, M., Bacaro, G., & Monti, F. (2020). Shift in proximate causes of mortality for six large migratory raptors over a century. *Biological Conservation*, *251*, 108793. https://doi.org/10.1016/j.biocon.2020.108793

Dixon, A., Rahman, M. D. L., Galtbalt, B., Bold, B., Davaasuren, B., Batbayar, N., & Sugarsaikhan, B. (2019). Mitigation techniques to reduce avian electrocution rates. *Wildlife Society Bulletin*, *43*(3), 476–483. https://doi.org/10.1002/wsb.990

Eddelbuettel, D. (2018). *Anytime: An R package for working with "POSIXct" (or 'Date') objects*. Retrieved from http://dirk.eddelbuettel.com/code/anytime.html

Eichhorn, M., Tafarte, P., & Thrän, D. (2017). Towards energy landscapes – "Pathfinder for sustainable wind power locations". *Energy*, *134*, 611–621. https://doi.org/10.1016/j.energy.2017.05.053

ESRI. (2019). *ArcGIS release 10.6.1*. Environmental Systems Research Institute.

Fritz, J., Unsoeld, M., & Voelkl, B. (2019). Back into European wildlife: The reintroduction of the northern bald ibis (*Geronticus eremita*). In A. B. Kaufman, M. Bashaw, & T. Maple (Eds.) *Scientific foundations of zoos and aquariums: Their role in conservation and research*. Cambridge University Press; ISBN 978-1-316-64865-0. https://doi.org/10.1017/9781108183147.014

Garret, R. (2018). *The open source infrastructure project*, *OpenInfra*. Retrieved from https://openinframap.org

Gauld, J., Silva, J. P., Atkinson, P. W., Record, P., Acácio, M., Arkumarev, V., Blas, J., Bouten, W., Burton, N., Catry, I., Champagnon, J., Clewley, G., Dagys, M., Duriez, O., Exo, K. M., Fiedler, W., Flack, A., Friedemann, G., Fritz, J., … Franco, A. M. A. (2022). *Data from: Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa*. Dryad Digital Repository, https://doi.org/10.5061/dryad.jm63xsjcw

Gouhier, T. C., & Pillai, P. (2020). Avoiding conceptual and mathematical pitfalls when developing indices to inform conservation. *Frontiers in Ecology and Evolution*, *8*(September), 1–5. https://doi.org/10.3389/fevo.2020.00263

Gove, B., Langston, R., McCluskie, A., Pullan, J., & Scrase, I. (2013). *Wind farms and birds: An updated analysis of the effects of wind farms on* *bird, and best practice guidance on integrated planning and impact assessement TPVS/inf*. Council of Europe.

Gyimesi, A., & Prinsen, H. A. M. (2015). Guidance on appropriate means of impact assessment of electricity power grids on migratory soaring birds in the Rift Valley/red sea flyway - final report', p. 56.

Harker, K. (2018). 'Overhead line design', *high voltage power network construction*, 123–150. https://doi.org/10.1049/pbpo110e_ch6

Harrell, F. E. Jr. (2018). Hmisc: Harrell miscellaneous (Version 4.1-1). Cran. http://CRAN.R-project.org/package=Hmisc

Hedenström, D., & Strandberg, A. (1993). Protocol S1 supplementary list of flight speeds and biometry of bird species. *Pennycuick Greenewalt Hedenström*, *135*(1), 1–4.

Hernández-Lambraño, R. E., Sánchez-Agudo, J. Á., & Carbonell, R. (2018). Where to start? Development of a spatial tool to prioritise retrofitting of power line poles that are dangerous to raptors. *Journal of Applied Ecology*, *55*(6), 2685–2697. https://doi.org/10.1111/1365-2664.13200

Hijmans, R. J. (2019). *Raster: An R package for working with raster data*. Retrieved from https://www.rspatial.org/

Hijmans, R. J., Williams, E., & Vennes, C. (2015). CRAN. R-project. *Geosphere: Spherical trigonometry*. Retrieved from https://CRAN.R-project.org/package=geosphere

Horns, J. J., & Şekercioğlu, Ç. H. (2018). Conservation of migratory species. *Current Biology*, *28*(17), R980–R983. https://doi.org/10.1016/j.cub.2018.06.032

Infante, O., & Peris, S. (2003). Bird nesting on electric power supports in northwestern Spain. *Ecological Engineering*, *20*(4), 321–326. https://doi.org/10.1016/S0925-8574(03)00013-2

IPCC. (2018). IPCC special report on the impacts of global warming of 1.5 °C - Summary for policy makers. http://www.ipcc.ch/report/sr15/

Janss, G. F. E. (2000). Avian mortality from power lines: A morphologic approach of a species-specific mortality. *Biological Conservation*, *95*(3), 353–359. https://doi.org/10.1016/S0006-3207(00)00021-5

JAXA. (2016). *ALOS Global Digital Surface Model (AW3D30)*, *OpenTopography*. Retrieved from http://opentopo.sdsc.edu/raster?opentopoID=OTALOS.112016.4326.2

Jenkis, A. R., Smallie, J. J., & Diamond, M. (2010). Avian collisions with power lines: A global review of causes and mitigation with a South African perspective. *Bird Conservation International*, *20*(3), 263–278. https://doi.org/10.1017/s0959270910000122

Kiesecker, J., Baruch-Mordo, S., Kennedy, C. M., Oakleaf, J. R., Baccini, A., & Griscom, B. W. (2019). Hitting the target but missing the mark: Unintended environmental consequences of the Paris climate agreement. *Frontiers in Environmental Science*, *7*(October), 1–11. https://doi.org/10.3389/fenvs.2019.00151

Kleyheeg-Hartman, J. C., Krijgsveld, K. L., Collier, M. P., Poot, M., Boon, A. R., Troost, T. A., & Dirksen, S. (2018). Predicting bird collisions with wind turbines: Comparison of the new empirical flux collision model with the SOSS band model. *Ecological Modelling*, *387*(March), 144–153. https://doi.org/10.1016/j.ecolmodel.2018.06.025

Lees, K. J., Guerin, A. J., & Masden, E. A. (2016). Using kernel density estimation to explore habitat use by seabirds at a marine renewable wave energy test facility. *Marine Policy*, *63*, 35–44. https://doi.org/10.1016/j.marpol.2015.09.033

Lewis, J., & Sauro, J. (2006). When 100% really isn't 100%: Improving the accuracy of small-sample estimates of completion rates. *Journal of Usability Studies*, *1*(3), 136–150.

Loss, S. R., Dorning, M. A., & Diffendorfer, J. E. (2019). Biases in the literature on direct wildlife mortality from energy development. *Bioscience*, *69*(5), 348–359. https://doi.org/10.1093/biosci/biz026

Lott, A., & Reiter, J. P. (2020). Wilson confidence intervals for binomial proportions with multiple imputation for missing data. *American Statistician*, *74*(2), 109–115. https://doi.org/10.1080/00031305.2018.1473796

Marques, A. T., Batalha, H., Rodrigues, S., Costa, H., João, M., Pereira, R., Fonseca, C., Mascarenhas, M., & Bernardino, J. (2014). Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. *Biological Conservation*, *179*, 40–52. https://doi.org/10.1016/j.biocon.2014.08.017

Marques, A. T., Santos, C. D., Hanssen, F., Muñoz, A.-R., Onrubia, A., Wikelski, M., Moreira, F., Palmeirim, J. M., & Silva, J. P. (2020). Wind turbines cause functional habitat loss for migratory soaring birds. *Journal of Animal Ecology*, *89*(1), 93–103. https://doi.org/10.1111/1365-2656.12961

Martín, B., Perez-Bacalu, C., Onrubia, A., De Lucas, M., & Ferrer, M. (2018). Impact of wind farms on soaring bird populations at a migratory bottleneck. *European Journal of Wildlife Research*, *64*(3). https://doi.org/10.1007/s10344-018-1192-z

Martin, G. R., & Shaw, J. M. (2010). Bird collisions with power lines: Failing to see the way ahead? *Biological Conservation*, *143*, 2695–2702. https://doi.org/10.1016/j.biocon.2010.07.014

May, R. F. (2015). A unifying framework for the underlying mechanisms of avian avoidance of wind turbines. *Biological Conservation*, *190*, 179–187. https://doi.org/10.1016/j.biocon.2015.06.004

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution*, *10*(16), 8927–8935. https://doi.org/10.1002/ece3.6592

McClure, C. J. W., Martinson, L., & Allison, T. D. (2018). Automated monitoring for birds in flight: Proof of concept with eagles at a wind power facility. *Biological Conservation*, *224*, 26–33. https://doi.org/10.1016/j.biocon.2018.04.041

Mckinsey & Company. (2010). *Transformation of Europe's power system until 2050 including specific considerations for Germany electric power and natural gas practice*. Düsseldorf. Retrieved from https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/epng/pdfs/transformation_of_europes_power_system.ashx

Morris, G., & Conner, L. M. (2017). Assessment of accuracy, fix success rate, and use of estimated horizontal position error (EHPE) to filter inaccurate data collected by a common commercially available GPS logger. *PLoS ONE*, *12*(11), 1–12. https://doi.org/10.1371/journal.pone.0189020

Movebank. (2019). *Movebank Data Repository*. Retrieved from https://www.movebank.org/

National Grid. (2014). *Design drawings 132kV overhead lines: Hinkley point C connection project application reference EN020001*. *Electricity Transmission Plc*. https://cupdf.com/document/487-design-drawings-132kv-overhead-lines1.html

National Science Foundation. (2019). *Open Topography Data Portal*, *OpenTopography*. Retrieved from https://opentopography.org/news/three-new-global-topographic-datasets-available-srtm-ellipsoidal-alos-world-3d-gmrt

NGA and NASA. (2000). *Shuttle Radar Topography Mission (SRTM GL1) Global 30m Ellipsoidal*, *OpenTopography*. Retrieved from http://opentopo.sdsc.edu/raster?opentopoID=OTSRTM.082016.4326.1

O'Donoghue, P., & Rutz, C. (2016). Real-time anti-poaching tags could help prevent imminent species extinctions. *Journal of Applied Ecology*, *53*(1), 5–10. https://doi.org/10.1111/1365-2664.12452

OpenStreetMap. (2018). *Classification of power lines*, *OpenStreetMap Wiki*. Retrieved from https://wiki.openstreetmap.org/wiki/Classification_of_power_lines

OpenStreetMap. (2019a). *Guidance for digitising power line data into OpenStreetMap*, *OpenStreetMap Wiki*. Retrieved from https://wiki.openstreetmap.org/wiki/Power_lines

OpenStreetMap. (2019b). *OpenStreetMap world light Gray Base*, ESRI Web Map Service. Retrieved from http://goto.arcgisonline.com/maps/World_Light_Gray_Base

Oppel, S., Ruffo, A. D., Bakari, S., Tesfaye, M., Mengistu, S., Wondafrash, M., Endris, A., Pourchier, C., Ngari, A., Arkumarev, V., & Nikolov, S. C. (2021). Pursuit of 'sustainable' development may contribute to vulture crisis in East Africa. *Bird Conservation International*, 1–15. https://doi.org/10.1017/S0959270921000307

Péron, G., Fleming, C. H., Duriez, O., Fluhr, J., Itty, C., Lambertucci, S., Safi, K., Shepard, E. L. C., & Calabrese, J. M. (2017). The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. *Journal of Applied Ecology*, *54*(6), 1895–1906. https://doi.org/10.1111/1365-2664.12909

Péron, G., Calabrese, J. M., Duriez, O., Fleming, C. H., García-Jiménez, R., Johnston, A., Lambertucci, S. A., Safi, K., & Shepard, E. L. C. (2020). The challenges of estimating the distribution of flight heights from telemetry or altimetry data. *Animal Biotelemetry*, *8*(1). https://doi.org/10.1186/s40317-020-00194-z

Pierrot, M. (2018). The wind power: Wind energy market intelligence. Retrieved from https://www.thewindpower.net

QGIS Development Team. (2019). *QGIS geographic information system*. Open Source Geospatial Foundation Project.

Reichensdörfer, E., Odenthal, D., & Wollherr, D. (2017). Grammatical evolution of robust controller structures using wilson scoring and criticality ranking. In *Genetic Programming: 20th European Conference*, *EuroGP 2017 Amsterdam*, *The Netherlands*, *April 19–21*, *2017 Proceedings*, *10196 LNCS*, pp. 194–209). Springer. https://doi.org/10.1007/978-3-319-55696-3_13

Ross-Smith, V. H., Thaxter, C. B., Masden, E. A., Shamoun-Baranes, J., Burton, N. H. K., Wright, L. J., Rehfisch, M. M., & Johnston, A. (2016). Modelling flight heights of lesser black-backed gulls and great skuas from GPS: A Bayesian approach. *Journal of Applied Ecology*, *53*(6), 1676–1685. https://doi.org/10.1111/1365-2664.12760

Rotics, S., Kaatz, M., Turjeman, S., Zurell, D., Wikelski, M., Sapir, N., Eggers, U., Fiedler, W., Jeltsch, F., & Nathan, R. (2018). Early arrival at breeding grounds: causes, costs and a trade-off with overwintering latitude. *Journal of Animal Ecology*. https://doi.org/10.1111/1365-2656.12898

Ryberg, D. S., Caglayan, D. G., Schmitt, S., Linßen, J., Stolten, D., & Robinius, M. (2019). The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs. *Energy*, *182*, 1222–1238. https://doi.org/10.1016/j.energy.2019.06.052

Schaub, T., Klaassen, R. H. G., Bouten, W., Schlaich, A. E., & Koks, B. J. (2020). Collision risk of montagu's harriers circus pygargus with wind turbines derived from high-resolution GPS tracking. *Ibis*, *162*(2), 520–534. https://doi.org/10.1111/ibi.12788

Sequeira, A. M. M., O'Toole, M., Keates, T. R., McDonnell, L. H., Braun, C. D., Hoenner, X., Jaine, F. R. A., Jonsen, I. D., Newman, P., Pye, J., Bograd, S. J., Hays, G. C., Hazen, E. L., Holland, M., Tsontos, V. M., Blight, C., Cagnacci, F., Davidson, S. C., Dettki, H., … Weise, M. (2021). A standardisation framework for bio-logging data to advance ecological research and conservation. *Methods in Ecology and Evolution*, *12*(6), 2041–2210. https://doi.org/10.1111/2041-210X.13593

Serrano, D., Margalida, A., Pérez-García, J. M., Juste, J., Traba, J., Valera, F., Carrete, M., Aihartza, J., Real, J., Mañosa, S., Flaquer, C., Garin, I., Morales, M. B., Alcalde, J. T., Arroyo, B., Sánchez-Zapata, J. A., Blanco, G., Negro, J. J., Tella, J. L., … Donázar, J. A. (2020). Renewables in Spain threaten biodiversity. *Science*, *370*(6522), 1282–1283. https://doi.org/10.1126/science.abf6509

Silva, R., Afán, I., Gil, J. A., & Bustamante, J. (2017). Seasonal and circadian biases in bird tracking with solar GPStags. *PLoS One*, *12*(10), 1–19. https://doi.org/10.1371/journal.pone.0185344

Storchová, L., & Hořák, D. (2018). Life-history characteristics of European birds. *Global Ecology and Biogeography*, *27*(4), 400–406. https://doi.org/10.1111/geb.12709

Svensson, L., Mullarney, K., & Zetterström, D. (2016). *Collins bird guide* (2nd ed.). Harper Collins Publishers.

Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., Tobias, J. A., Foden, W. B., O'Brien, S., & Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1862), 1–10. https://doi.org/10.1098/rspb.2017.0829

Thaxter, C. B., Ross-Smith, V. H., Bouten, W., Clark, N. A., Conway, G. J., Masden, E. A., Clewley, G. D., Barber, L. J., & Burton, N. H. (2019). Avian vulnerability to wind farm collision through the year: Insights from lesser blackbacked gulls (*Larus fuscus*) tracked from multiple breeding colonies. *Journal of Applied Ecology*, *56*(11), 2410–2422. https://doi.org/10.1111/1365-2664.13488

Thomson, J. A., Börger, L., Christianen, M. J. A., Esteban, N., Laloë, J.-O., & Hays, G. C. (2017). Implications of location accuracy and data volume for home range estimation and fine-scale movement analysis: Comparing Argos and Fastloc-GPS tracking data. *Marine Biology*, *164*(10), 1–9. https://doi.org/10.1007/s00227-017-3225-7

Timmerberg, S., Sanna, A., Kaltschmitt, M., & Finkbeiner, M. (2019). Renewable electricity targets in selected MENA countries – Assessment of available resources, generation costs and GHG emissions. *Energy Reports*, *5*, 1470–1487. https://doi.org/10.1016/j.egyr.2019.10.003

Tomé, R., Canário, A., Leitão, A.H., Pires, N., & Repas, M. (2017). Radar assisted shutdown on demand ensures zero soaring bird mortality at a wind farm located in a migratory flyway. In *Wind Energy and Wildlife Interactions: Presentations from the CWW2015 Conference* (pp. 119–133). https://doi.org/10.1007/978-3-319-51272-3_7

Vasilakis, D. P., Whitfield, D. P., Schindler, S., Poirazidis, K. S., & Kati, V. (2016). Reconciling endangered species conservation with wind farm development: Cinereous vultures (*Aegypius monachus*) in South-Eastern Europe. *Biological Conservation*, *196*, 10–17. https://doi.org/10.1016/j.biocon.2016.01.014

Warwick-Evans, V., Atkinson, P. W., Walkington, I., & Green, J. A. (2017). Predicting the impacts of wind farms on seabirds: An individual-based model. *Journal of Applied Ecology*, (August), *55*(2), 1–13. https://doi.org/10.1111/1365-2664.12996

DATA SOURCES

Anselin, A., Desmet, P., Milotic, T., Janssens, K., T'Jollyn, F., De Bruyn, L., & Bouten, W. (2019). MH_WATERLAND – Western marsh harriers (*Circus aeruginosus*, Accipitridae) breeding near the Belgium-Netherlands border, *Zenodo*. https://doi.org/10.5281/zenodo.3826591

Carrapato, C. (2016). *Iberian Imperial Eagle movement ecology 2014–2015*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study28407489

Carrapato, C. (2016). *Iberian Imperial eagle movement ecology 2016*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study163340351

Carrapato, C. (2017). *Iberian Imperial eagle movement ecology 2017*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study292890255

Champagnon, J. (2017). *Eurasian spoonbill – Tour du Valat – Camargue (France)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study311803430

Clewley, G. C., Thaxter, C. B., Scragg, E., & Burton, N. (2015). *BTO – Bowland 2015 – Lesser black-backed Gull. Movebank study ID: 74375353*. Retrieved from www.movebank.org

Clewley, G. C., Thaxter, C. B., Scragg, E., & Burton, N. (2017). *BTO – Bowland 2017 – Lesser black-backed Gull. Movebank study ID: 277843980*. Retrieved from www.movebank.org

Clewley, G. C., Thaxter, C. B., Scragg, E., & Burton, N. (2017). *BTO – Ribble Estuary 2017 – Lesser Black-backed Gull. Movebank study ID: 277841852*. Retrieved from www.movebank.org

Clewley, G. C., Thaxter, C. B., Scragg, E., & Burton, N. (2018). *BTO – Ribble Estuary 2018 – Lesser Black-backed Gull. Movebank study ID: 482136485*. Retrieved from www.movebank.org

Duriez, O., Péron, G., Grémillet, D., Sforzi, A., Monti, F. (2018). Migrating ospreys use thermal uplifts over the open sea. *Biology Letters 14*(12). https://doi.org/10.1098/rsbl.2018.0687. Retrieved from www.movebank.org

Duriez, O., Sforzi, A., & Monti, F. (2018). Osprey in Mediterranean (Corsica, Italy, Balearics), Data From: Monti, F., Grémillet, D., Sforzi, A., Sammuri, G., Dominici, J. M., Triay Bagur, R., Muñoz Navarro, A., Fusani, L., & Duriez, O. (2018). Migration and wintering strategies in vulnerable Mediterranean osprey populations. *Ibis*. 10.1111/ibi.12567; Monti, F., Grémillet, D., Sforzi, A., Dominici, J.

M., Triay Bagur, R., Muñoz Navarro, A., Fusani, L., Klaassen, R. H. G., Alerstam, T., & Duriez, O. (2018). Migration distance affects stopover use but not travel speed: Contrasting patterns between long- and short distance migrating ospreys. *Journal of Avian Biology*, 49, e01839. https://doi.org/10.1111/jav.01839

Exo, K. M. (2008). *Migration timing in barnacle geese (Barents Sea) (data from Kölzsch et al. and Shariatinajafabadi et al. 2014)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study29799425

Exo, K. M., & Griffin, L. (2006). *Migration timing in barnacle geese (Svalbard) (data from Kölzsch et al. and Shariatinajafabadi et al. 2014)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study20039459

Fiedler, W. (2013). *Lifetrack White Stork Greece Evros Delta*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study10449535

Fiedler, W. (2013). *Lifetrack White Stork Loburg*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study10449318

Fiedler, W. (2013). *Lifetrack White Stork Tunisia*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study10157679

Fiedler, W. (2014). *Lifetrack White Stork Poland ECG*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study25166516

Fiedler, W. (2014). *Lifetrack White Stork Bavaria*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study24442409

Fiedler, W. (2015). *Lifetrack White Stork Rheinland-Pfalz*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study76367850

Fiedler, W. (2016). *Lifetrack White Stork Bulgaria*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study128184877

Fiedler, W. (2016). *Lifetrack White Stork Vorarlberg*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study173641633

Fiedler, W. (2017). *LifeTrack Lake Constance Ducks*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study236953686

Fiedler, W. (2017). *Lifetrack Black Stork*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study291047293

Fiedler, W., Blas, J., & Wilkelsi, M. (2013). *Lifetrack White Stork Spain Donana*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study2988357

Fiedler, W., & Wikelski, M. (2011). *MPIO Lake Constance Mallards GPS*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study446579

Fiedler, W., & Wilkelsi, M. (2013). *Lifetrack White Stork Poland*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study10763606

Flack, A., Fiedler, W., & Wikelski, M. (2017). Fall migration of white storks in 2014, Data from: Wind estimation based on thermal soaring of birds. *Movebank Data Repository*. https://doi.org/10.5441/001/1.bj96m274

Franco, A. M. A. (2014). *White Stork Juveniles 2014 UEA*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study83544657

Franco, A. M. A. (2016). *White stork adults and juveniles*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study159302811

Franco, A. M. A. (2017). *White stork juveniles (2017)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study279646867

Franco, A. M. A., & Acacio, M. S. (2018). *White stork adults 2018*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study451464940

Franco, A. M. A., & Acacio, M. S. (2018). *White stork juveniles 2018*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study495405707

Franco, A. M. A., & Acacio, M. S. (2018). *Black storks Portugal 2018*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study518635174

Franco, A. M. A., Acacio, M. S., Rogerson, K., (2017). *White stork adults 2017*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study229412850

Friedemann, G. (2011). *Movements of long-legged buzzards and short-toed eagles*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study34551859

Fritz, J., Wikelski, M., & Pixner, E. (2018). *Bald Ibis Waldrappteam 2*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study18957668

Garthe, S. (2016). FTZ: Foraging in lesser black-backed gulls; Data from Garthe, S., Schwemmer, P., Paiva, V. H., Corman, A.-M., Fock, H. O., Voigt, C. C., Adler, S. (2016). Terrestrial and marine foraging strategies of an opportunistic seabird species breeding in the Wadden Sea. *PLoS ONE*, 11(8), e0159630. https://doi.org/10.5441/001/1.nk286sc0. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study82452206

Giunchi, D. (2015). Eurasian stone curlew Italy, Data from: Giunchi, D., Caccamo, C., Mori, A., Fox, J. W., Rodríguez-Godoy, F., Baldaccini, N. E., & Pollonara, E. (2015). Pattern of non-breeding movements by Stone-curlews *Burhinus oedicnemus* breeding in North Italy. *Journal of Ornithology*, 1–8. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study12883793

Hollerbach, S. (2016). *Ciconia ciconia sudewiesen*. Retrieved from storkenkate@gmx.de

Jansen, R. (2010). *Eagle owls - 3 breeding pairs - Southern Part The Netherlands*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study4502577

Kölzsch, A. (2015). *Foraging by white-fronted geese after disturbance (data from Nolet et al. 2016)*. https://doi.org/10.5441/001/1.7tp81b7b. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study163020445

Kölzsch, A., Bauer, S., de Boer, R., Griffin, L., Cabot, D., Exo, K.-M., van der Jeugd, H. P., & Nolet, B. A. (2014). Forecasting spring from afar? Timing of migration and predictability of phenology along different migration routes of an avian herbivore. *Journal of Animal Ecology*. https://doi.org/10.1111/1365-2656.12281

Lameris, T. K., & Bouten, W. (2018). *Barnacle geese – Netherlands and North-Western Russia*. 10.1016/j.cub.2018.05.077; https://doi.org/10.1007/s10336-012-0908-1

López-López, P. (2007). *Egyptian vulture EB Terra Natura UA Spain*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study20106351

Lopez-Vazquez, J.M., (2013). *Proyecto Eremita Geronticus eremita Reintroduction in Andalusia (Spain)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study463673774

Milotic, T., Desmet, P., Anselin, A., De Bruyn, L., De Regge, N., Janssens, K., Klaassen, R., Koks, B., Schaub, T., Schlaich, A., Spanoghe, G., T'jollyn, F., Vanoverbeke, J., & Bouten, W. (2020). GPS tracking data of Western marsh harriers breeding in Belgium and the Netherlands. *ZooKeys*, *947*, 143–155. https://doi.org/10.3897/zookeys.947.52570

Nathan, R. (2012). *Eastern flyway spring migration of adult white storks (data from Rotics et al. 2018)*. https://doi.org/10.5441/001/1.v8d24552 Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study560041066

Nathan, R., & Harel, R. (2012). *Soaring flight in Eurasian griffon vultures (HUJ) (data from Harel and Nathan, 2018)*. https://doi.org/10.5441/001/1.46t5141d. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study467005392

Nathan, R., & Harel, R. (2016). *Eurasian Griffon Vultures 1 Hz HUJ (Israel)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study16924201

Oppel, S., & Nikolov, S. (2018). *Neophron percnopterus Bulgaria/Greece LIFE+ "The return of the Neophron" - LIFE10 NAT/BG/000152*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study15869951

Peshev, H. (2016). *Gyps fulvus Griffon vulture FWFF Kresna Gorge*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study305278048

Pokrovsky, I. (2015). *LifeTrack Peregrine Falcon*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study103426553

Pokrovsky, I. (2016). *LifeTrack rough-legged buzzards*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study9493874

Séchaud, R. (2016). *Barn owl (Tyto alba)*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study231741797

Silva, J. P. (2015). *Little Bustard Movement Ecology 2015–2016*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study56464970

Silva, J. P. (2017). *Little Bustard Movement Ecology 2017–2018*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study253940991
Silva, J. P. (2018). *Little Bustard Movement Ecology 2018–2019*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study461568973
Thaxter, C.B., Clewley, G.C., Scragg, E. & Burton, N. (2016). BTO – North West England 2016 - lesser black-backed Gull. Movebank study ID: 167983392, available on agreement and request from: www.movebank.org
Thaxter, C. B., Ross-Smith, V. H., Bouten, W., & Burton, N. H. K. (2011). *Lesser Black-backed Gull Orford Ness*. Retrieved from https://www.uva-bits.nl
Thaxter, C. B., Ross-Smith, V. H., Bouten, W., & Burton, N. H. K. (2014). *Lesser Black-backed Gull Walney*. Retrieved from https://www.uva-bits.nl
Thaxter, C. B., Ross-Smith, V. H., Bouten, W., & Burton, N. H. K. (2014). *Lesser Black-backed Gull Skokholm*. Retrieved from https://www.uva-bits.nl
Van Toor, M., & Waldenström, J. (2018). *Eurasian wigeons spring 2018*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study412700082
Vansteelant, W. (2008). *Honey_Buzzard_NL*. https://doi.org/10.1111/jav.00457; 10.1111/1365-2656.12593
Vornweg, B., & Fiedler, W. (2016). *Lifetrack Circus pygargus*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study166943336
Wikelski, M. (2015). *LifeTrack Whooper Swan Latvia*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study92261778
Žydelis, R. (2015). *Hybrid Spotted Eagles Lithuania GPS 2015–2017*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study150764908
Žydelis, R., & Dagys, M. (2015). *Common Crane Lithuania GPS, 2015–2016*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study146932094
Žydelis, R., & Dagys, M (2016). *Common Crane Lithuania GPS, 2016*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study195375760
Žydelis, R., & Desholm, M. (2013). *GPS Telemetry of Common Cranes, Sweden*. Retrieved from https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study10722328

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Gauld, J. G., Silva, J. P., Atkinson, P. W., Record, P., Acácio, M., Arkumarev, V., Blas, J., Bouten, W., Burton, N., Catry, I., Champagnon, J., Clewley, G. D., Dagys, M., Duriez, O., Exo, K-M, Fiedler, W., Flack, A., Friedemann, G., Fritz, J., Garcia-Ripolles, C., Garthe, S., Giunchi, D., Grozdanov, A., Harel, R., Humphreys, E. M., Janssen, R., Kölzsch, A., Kulikova, O., Lameris, T. K., López-López, P., Masden, E. A., Monti, F., Nathan, R., Nikolov, S., Oppel, S., Peshev, H., Phipps, L., Pokrovsky, I., Ross-Smith, V. H., Saravia, V., Scragg, E. S., Sforzi, A., Stoynov, E., Thaxter, C., Van Steelant, W., van Toor, M., Vorneweg, B., Waldenström, J., Wikelski, M., Žydelis, R. & Franco, A. M. (2022). Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa. *Journal of Applied Ecology*, *00*, 1–17. https://doi.org/10.1111/1365-2664.14160