WIMBY

Wind in My Backyard: Using holistic modelling tools to advance social awareness and engagement on large wind power installations in the EU

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Terrestrial birds and bats collision risk models and maps (a)

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SHORT ABSTRACT FOR DISSEMINATION PURPOSES

Abstract In line with Europe's decarbonization goals, the number and the capacity of wind-power farms is projected to increase in coming decades. However, wind farms can pose risks to biodiversity: flying animals can fatally collide with wind-farm infrastructure and bats can experience deadly barotrauma when flying close to turbines. To inform the deployment of wind farms at the European scale and minimise risks to wildlife, here we aimed to assess collision-mortality risk across European bird and bat species. We present the first version (*Version (a)*) of collision-mortality risk models, and associated outputs for 477 birds and 27 bats known to occur in Europe. To generate these, we used a compilation of recorded collisions for birds and bats from published papers and reports, which we combined with data on species traits, wind-farm characteristics, and landscape characteristics. We investigated associations between these variables and collision mortality at the species level using statistical models. We used our models' outcomes to create collision-mortality risk maps, with the aim of informing spatial deployment of wind power projects and possible mitigation measures.

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ABBREVIATIONS

Acronym	Description
GVIF	Generalised Variance Inflation Factor
MW	Megawatts

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EXECUTIVE SUMMARY

In line with the European Climate Law, wind-power's total installed capacity is projected to increase in the coming years. While deploying more wind-power farms is important to reducing greenhouse gas emissions, wind farms can also impact biodiversity. In particular, birds and bats can fatality collide with wind-farm turbines or turbine hubs, which can lead to decreases in the demographic rates of some species, raising questions about their impacts on the long-term viability of different animal populations. The objectives of this Deliverable are to present a first version (*Version (a)*) of the assessment of collision-mortality risk for European birds and bats. We assessed collision-mortality rates in terms of number of collision victims per wind turbine and per year. We used a compilation of recorded fatal collisions for birds and bats around wind-farm sites mostly located in Europe (16 sites for birds, 41 for bats) and North America (49 sites for birds). We combined the collision data with information on individual species characteristics, wind turbine capacity, and mean wind speed at the wind-farm locations, and we assessed whether these variables were associated with collision mortality using statistical models. We then used the models' outputs to predict the mean collision-mortality rates across 477 European bird species (about 90% of 544 birds species known to occur across Europe) and 27 European bat species (about 60% of the 47 bat species known to occur in Europe). Using spatial data on species occurrence, we mapped estimated collision-mortality rates at the species-level and at the assemblage level, providing summary statistics of collision-mortality rates across all species occurring in a grid cell. Thus, we present *Version (a)* of the collision-mortality risk models and the collision-mortality risk maps for European birds and bats. These maps can inform further tasks of the project, notably the spatial optimisation of wind-farm deployment (Work Package 4). This work will be consolidated towards *Version (b)* in the upcoming months, for a finalised version to be delivered in Month 18 (D1.6).

1. INTRODUCTION

With the adoption of the European Climate Law in 2021, the European Union has committed to becoming climate-neutral by 2050, i.e., to reaching net-zero greenhouse gas emissions. An intermediate target aims at reducing greenhouse gas emissions by 55% by 2030, compared to emission levels of 1990. Key to the EU's decarbonisation and climate-change-mitigation strategy is the transformation of European energy systems, most notably the reduction of fossil fuels in the energy mix, coupled with increases in the share of renewable energy sources. In addition to contributing to the EU's decarbonisation goals, the development of renewable energy diversifies local energy supplies and allows for a greater independence from conventional resources. Between 2000 and 2019, renewable energy consumption increased by an average 200% in the EU-27 across all sectors (Tutak & Brodny, 2022). In 2022, wind power alone accounted for about 16% of the electricity demand in the European Union (WindEurope 2022). As of 2022, with an installed capacity of 204 GW, the EU was among the biggest producers of wind energy. Most of this capacity (92%) was installed onshore (WindEurope 2022). In line with the European Climate Law, the installed capacity could need to increase by more than 100% to meet the 2030 targets (to reach a total capacity of 440 GW by 2030 with regards to the REPower EU energy target; WindEurope 2022).

While wind energy is a key sector for renewable energy production, wind-power farms can have adverse impacts on biodiversity (Loss et al., 2013; Schöll & Nopp-Mayr, 2021). These impacts can be an important barrier to the social acceptance of wind power (Voigt et al., 2019; Vuichard et al., 2022). Negative biodiversity impacts can be attributed to land-use change and habitat disturbance occurring from the construction phase of the wind farms and necessary structures (e.g., roads and power lines). Habitat disturbance can lead to the displacement of species through the loss of suitable habitat (Marques et al., 2020), and to reductions in local abundance and population densities (Fernández-Bellon et al., 2019). For flying animals, the presence of wind farms can lead to alterations of flight paths and

migratory routes through a barrier or displacement effect inducing avoidance behaviour (Cabrera-Cruz & Villegas-Patraca, 2016; Santos et al., 2022a). However, wind farms also constitute a collision hazard for flying animals, birds and bats in particular (Smallwood, 2013; Thaxter et al., 2017), but also insects (Voigt, 2021), as these animals can fatally collide with wind-farm infrastructure, and, in the case of bats, experience deadly barotrauma when flying close to rotating turbines (Baerwald et al., 2008). Negative impacts of wind-power farms on birds and bats through collision mortality can be of concern for the long-term viability of animal populations (Duriez et al., 2023; Gómez-Catasús et al., 2018; May et al., 2019; Sanz-Aguilar et al., 2015; Schippers et al., 2020). Of particular concern are species that cumulate different vulnerability factors to human pressures, such as low population densities or slow pace of life, and/or species that are already characterised as threatened (Carrete et al., 2009; Desholm, 2009; Kuvlesky Jr. et al., 2010). For instance, large soaring birds have been a group of interest since their reliance on wind resources to gain altitude (thermal and orographic updrafts in particular) can conflict with areas favourable for wind-energy developments (Farfán et al., 2023; Santos et al., 2022b; Smeraldo et al., 2020). Further, poor flight manoeuvrability can make them particularly exposed to collision mortality, while low reproductive outputs can make the species more sensitive to such added mortality (Bellebaum et al., 2013; Dahl et al., 2013). It is thus important to assess the collision-mortality risk that wind farms pose to different species, to inform wind-farm spatial deployment and to minimise biodiversity impacts.

Collision-mortality risk for onshore wind farms is typically empirically estimated from the field using search protocols around operational turbines, aiming at identifying and counting collision victims (Bernardino et al., 2013; Domínguez del Valle et al., 2020). Past research has shown that collision risk is influenced by a wide range of factors, which can be broadly classified into three categories (Marques et al., 2014): (1) site-specific factors that relate to local landscape configuration and environmental features, such as wind speed, weather, landforms, habitat availability for different species, etc; (2) characteristics of the wind farms, such as spatial

configuration, turbine capacity, lighting, etc; and (3) species-specific characteristics, such as seasonal occurrence, morphology, sensorial perception, flight strategy, migratory behaviour, behavioural plasticity and adaptability, etc (De Lucas et al., 2008; Farfán et al., 2023; May et al., 2015). Collision mortality risk is influenced by complex interactions among these factors (Drewitt & Langston, 2008). Such interactions point to an important degree of context-specificity in collision-mortality risk, supported by widespread reported estimates of collision-mortality rates at different wind farms. While low fatality numbers are reported for many wind farms, many fatal collisions have occurred at other wind farms – e.g., Altamont Pass Wind Resource Area in California or Tarifa in Southern Spain (Arnett et al., 2016; de Lucas et al., 2012; Kuvlesky Jr. et al., 2010; Marques et al., 2014; Powlesland, 2009; Rydell et al., 2012; Sebastián-González et al., 2018; Voigt et al., 2022). Consequently, the siting of wind farms and their spatial configuration are of prime importance to reduce collision-mortality risk (Carrete et al., 2012; Schaub, 2012). As species are unevenly affected by the presence of wind farms, understanding which factors explain interspecific variation in collision-mortality risk can help putting into place appropriate mitigation measures.

In a quantitative synthesis of collision-mortality data for birds and bats, Thaxter et al. (2017) investigated whether ecological characteristics measurable at the species level (also termed 'traits') and turbine capacity were associated with collision risk. They showed that traits relating to species' movement (i.e., dispersal ability), migratory status, and habitat preferences were significantly associated with collision risk in birds, and that dispersal ability was significantly associated with collision-mortality risk in bats. In addition, they found that turbine capacity was positively associated with collision-mortality risk in birds and bats (although they found that deploying fewer turbines with larger capacities tended to reduce collision risk). Thaxter et al. (2017) then used information on individual species' traits to estimate the collision-mortality risk for birds and bats globally.

In this task of the WIMBY project (T1.3), we built upon Thaxter et al. (2017) to conduct a continental-scale assessment of collision-mortality risk

for European birds and bats. Using the collision-mortality data collected in Thaxter et al. (2017), we investigated associations between species-level and site-level characteristics and collision-mortality rates using statistical models. We then used our models' outcomes to predict collision-mortality rates across 477 European bird species and 27 bat species (i.e., for about 90% of the species of birds known to occur in Europe, and for about 60% of the bat species known to occur in Europe). Collision-mortality rates were estimated as the average number of collision victims per year and per turbine (or in other words, per year-turbine), at the species level. We mapped the collision-mortality rate estimates at the species level and at the assemblage level (i.e., for all species found to occur at a particular location), providing summary statistics of collision-mortality rates across all species occurring in a grid cell. We therefore present here *Version (a)* of the collision-mortality risk models and the collision risk maps for 477 European birds and 27 European bats. These models and outputs will be developed and consolidated towards *Version (b)* (D1.6, Month 18).

2. METHODS

All data processing and analyses were conducted with R v.4.2.3 (R Core Team) and Python v2.7 (van Rossum, G., 1995; for the processing of species' distribution maps; see sections 2.3.1 & 2.3.2).

2.1 Data collection

2.1.1   Collision data for birds and bats: Thaxter et al. (2017)

Thaxter et al. (2017) investigated whether species ecological characteristics and wind-turbine capacity (in Megawatts, MW) were associated with collision risk in birds and bats. To this end, they compiled data from a range of peer-reviewed and non-peer-reviewed studies and reports that recorded or estimated collision mortality at wind farms for birds and bats. They used a literature search on the terms: *"(bird* OR avian OR bat) AND wind AND (farm* OR energy OR windfarm* OR industry* OR wind-farm* OR park* OR development* OR facilit*)"* to identify relevant sources, using Web of Science, Google© and Google Scholar©. Thaxter et al. (2017) identified 88 sources for birds and 87 studies for bats that were suitable for inclusion, spanning a range of countries with a bias towards European and North American locations. The compiled data included 93 and 134 onshore and coastal wind farms for birds and bats respectively (several wind farms being sometimes considered in a single study). Wind farms varied in the number of operational wind turbines, with some wind farms consisting of single wind turbines while others consisted of several turbines. The sampling year(s), the employed search protocol or methodology, as well as the duration of each study were varied. Thaxter et al. (2017) reported mortality estimates at the wind-farm level, along with turbine capacity, number of wind turbines within each wind farm, location of the wind farm (central longitude and latitude of all wind turbines within a wind farm), and the duration of each study. In addition, Thaxter et al. (2017) estimated the quality of each study, that is, whether studies corrected for the detectability of collision victims after field searches (Huso & Dalthorp, 2014; Nilsson et al., 2023), characterising study quality as "very low", "low", "medium", or "high", depending on if and how

correction factors were applied. For further methodological details on the collision-mortality data collection, see Thaxter et al. (2017).

2.1.2 Processing and standardizing the collision data

We used the collision data for birds and bats from Thaxter et al. (2017), accessible at:

https://datadryad.org/stash/dataset/doi:10.5061/dryad.h9s55

(retrieved 10/05/2023). As the collected data came from diverse sources that used different methods to estimate mortality, the metrics reported in the data varied. >80% of the records reported (annual) mortality per turbine; and about 2% of the records reported counts of collision (or barotrauma) victims. We subsetted the data to include records that reported mortality rates (e.g., "annual mortality per turbine") or counts of collision victims (e.g., "total fatalities") and for which study duration and number of turbines were known. We standardised the values across all studies to obtain annual mortality rates per turbine (collisions victims.year^{-1}.turbine^{-1}). These rates were converted back to count data prior to fitting the models (see next section 2.1.3Modelling framework), as Poisson models require count data as dependent variables. The use of an offset variable then allows to control for uneven study duration and varying number of turbines (see section 2.2.1).

2.1.3 From collision rates to counts to counts of collision victims

We converted the standardised collision rates (number of collision victims per year-turbine) to counts of collision victims, by multiplying the standardised rates in the original data with study duration and number of turbines within each wind farm. Since doing so did not necessarily generate integers – required to fit the models with a Poisson error distribution–, we rounded the estimates to the nearest integers. To get more precise estimates of the number of collision victims with a more accurate rounding, we increased the study duration by 10 years, multiplying both estimated rates and study duration by 10 before rounding. This allowed by a better estimation of rounded counts since initial counts of e.g., 0.2 over 1 year became 2 over 10 years, without affecting the rate itself. We further verified that this rounding procedure did not affect the estimated rates, by

comparing the initial standardised collision rates with collision rates derived from the rounded counts (Figure A1). We filtered out species that were never recorded to be collision victims (0 collision victims reported across all locations).

2.1.4   Trait data (species-level characteristics)

We combined the collision data with species-level trait data and ecological characteristics for birds and bats (Thaxter et al. (2017) showed that traits related to species movement (i.e., dispersal distance for birds and bats, as well as migratory status for birds and habitat affinity) were associated with collision risk. Thus, we targeted traits that related to species movement, as well as habitat affinity for birds.

The set of traits we collected for birds and bats differed in part, since these two taxonomic groups have distinct characteristics that are not always directly comparable. For both groups, we obtained traits that related to species morphology, movement, and ecology, targeting characteristics that could be associated with collision risk, and that were available for a maximum of species occurring in the collision data. We excluded traits that were too strongly associated with each other, checking both Pearson's correlation coefficients among continuous traits, as well as Generalised Variance Inflation factors among continuous and categorical traits (GVIF; Dormann et al. (2013)), to avoid multicollinearity issues in the models (see section 2.2). For instance, in bats, forearm length and body mass were too highly correlated to be considered simultaneously (Pearson's correlation coefficient >0.9). We further excluded variables with GVIF >5. The resulting sets of selected species-level ecological characteristics that we considered in the models are defined in Table 1.

Table 1: Ecological characteristics collected for birds and bats, definitions, and data sources. These characteristics were included as predictors in the models investigating associations between species-level characteristics and collision-mortality rates.

Taxon	Ecological characteristic	Definition	Sources
Birds	**Migratory status** (categorical)	Species classified as: - migratory (long-distance migration occurs across most of the species' population) - partially migratory (short-distance migration occurs across most of the species' population) - sedentary.	Tobias et al. (2022)
	Hand-wing index (HWI) (continuous, unitless)	HWI is a standardisation of Kipp's distance (distance between tip of 1st secondary feather to tip of the longest primary feather) with wing length. It is a widely-used proxy for dispersal ability (Sheard et al., 2020; Weeks et al., 2022).	Tobias et al. (2022)
	Species' habitat density (categorical)	Description of species' preferred habitat's density: - open (e.g., grassland) - semi-open (e.g., shrubland) - dense (e.g., forest)	Tobias et al. (2022)
	Flight mode (categorical)	Following (Watanabe, 2016), we classified species as soaring when belonging to the following Families: *Accipitridae*, *Cathartidae*, *Ciconiidae*, *Diomedeidae*, *Pandionidae*, and *Procellariidae*; flapping when belonging to any other family. Soaring species mainly rely on thermal updrafts to gain altitude, while flapping species use flap-powered flight (Santos et al., 2020); some species are able to use both modes, but we do not account for this here.	Ad-hoc classification
Bats	**Adult body mass (g)** (continuous)	Species-level average for adult body mass (not sex-specific).	Etard et al. (2020) and

			Froidevaux et al. (2023)
Home range (ha) (continuous)	Mean area used to satisfy daily individual needs (foraging, etc)		Froidevaux et al. (2023)
Max recorded movement (km) (continuous)	Maximum seasonal movement recorded (including migration distances)		Froidevaux et al. (2023)

2.1.5 Mean wind speed at the wind-farm central locations (m/s)

At the central location of the wind farms, we obtained mean wind speed at a height of 100 metres from the Global Wind Atlas (https://globalwindatlas.info/en; spatial data downloaded 23/10/2023 and aggregated at a resolution of 1 km by 1 km). We initially used different buffer sizes (0, 10, 100, 500, 1000, and 5000 metres) around each wind-farm location to estimate mean wind speed across the buffer cells, and we assessed whether the estimations were sensitive to buffer size. Mean wind speed was not sensitive to the choice of buffer size (Figure A2), and we used a buffer of 1 km around each point to estimate mean wind speed.

2.1.6 Wind turbine capacity

Turbine capacity (in MW) was directly obtained from the data compiled by Thaxter et al. (2017).

2.1.7 Study quality

The quality of each original data source in the collision dataset was estimated by Thaxter et al. (2017) as "very low", "low", "medium", "high". This classification reflected whether collision-mortality data collected from the field were corrected for carcass detectability. Data collected from the field not corrected for carcass detectability typically tend to underestimate counts of collision victims (Domínguez del Valle et al., 2020).

2.2 Modelling framework

2.2.1   Overview

We investigated whether species' ecological characteristics, mean wind speed at wind farms' locations, and wind turbine capacity were associated with collision-mortality rates using generalized linear mixed-effects models, fitted with a Bayesian framework implemented with the R package 'brms' (Bürkner, 2017, 2018, 2021). We fitted counts of collision victims as the response variable, using a zero-inflated Poisson error distribution (zero-inflation occurred as collision-mortality counts were reported as 0 for some species). We created an offset variable to control for uneven study duration and varying number of turbines within a wind farm.

Thaxter et al. (2017) showed that study quality influenced collision risk, with lower-quality studies (that is, those that didn't correct collision counts for carcass detectability) underestimating the number of collision victims. Thus, we included study quality as a fixed predictor in the models. In all models, two random intercepts accounted for the identity of studies and of sites, to control for variation in experimental design across studies and for the spatial structuring of sites within studies; another random intercept accounted for the identity of species, to control for repeated observations among species and for taxonomic non-independence. We fitted separate models for birds and bats. The general form of the models was:

> Number of collision victims ~
> Species-level predictors +
> Mean wind speed +
> Turbine capacity +
> Study quality +
> Offset variable +
> (1|Study ID) +
> (1|Site ID) +
> (1|Species identity)

The offset used was: log(study duration * number of turbines). We ran the Bayesian models using 4 chains, 5000 warm-up iterations, 50.000 sampling iterations, and thinning intervals of 10. We used non-informative priors.

2.2.2 Multicollinearity checks on the fixed predictors

We ran multicollinearity checks before fitting the models, using Generalised Variance Inflation Factors (GVIFs). The selected predictors all had GVIF <5, indicating that multicollinearity was not an issue in the models (Table 2).

Table 2: Generalised Variance Inflation Factors for all fixed predictors included the models investigating associations of collision-mortality rates with species-level characteristics, mean wind speed at the wind farms' central locations, and turbine capacity.

Taxon	Predictor	GVIF	Type
Birds	Flight mode	1.08	Species-level characteristic
	Migration	1.24	Species-level characteristic
	Study quality	1.37	Study-level characteristic
	Hand-wing index (log)	1.37	Species-level characteristic
	Habitat density	1.77	Species-level characteristic
	Mean wind speed	1.81	Site-level characteristic
	Turbine capacity	2.25	Wind-turbine characteristic
Bats	Mean wind speed	1.03	Site-level characteristic
	Turbine capacity	1.11	Wind-turbine characteristic
	Study quality	1.13	Study-level characteristic
	Home range (log)	1.17	Species-level characteristic
	Recorded movement	1.20	Species-level characteristic
	Body mass (log)	1.30	Species-level characteristic

2.2.3 Models sample sizes and spatial distribution of sampling sites

For birds, the fitted data included 1,893 records of collision counts from 330 species spanning 65 avian families, including 123 European bird species from 39 families (note that these were species figuring in the fitted data, but we further generated predictions from the models for more species, see section 2.3.1). These records were compiled from 80 different sources across 68 sampling sites distributed worldwide (Figure 1). There are about 544 species of birds known to occur regularly across Europe (European Red List of Birds, BirdLife International, http://datazone.birdlife.org/info/euroredlist2021), so the fitted data represented about 23% of the European bird species.

For bats, the fitted data included 103 records of collision counts from 11 species, spanning 3 taxonomic families. These records were compiled from

11 different sources across 41 sampling sites located in Europe (Figure 1). There are about 47 species of bats occurring across Europe (Froidevaux et al., 2023), so the fitted data also represented about 23% of the European species.
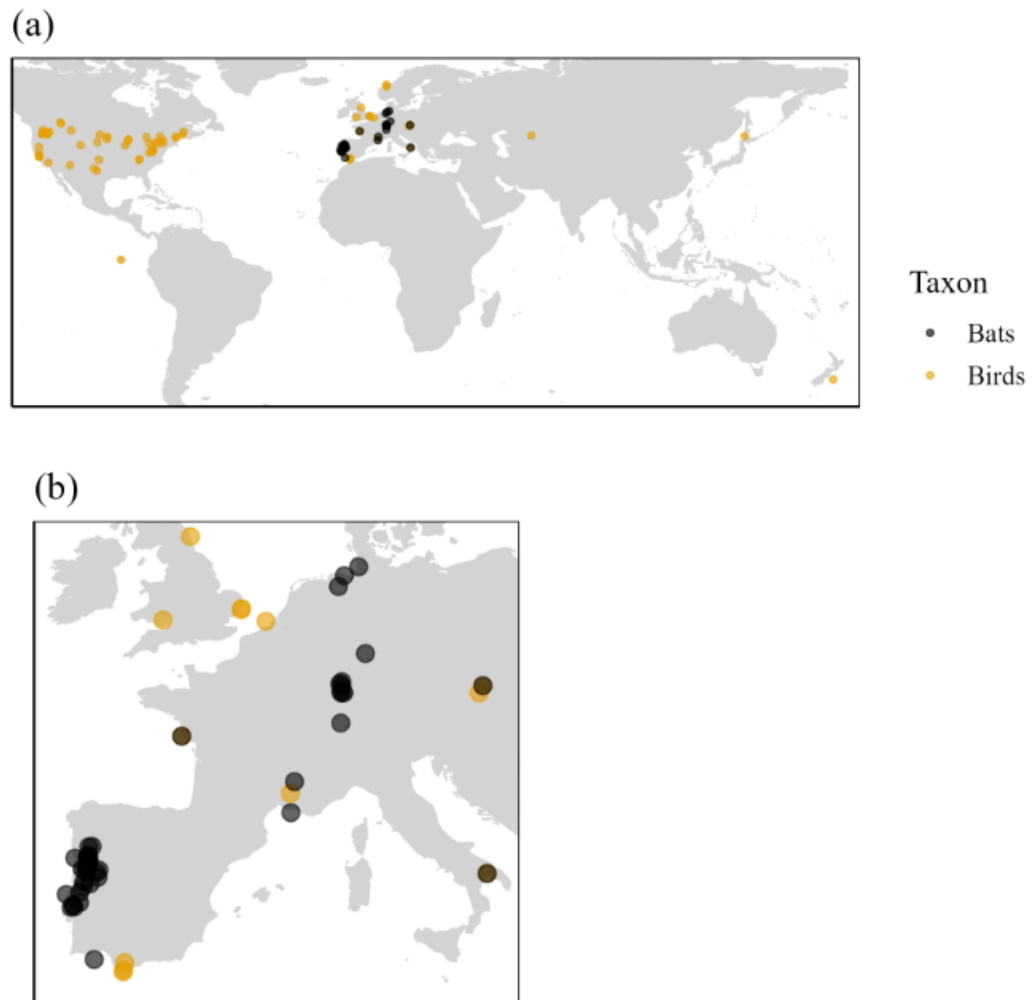
Figure 1: (a) Spatial distribution of all sampling sites (wind farms' central locations) included in the fitted data of the statistical models for birds and bats. (b) Location of European sites. Country shapes were obtained from the 'rnaturalearth' R package.

2.3 Model predictions: estimations of collision-mortality rates at the species level and mapping of outputs

2.3.1 Species-level predictions

From the fitted models, we generated species-level estimates of collision-mortality rates for 477 European bird species and 27 bat species, known to

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occur in Europe regularly. To identify species occurring in Europe, we used species distribution maps from BirdLife International for birds (http://datazone.birdlife.org/species/requestdis), and from the IUCN Red List of Threatened Species for bats (IUCN, 2020) (https://www.iucnredlist.org/resources/spatial-data-download). The maps were processed to include areas occupied by species during breeding and non-breeding seasons, while excluding areas falling outside species known elevational limits (following Etard et al. (2020)). All maps were projected with Behrmann's equal-area projection, with a resolution of 10 km by 10 km.

For the species identified to occur in Europe, we estimated the number of collision victims per year-turbine (mean ± 95% credible interval) from the models. We used information on individual species traits to estimate species-level collision-mortality rates from the effects of the fitted models. We generated predictions of collision-mortality rates at the species level for a turbine capacity of 2MW, a wind speed of 6 m/s at 100 metres, and for the highest study quality. For species that figured in the fitted data (123 species for birds, and 11 species for bats), we included the random effects of species identity in the predictions. For other additional species (354 species for birds and 16 species for bats), we used the models fixed effects only to generate the predictions.

Additionally, we extracted the current threat status of each species from the IUCN Red List of Threatened Species, using the 'iucn_status' function of the 'taxize' R package (Chamberlain & Szöcs, 2013).

2.3.2 Mapping collision-mortality rates

For each species, we mapped the estimated collision-mortality rate by transferring the predicted value onto the species range. As there was no variation in estimated collision-mortality rate within species, and given that we generated predictions for a fixed wind speed value and a fixed turbine capacity, the mapped estimates are spatially uniform at the species level.

At the grid-cell level, we obtained summary statistics of collision-mortality rates across species. Specifically, by stacking the maps for a specified group of species, we calculated:

- the cumulative collision-mortality rate (sum of estimated collision-mortality rates across all species occurring in a grid cell; in other words, total predicted number of collision-mortality victims per year-turbine across all species occurring in a grid cell).

- the mean and median collision-mortality rate (mean and median of estimated collision-mortality rates across all species occurring in a grid cell).

- the standard deviation in collision-mortality rate (standard deviation in estimated collision-mortality rates across all species occurring in a grid cell).

In addition, we obtained species richness for each group of species (number of species occurring in each grid cell).

The summary statistics can be obtained for any subsets of species that are of interest. Here, we present summary statistics across all the bird and bat species we considered. Further, as an example, we present the summary statistics for different taxonomic groups, choosing the four most speciose avian taxonomic Orders in our sample to illustrate this (i.e., *Accipitriformes* – Order containing eagles, hawks, kites, and vultures; *Anseriformes* – Order containing ducks, geese, and swans; *Charadriiformes* – Order which includes shorebirds such as waders, gulls, and auks; and *Passeriformes*, also commonly referred to as 'perching birds'.)

3. RESULTS AND OUTPUTS

3.1 Fitted models

In birds, hand-wing index, mean wind speed, and turbine capacity were significantly positively associated with the number of collision victims (Figure 2; Table A1; note that model coefficients are presented on the log-scale); species' habitat preferences had near-significant effects. The mean number of collision victims (back-transformed estimate of the model's intercept) was 0.0036 collision victims per year-turbine (95% credible interval: 0.00034-0.033). However, the fixed effects explained only a small proportion of the overall variation in the number of collision victims, partly because the random effects explained an important part of the variation (conditional pseudo-R^2: 0.76; marginal pseudo-R^2: 0.002). There were significant differences in the estimated random-effects estimates of species' identity, showing that the mean number of collision victims varied significantly among species (Figure A3).

In bats, we did not detect significant associations between species ecological characteristics and the number of collision victims (Figure 2;

Table A2). The mean number of collision victims (back-transformed estimate of the model's intercept) was 1.4 collision victims per year-turbine (95% credible interval: 0.0069-293). The fixed effects explained only a small proportion of the overall variation in the number of collision victims, while the random effects explained only slightly more variation (conditional pseudo-R^2: 0.18; marginal pseudo-R^2: 0.065). There were few significant differences among the random-effects estimates of species' identity (Figure A3).
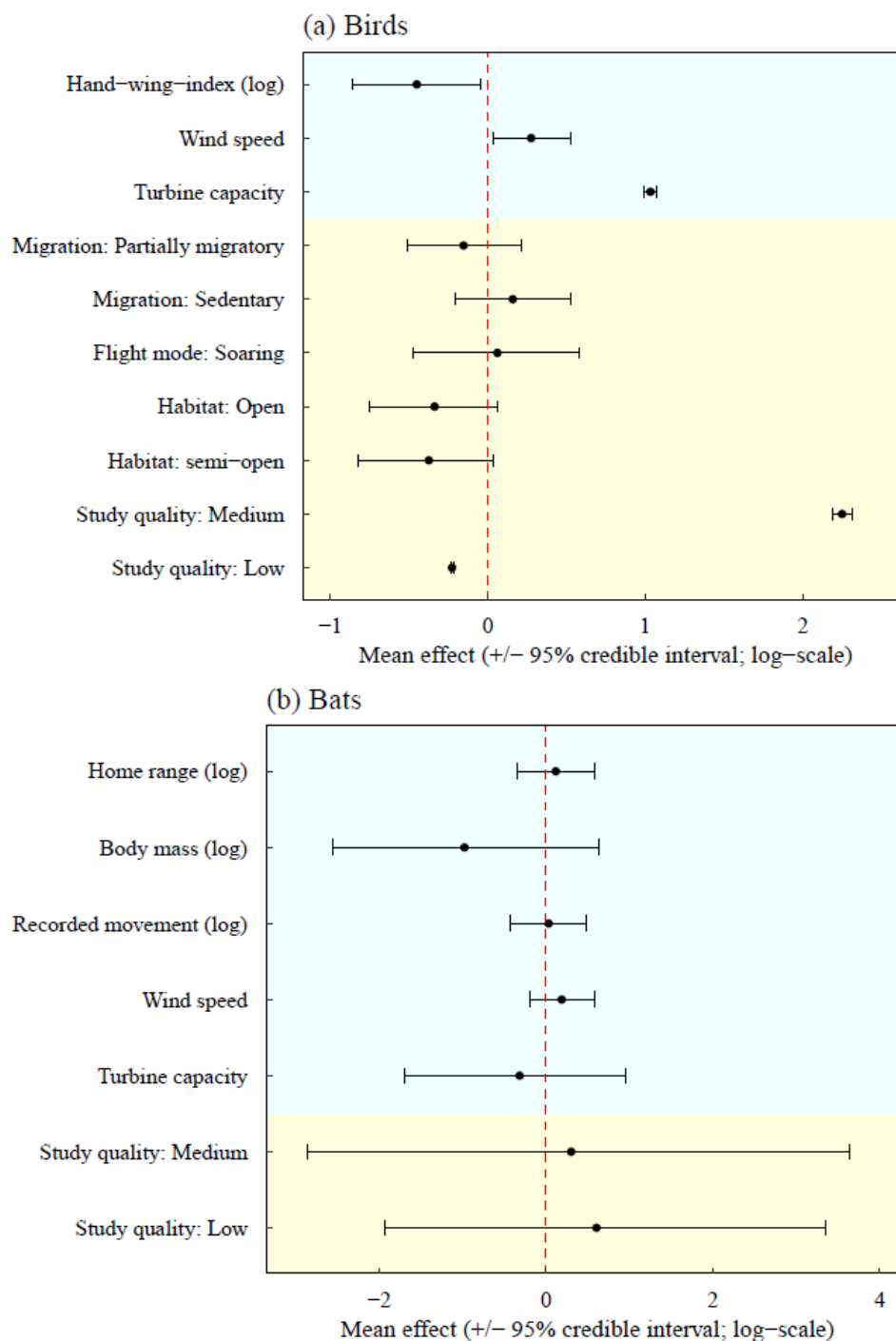
Figure 2: Estimated effects of the fixed predictors for the model fitted on (a) birds and (b) bats, mean ±95% credible interval. Light blue backgrounds highlight continuous predictors, while light yellow backgrounds highlight categorical predictors.

3.2 Estimated collision-mortality rates in birds and bats

3.2.1   Species-level estimates of collision-mortality rates

For 477 birds found to occur in Europe, mean estimated collision-mortality rates ranged between 0.00064 victims per year-turbine (95% credible interval: 0.00038 – 0.001) for the black-crowned night-heron (*Nycticorax nycticorax*), to 1.1 victims per year-turbine (95% credible interval: 0.15 – 4.3) for the common murre (*Uria aalge*). For 95% of the species, the mean estimated collision-mortality rate fell between 0.0025 and 0.081 victims per year-turbine. 2.5% of the species (i.e., 12 species) had an estimated collision rate >0.090 (Figure 3; estimates are presented on the log-scale). There were differences in collision-mortality rates among avian taxonomic Orders (Figure 4). *Piciformes* (Order including woodpeckers and their relatives) had the highest median collision-mortality rate (0.034 victims per year-turbine). *Accipitriformes* (Order including eagles, hawks, kites, and vultures) had the highest mean collision-mortality rate (0.045 victims per year-turbine) after *Columbiformes* (Order including doves and pigeons; mean collision-mortality rate: 0.063 victims per year-turbine).

For bats, mean estimated collision-mortality rates ranged between 0.085 victims per year-turbine (95% credible interval: 0.0016 – 0.49) for Geoffroy's bat (*Myotis emarginatus*), to 2.3 victims per year-turbine (95% credible interval: 0.044 – 13) for the common pipistrelle (*Pipistrellus pipistrellus*). For 95% of the species, the mean estimated collision mortality fell between 0.15 and 1.9 victims per year-turbine. One species (*Pipistrellus pipistrellus*) had an estimated collision-mortality rate >1.9 (Figure 3; estimates are presented on the log-scale).
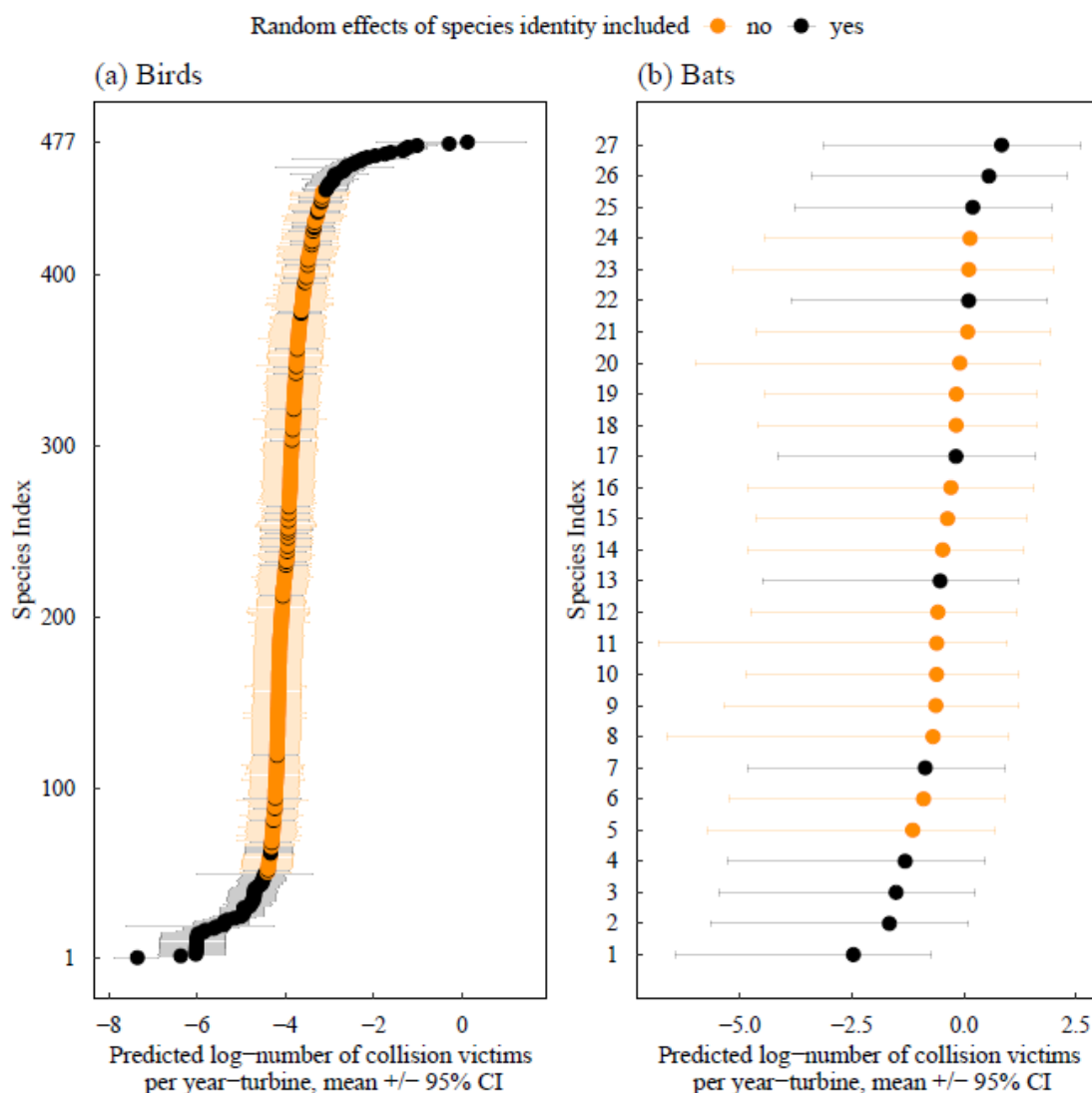
Figure 3: Predicted number of collision victims per year-turbine (mean ± 95% credible interval) for (a) 477 bird species and (b) 27 bat species known to occur in Europe. The predictions are plotted on the log-scale. The predictions were generated for a turbine capacity of 2MW, a mean wind speed at 100m of 6m/s, and a high study quality.
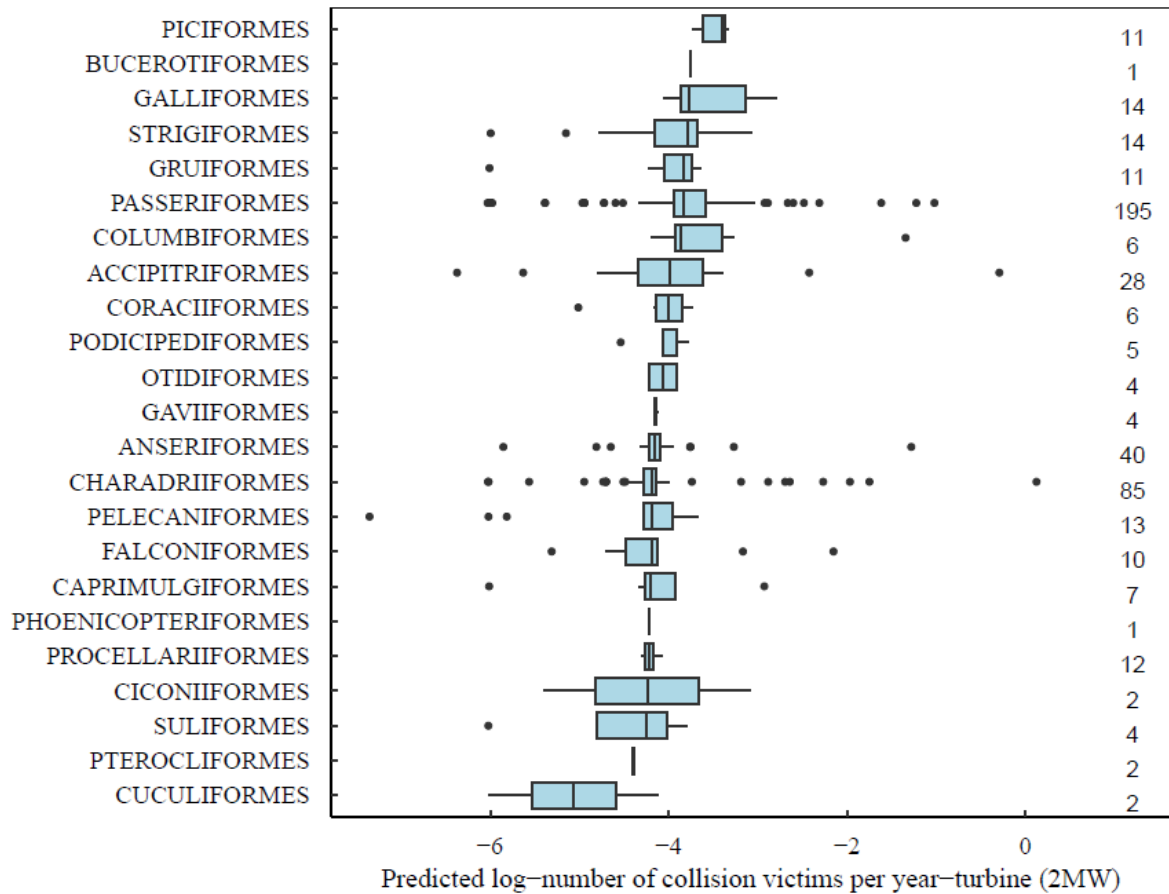
Figure 4: Distribution of predicted number of collision victims per year-turbine within avian taxonomic Orders. Numbers on the right-hand side of the plot show the sample sizes (number of species) in each Order. The predictions are plotted on the log-scale. The predictions were generated for a turbine capacity of 2MW, a mean wind speed at 100m of 6m/s, and a high study quality.

3.2.2 Distribution of estimated collision-mortality rates among IUCN threat status groups

Among the species of birds we considered, 32 were listed as threatened (i.e., vulnerable, endangered, or critically endangered) according to the IUCN Red List of Threatened Species; three species of bats were listed as vulnerable (Figure 5).
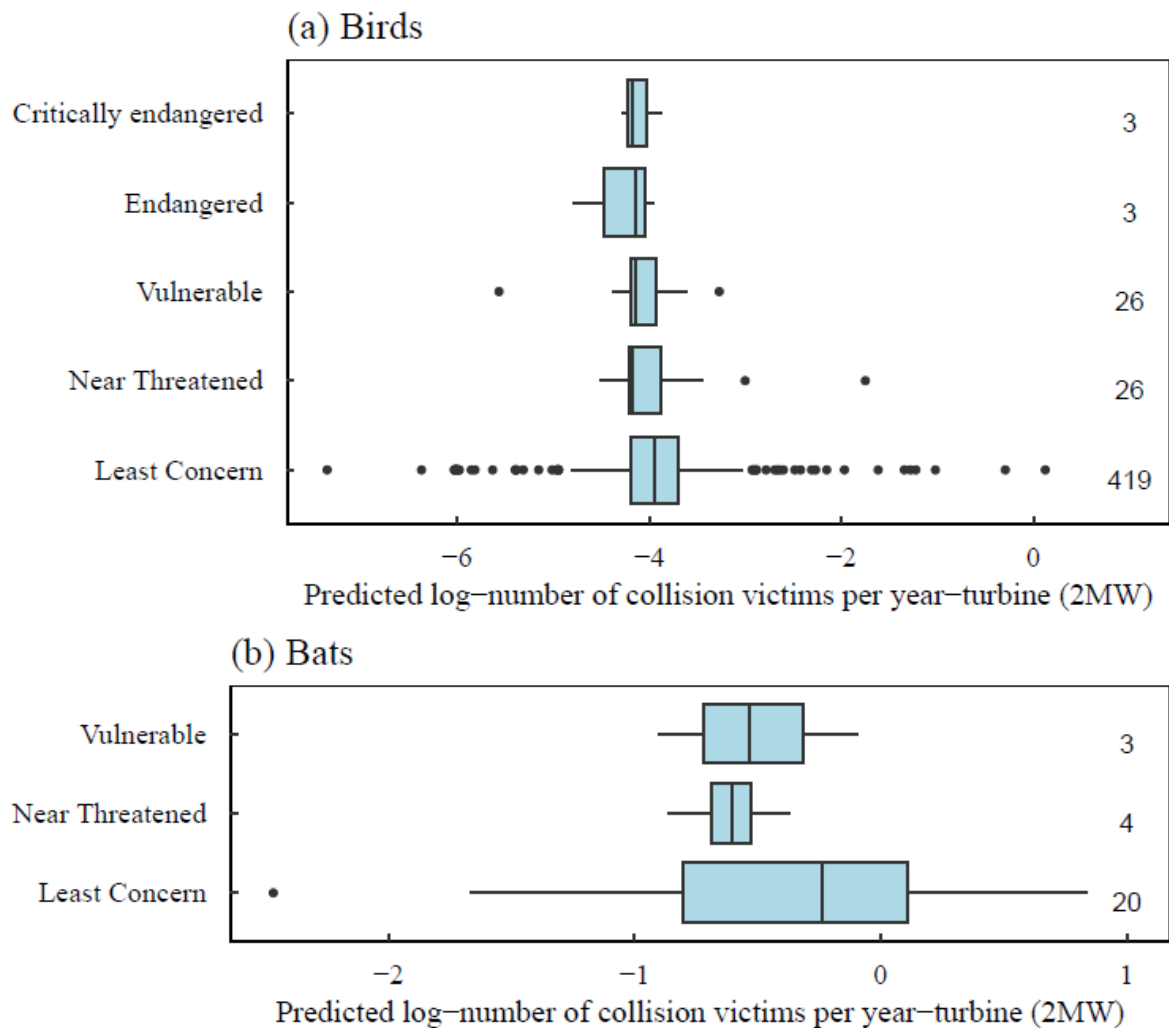
Figure 5: Distribution of predicted number of collision victims per year-turbine by threat status. Numbers on the right-hand side of the plot show the sample sizes (number of species) in each threat status group. The predictions are plotted on the log-scale. The predictions were generated for a turbine capacity of 2MW, a mean wind speed at 100m of 6m/s, and a high study quality.

3.3 Mapping estimated collision-mortality rates onto species distributions

For each species, we transferred the value of the estimated collision-mortality rate onto the species range. By stacking the maps across a specified group of species, we obtained summary statistics (sum, mean, median and standard deviation of estimated collision-mortality rates across all species occurring in a grid cell). Summary maps can be obtained for any group of species of interest. Here, we provide examples of summary maps for all considered bats and birds, as well as for the four most speciose

avian Orders in our sample (*Accipitriformes, Anseriformes, Charadriiformes,* and *Passeriformes*).

3.3.1   Summary maps across all considered bat species

In bats, the cumulative mortality rate (sum of collision-mortality rates across all species occurring in a grid cell) reflected patterns of bat species richness for the considered species (Figure 6), likely because there were few significant differences in estimated collision-mortality rates across the 27 species. Consequently, there was little spatial variation in mean, median, and standard deviation in estimated collision-mortality rates.
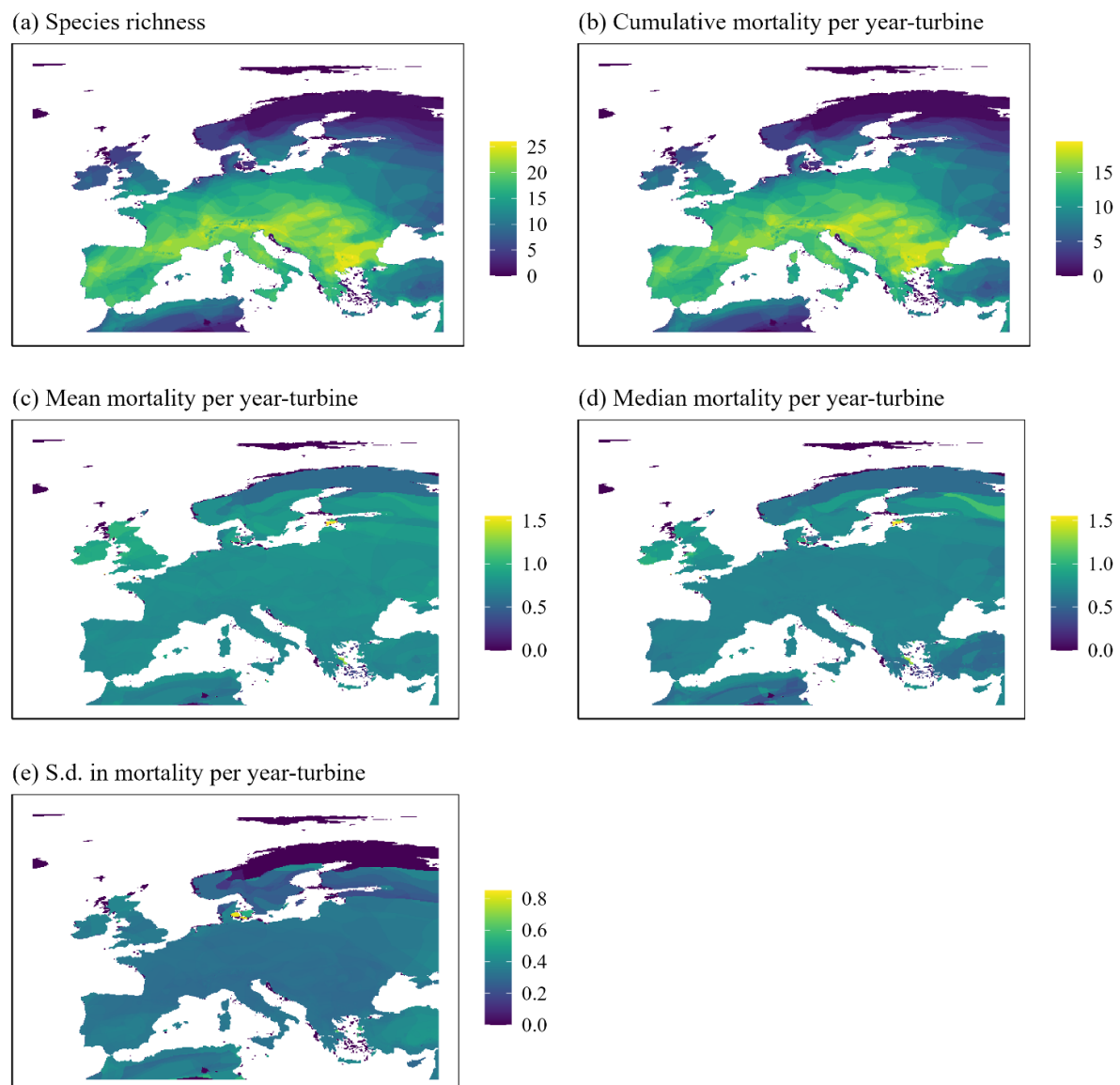
Figure 6: (a) Number of bat species found to occur in each grid cell (species richness, for the 27 species considered); both breeding and non-breeding parts of

the ranges are included. (b)(c)(d)(e) Summary statistics of estimated collision-mortality rates across all bat species occurring in a grid cell (sum, mean, median, and standard deviation).

3.3.2   Summary maps across all considered bird species

In birds, cumulative mortality rate varied spatially, and did not reflect spatial patterns of species richness (Figure 7), likely because there were significant differences in estimated collision-mortality rates across species.
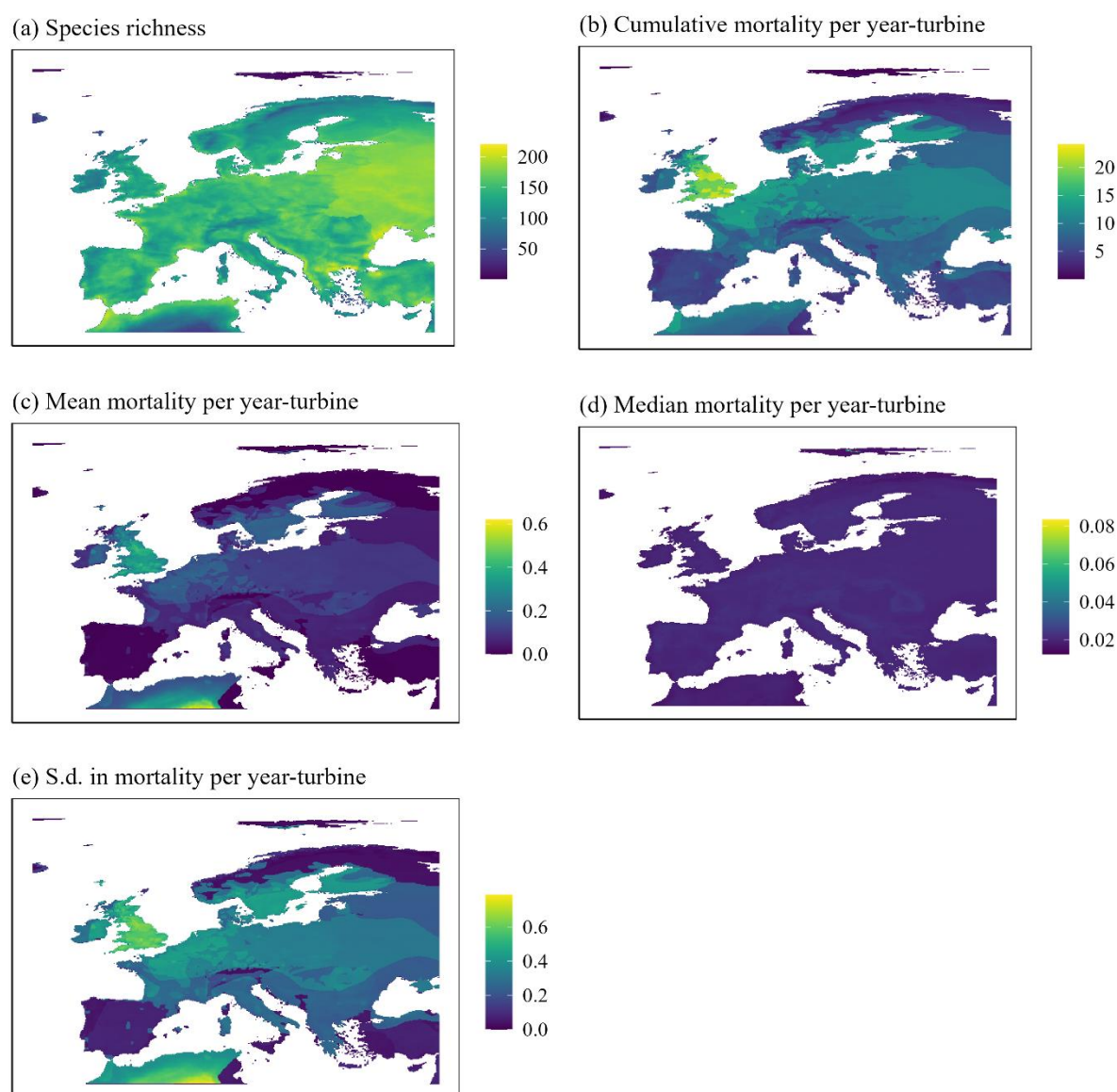
Figure 7: (a) Number of bird species found to occur in each grid cell (species richness, for the 477 species considered); both breeding and non-breeding parts of the ranges are included. (b)(c)(d)(e) Summary statistics of estimated collision-mortality rates across all bird species occurring in a grid cell (cumulative sum, mean, median, and standard deviation).

3.3.3 Summary maps within four avian taxonomic Orders

Mapping cumulative mortality rate within four avian taxonomic Orders (Figure 8) illustrated how different Orders contributed to the overall pattern in cumulative mortality rate (across all birds; Figure 7). Spatial patterns in cumulative mortality rates differed among the four most speciose avian Orders we considered (Figure 8), highlighting the distinct contributions of different Orders to overall spatial variation in collision mortality. These distinct contributions highlight that collision mortality at any given location depends on the local composition of the ecological assemblage.
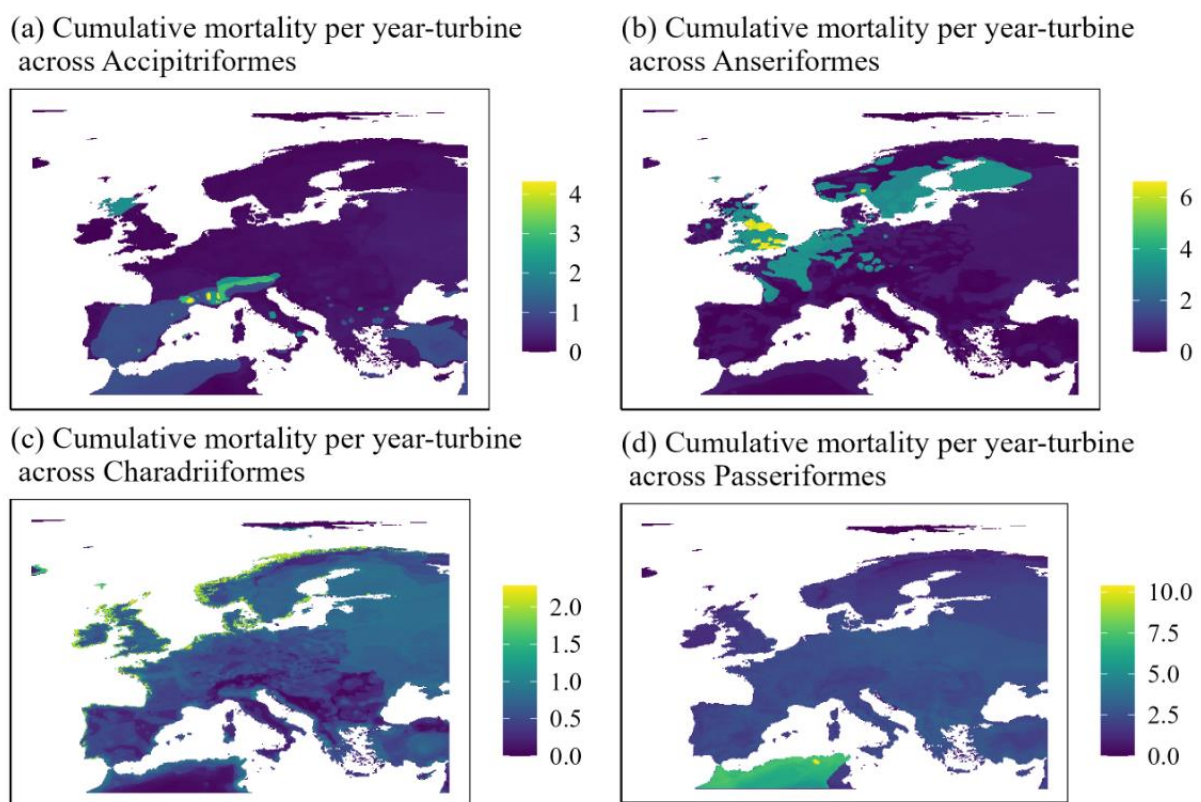
Figure 8: Estimated cumulative collision-mortality rate (sum of estimated collision-mortality rates across all species occurring in a grid cell), for the four most speciose avian taxonomic Orders in our sample: (a) *Accipitriformes*; (b) *Anseriformes*; (c) *Charadriiformes*; (d) *Passeriformes*.

We showed maps of cumulative mortality rates for four taxonomic Orders as examples, but these maps can also be generated for any group of species of interest.

3.4 Outputs

Some outputs described in Table 3 are accessible on the project's Yoda platform. The files and metadata are accessible under: ‹research-wimby-data/wimby_intermediate_results/D1.5_birds_bats_collision_mortality_rates›.

Table 3: Description of the outputs and results of the task (Task 1.3).

Result	Format and access
Dataset: Estimated collision-mortality rate at the species level, i.e., predicted number of collision victims per turbine-year, mean and 95% credible intervals. Provided for birds and bats separately.	2 datasets, .csv files, under *D1.5_birds_bats_collision_mortality_rates/ 1_species_level_predictions_tables*
Maps: Mean estimated collision-mortality rate projected onto each species range, processed to include breeding and non-breeding areas. Cropped around Europe; resolution of 10 km by 10 km; Behrmann's equal-area projection.	Code to generate outputs accessible upon request. Species distribution data freely accessible at https://www.iucnredlist.org/resources/spatial-data-download http://datazone.birdlife.org/home
Maps: species richness and summary statistics of collision-mortality rate across all species occurring in a grid cell; for all considered bats and birds, and for four avian taxonomic subsets (Accipitriformes, Anseriformes, Charadriiformes, Passeriformes).	Code to generate outputs accessible upon request. Species distribution data freely accessible at https://www.iucnredlist.org/resources/spatial-data-download http://datazone.birdlife.org/home

4. DISCUSSION, LIMITATIONS, AND POSSIBLE DEVELOPMENTS

Using compiled data on recorded collision mortality for bird and bats, we investigated whether species traits, mean wind speed at the central location of wind farms, and turbine capacity, were associated with collision-mortality rates. From the models, we predicted collision-mortality rates (estimated number of collision victims per year-turbine) for 477 bird and 27 bat species known to occur in Europe. We mapped the outputs to visualise spatial patterns in collision mortality across Europe. Our work contributes to assess potential areas of higher risk from wind-power developments for flying animals at the European scale and can be employed in further tasks and work packages of the WIMBY project. Our outputs also help to assess which species could be more affected by wind-power developments. However, we caution that the work and associated outputs presented here will be consolidated in the upcoming months towards Version (b).

We found that collision-mortality rates for birds were overall low (but see Nilsson et al. (2023)), but with significant variation around the mean attributed to fixed effects. We found hand-wing index, turbine capacity, and mean wind speed to be significantly positively associated with collision-mortality rates. In past work, larger turbines with higher capacity have also been found to be associated with higher collision rates (Thaxter et al., 2017), but Thaxter et al. (2017) emphasized that deploying fewer turbines of higher capacity should result in lower mortality overall than deploying more turbines of lower capacity. The positive association of hand-wing index and mean wind speed with collision mortality might indicate that species tending to disperse further, and areas of higher average wind speed, may experience higher collision mortality. Here, we maintained a fixed value for wind speed when generating estimates of collision mortality; in further developments, wind speed may be allowed to vary spatially.

However, the fixed-effects structure of the model fitted on birds explained only a small part of the overall variation in collision-mortality rate (~0.2%). The random-effects structure explained a more important part of the variation (~76%). Interspecific variation in collision mortality were notably captured by the random effects of species identity, again highlighting

significant differences in collision mortality across species. For instance, we found high collision mortality rates for the Griffon vulture (*Gyps fulvus*; estimated mean collision mortality rate: 0.75 victims per year-turbine) and the common murre (*Uria aalge*; estimated mean collision mortality rate: 1.1 victims per year-turbine). Further, collision mortality rates in bats were overall higher than in birds, but we did not detect any significant differences in collision-mortality rates among the considered bat species, such that spatial patterns in collision mortality reflected patterns in the species richness of the considered bats. This might indicate that bat species richness could be used as a proxy for collision mortality risk at the European scale. However, the sample size for bats was lower than for birds, with fewer sampled species and sites, which might impede our ability to detect potential effects. Further developments could include consolidating the collision mortality data for bats.

In both birds and bats, we fitted random effects of local site (wind farm) identity, to control for differences in collision-mortality rates among wind-farm locations. There were significant differences in estimated random effects of site identity (Figure A4), which highlights the importance of local, site-level characteristics for assessing collision-mortality risk. Local landscape characteristics are known to influence collision mortality (Kuvlesky Jr. et al., 2010; Moustakas et al., 2023), and context-specificity has been highlighted in past work (Marques et al., 2014). Our work emphasizes again the importance of local-scale assessments of collision-mortality risk for wind-power projects. Developments of our work could include investigations of the variation captured by the random effects of site identity, asking for example whether this variation can be explained by capturable site-level characteristics (e.g., terrain).

In bats, most of the variation (~82%) in collision mortality rates remained unexplained by our model's fixed- and random-effects structure, while in birds, about 24% of the variation remained unexplained. Unexplained variation could be attributable to factors influencing collision mortality that we did not capture in our models. Some of these factors may relate to environmental characteristics such as landscape and terrain, as well as to

variability in weather conditions, to wind-farm characteristics (e.g., lighting), or to species characteristics that we did not include. It is also possible that different factors have interactive effects on collision-mortality rates. Developments of our work could include investigations of other possible correlates of collision mortality, or investigations of interactive effects among species-level and site-level correlates of collision mortality.

A limitation of our work is that we did not account for intraspecific variation in collision-mortality rates. Collision-mortality rates may vary within a species, for instance with the age of individuals (Dahl et al., 2013). However, capturing intraspecific variation in trait values was infeasible in our work. Further, among the different factors that influence collision mortality, some may be capturable at the species- and landscape-level, but other factors (such as weather, or species behavioural plasticity) are difficult to capture in a quantitative synthesis such as ours. Ultimately, collision mortality is influenced by complex interactions among a wide range of factors (Drewitt & Langston, 2008; Marques et al., 2014), some of which possibly difficult to account for. Another limitation of our work is that the estimated collision-mortality rates are yearly averages; however, collision mortality can vary seasonally (Balmori-de la Puente & Balmori, 2023; Cabrera-Cruz & Villegas-Patraca, 2016; Lloyd et al., 2023), but we did not account for such temporal variations here.

Our work nevertheless provides species-level estimates of collision-mortality rates which can help assess which species and areas could be most affected by wind-power developments at the continental scale. An important question is how collision mortality impacts species populations and demography on the long term and over large spatial scales (Arnett & May, 2016; Chambert & Besnard, 2021; Desholm, 2009; Duriez et al., 2023; May et al., 2019). Long-term impacts of collision mortality depend on species' demography and population density. Further developments of our work could consider investigating collision-mortality rates in relation with species traits that pertain to demography, such as generation length or reproductive outputs.

Finally, while wind-power farms can negatively affect flying animals through collision mortality, the effectiveness of different mitigation measures for reducing collision mortality has been assessed in some past works (Marques et al., 2014), which show that mitigation measures can successfully reduce collision mortality at wind-power farms (Arnett et al., 2011; de Lucas et al., 2012; Ferrer et al., 2022). As anthropogenic pressures on biodiversity act in combination (Harfoot et al., 2021; Maxwell et al., 2016), it is notably important to ensure that wind farms do not increase the risk for species that are already threatened by multiple other anthropogenic pressures, by putting into place appropriate mitigation strategies (Arnett & May, 2016; Voigt et al., 2022).

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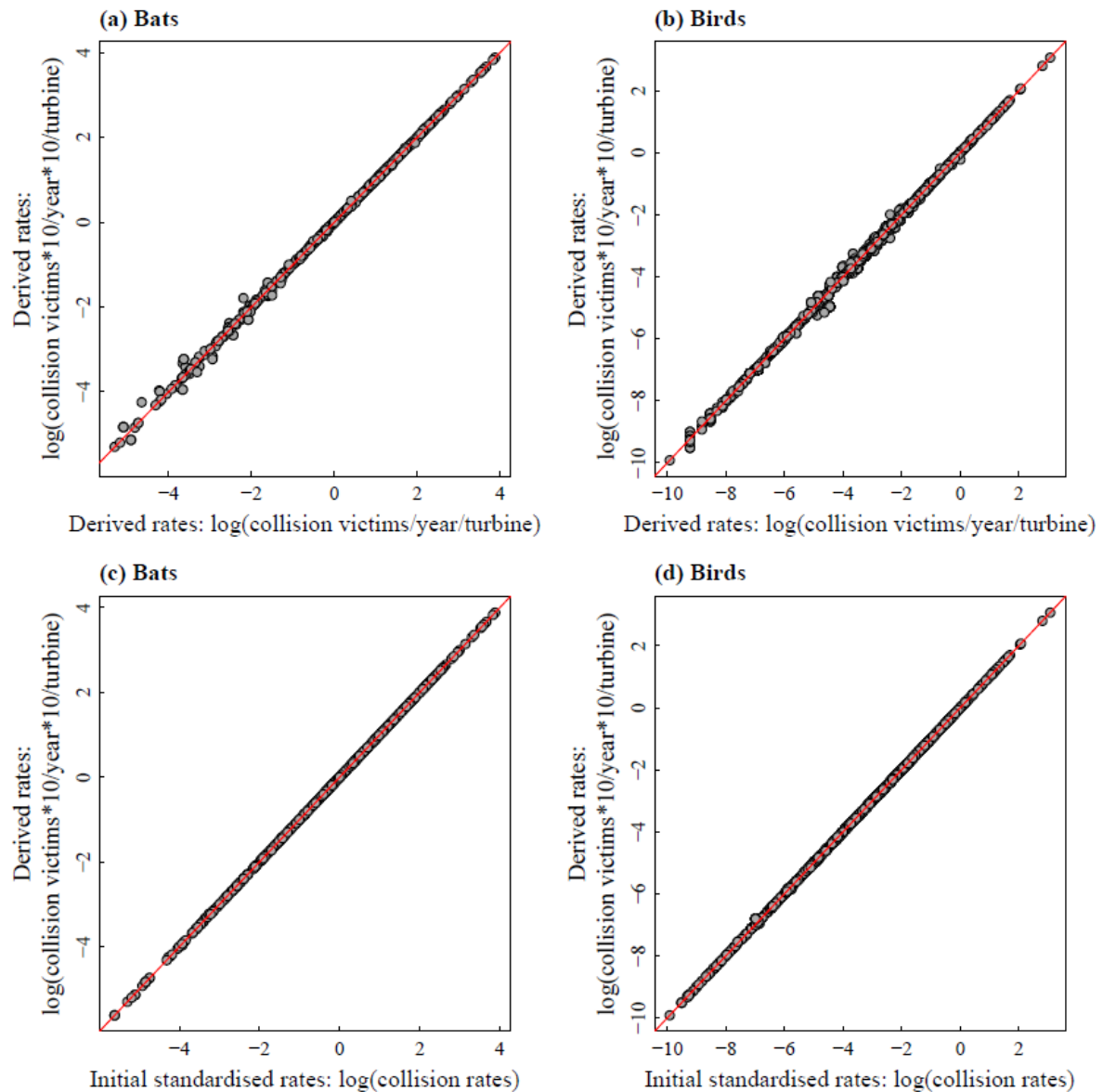
ANNEX

Figure A1: (a) and (b): Collision-mortality rates derived from the original compiled data, calculated after converting the original rates to counts of collision victims, either after multiplying original rates and study duration by 10 before rounding (y-axis), or rounding values directly without multiplying by 10 (x-axis). (c) and (d): Derived collision-mortality rates we used (from counts and study duration multiplied by 10; y-axis) against the original collision-mortality rates in the data.
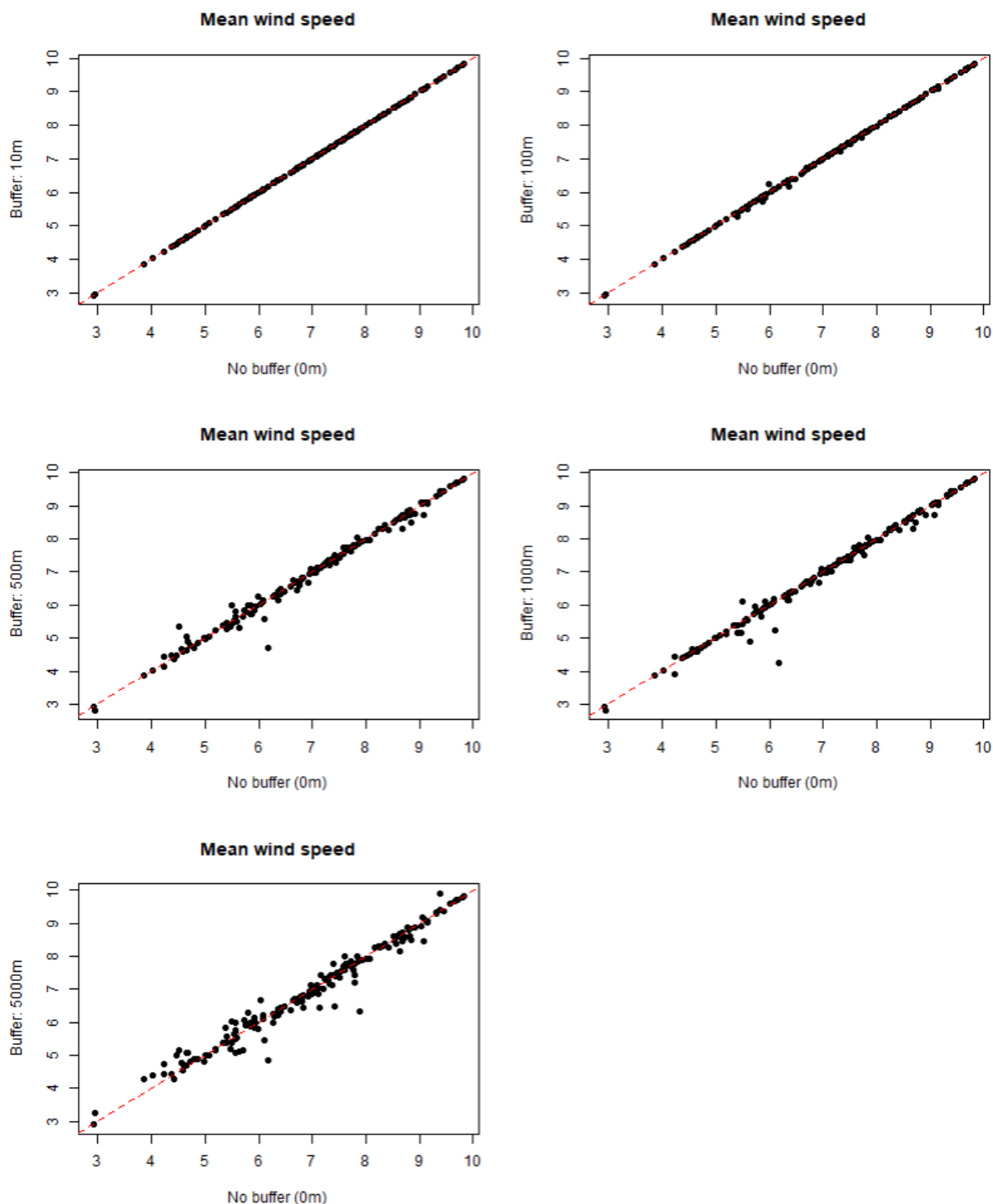
Figure A2: Mean wind speed (m/s) at 100 metres at the central wind farms' locations calculated using various buffer sizes around the locations: 0m (no buffer), 10m, 100m, 500m, 1000m, and 5000m.

Table A1: Summary of the model fitted for birds, investigating associations of collision-mortality rates with species-level characteristics, mean wind speed at the wind farms' central locations, and turbine capacity.

	Collision fatality counts	
Predictors	Log-Mean	CI (95%)
Intercept	-5.63	-7.98 – -3.41
Migration: partial migrant	-0.16	-0.51 – 0.21
Migration: sedentary	0.16	-0.21 – 0.53
Flight mode: soaring	0.07	-0.47 – 0.58
Habitat density: open	-0.33	-0.75 – 0.06
Habitat density: semi open	-0.37	-0.83 – 0.04
Hand-wing index (log)	-0.45	-0.86 – -0.04
Mean wind speed	0.27	0.03 – 0.53
Turbine capacity	1.03	0.99 – 1.07
Quality: Medium	2.25	2.19 – 2.31
Quality: Low	-0.23	-0.24 – -0.22
Random effects		
σ^2	10952284.16	
$N_{\text{Study ID}}$	80	
$N_{\text{Site ID}}$	68	
N_{Species}	330	
Observations	2204	
Marginal R^2 / Conditional R^2 0.002 / 0.761		

Table A2: Summary of the model fitted for bats, investigating associations of collision-mortality rates with species-level characteristics, mean wind speed at the wind farms' central locations, and turbine capacity.

|	Collision fatality counts	
Predictors	Log-Mean	CI (95%)
Intercept	0.32	−4.97 − 5.68
Home range (log)	0.12	−0.35 − 0.58
Body mass (log)	−0.97	−2.56 − 0.63
Recorded movement (log)	0.03	−0.43 − 0.48
Mean wind speed	0.19	−0.19 − 0.58
Turbine capacity	−0.30	−1.69 − 0.96
Quality: Medium	0.24	−2.85 − 3.65
Quality: Low	0.57	−1.93 − 3.36
Random effects		
σ^2	57248.26	
$N_{\text{Study ID}}$	11	
$N_{\text{Site ID}}$	41	
N_{Species}	11	
Observations	337	
Marginal R^2 / Conditional R^2 0.065 / 0.184		
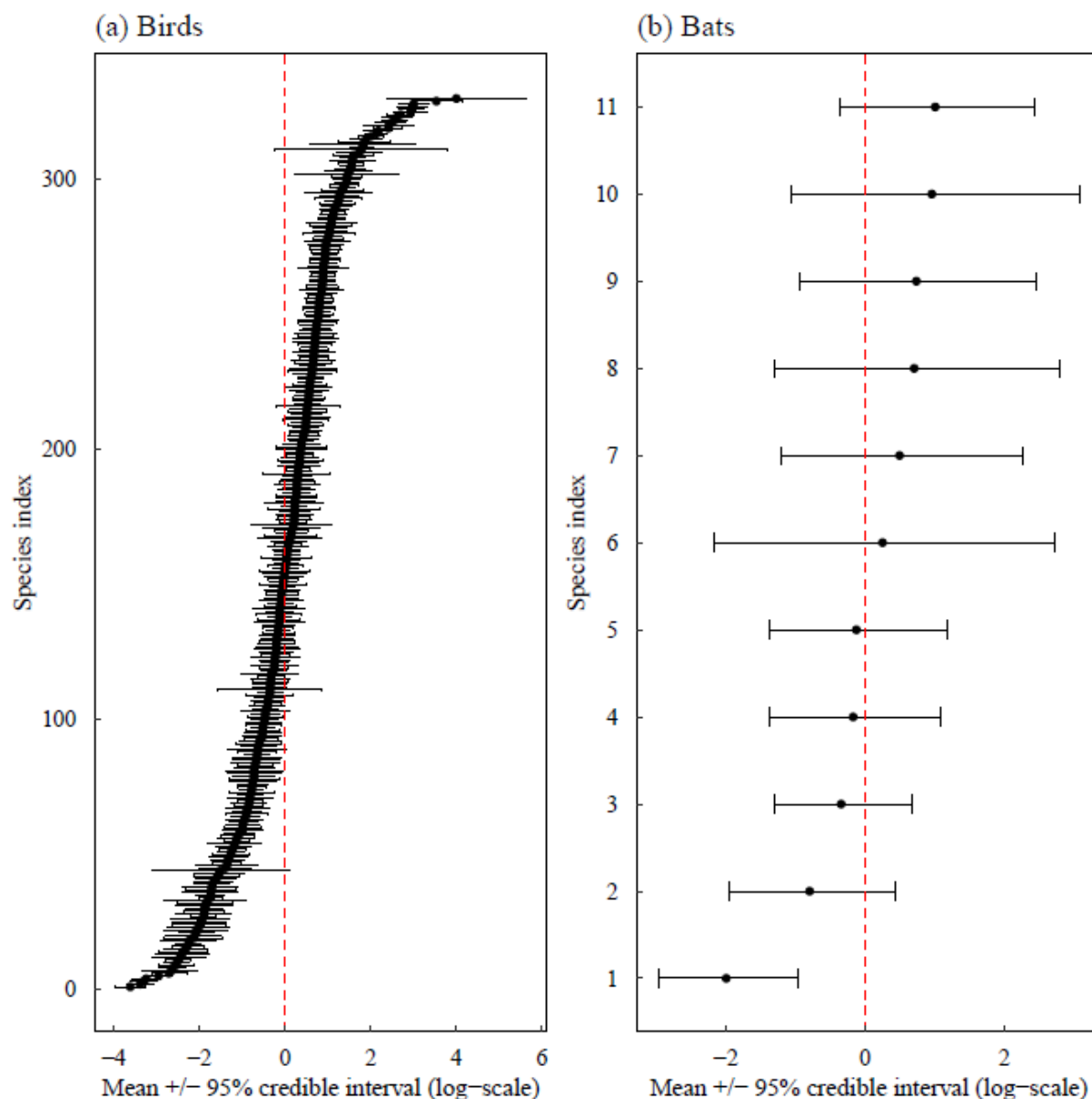
Figure A3: Random-effects estimates of species identity for the model fitted on (a) birds and (b) bats, investigating associations of collision-mortality rates with species-level characteristics, mean wind speed at the wind farms' central locations, and turbine capacity.
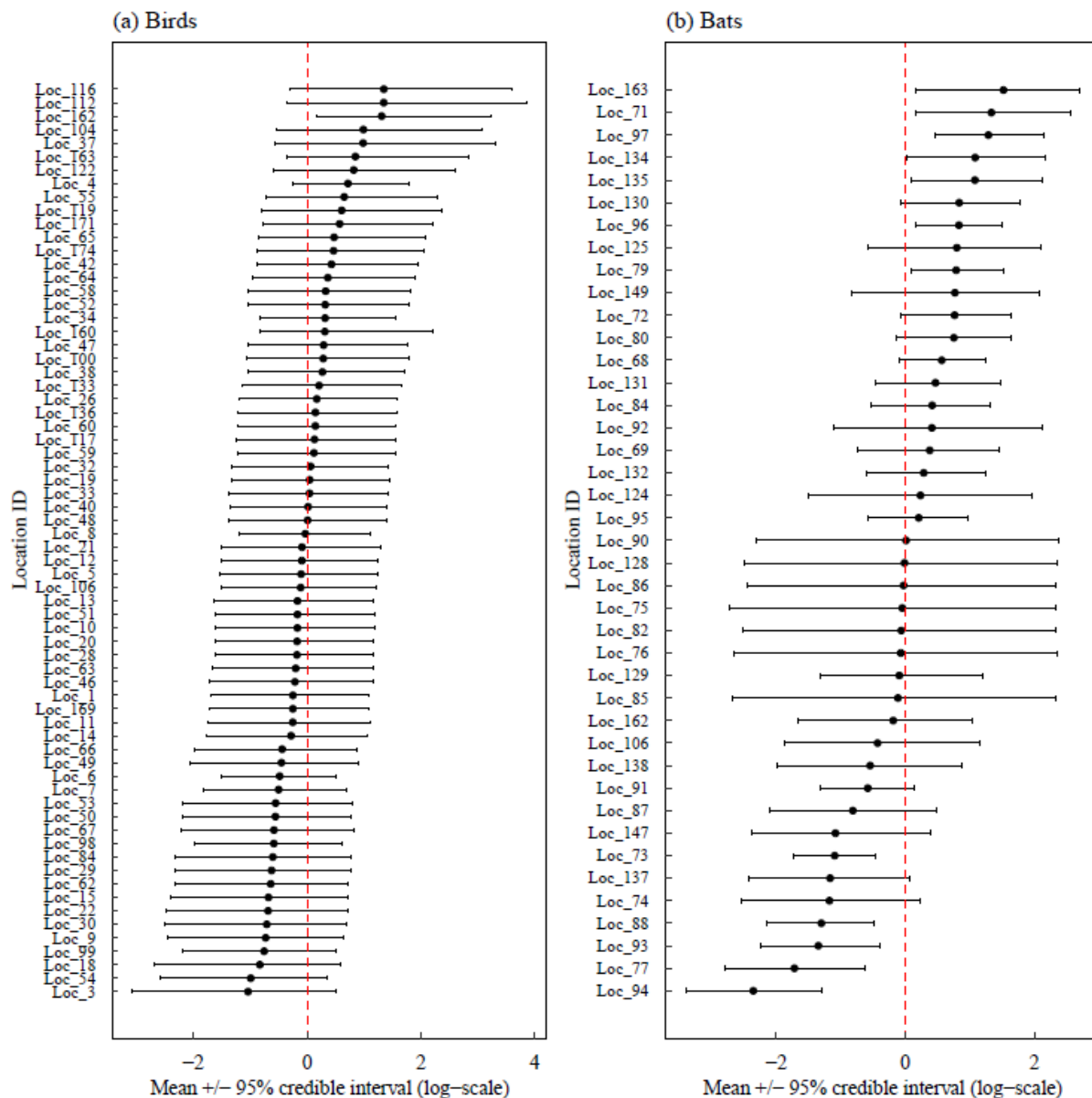
Figure A4: Random-effects estimates of site locations (central wind farms' locations) for the model fitted on (a) birds and (b) bats, investigating associations of collision-mortality rates with species-level characteristics, mean wind speed at the wind farms' central locations, and turbine capacity.