Different sources of wind turbine data produce sharp differences in collision risk estimates for foraging vultures

Jacopo Cerri [1], Ilaria Fozzi [1], Chiara Costantino [1], Dhyan Anaja Banic [2], Davide De Rosa [1], Joel Echeverria [3], Luce Pavin [4], Marco Muzzeddu [5], Martina Scacco [6 7], Dionigi Secci [5], Fiammetta Berlinguer [1]

1. *Department of Veterinary Medicine, University of Sassari, Via Vienna 2, 07100, Sassari, Italy* jcerri@uniss.it
2. *Faculty of Mathematics, Natural Sciences and Information Technologies, University of Primorska, Glagoljaška 8, 6000 Koper, Slovenia*
3. *Faculty of Biological Sciences, University of Valencia, Carrer del Dr. Moliner 50, 46100, Burjassot, Spain*
4. *Department of Biology, Faculty of Science, University of Zagreb, Roosveltov trg 6, 10 000 Zagreb, Croatia*
5. *Agenzia Forestale Regionale per lo Sviluppo del Territorio e l'Ambiente della Sardegna (Fo.Re.S.T.A.S.), Viale Luigi Merello 86, Cagliari 09123, Italy*
6. *Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany*
7. *Department of Biology, University of Konstanz, Konstanz, Germany*

Abstract

Multiple studies assessed the collision risk of different vulture species with wind turbines. However, they relied on different sources of wind turbine data, and the effect of this data heterogeneity, on the estimated collision risk and the comparability of these assessments, has not been investigated.

We used GPS and accelerometer data, collected from 6 adult Griffon Vultures (*Gyps fulvus*) living in Sardinia (Italy), a hotspot of wind energy development, to assess how the use of different wind turbine data sources influences collision risk assessments. As a measure of collision risk, we compared changes in the proportion of foraging grounds overlapping with the wind turbine locations obtained from three different sources available for Sardinia: Open Street Maps, a map available from Smeraldo *et al*. (2020), and a map obtained from aerial pictures, available from Cerri *et al*. (2024). We finally used information about planned wind turbines to evaluate how the overlap (area of collision risk) is likely to change in the near future.

We found that the source of wind turbine data can strongly influence the output of collision risk estimates. Turbines identified from aerial pictures overlapped more with foraging grounds (18.7%) than turbines from Open Street Maps (8.7%) and from Smeraldo et al. (15.9%). Finally, 31.4% of vultures' foraging grounds would overlap with turbines in the next few years, almost doubling the area currently considered at risk.

We suggest that developing reliable, accessible and periodically updated maps of existing and planned wind turbines should be a priority for environmental agencies, given its importance for conservation planning and the increase in renewable energy development.

keywords: anthropogenic infrastructures; insular populations; Google Satellite; scavengers; Mediterranean; foraging ecology; accelerometer;

Warning

This is a ***preprint***, not a peer-reviewed study. If you do not know what a preprint is, we encourage you to read more about this type of documents (https://en.wikipedia.org/wiki/Preprint), before evaluating and citing the study.

Introduction

Infrastructures associated with wind energy production have been an important focus of biodiversity conservation [1]. Wind turbines generate approximately 8% of the total energy produced worldwide (https://www.iea.org/energy-system/renewables) but are also known to impact species and ecosystems. Wind turbines decrease the quality of natural habitats [2], affect animal behavioural patterns [3] and increase wildlife mortality through collisions with rotating blades [4][5][6]. These impacts are particularly concerning for those areas of the world where terrestrial ecosystems are already characterized by a high human footprint, such as Europe [7].

The ecological impacts of wind power development could also indirectly affect human well-being, by disrupting crucial ecosystem services, through an increased mortality in keystone taxonomic groups [8][9][10][11]. In this sense, the impact of wind power development on vultures is of particular concern [12]. Vultures are apex scavengers delivering irreplaceable ecosystem services, such as the mitigation of greenhouse gas emissions, the disposal of organic materials and the containment of zoonotic diseases [13]. However, because of their low flight maneuverability and foraging behaviour, involving low-altitude flight while looking at the ground in search of carcasses [14], vultures are particularly exposed to collision risk. Griffon Vulture (*Gyps fulvus*) is reported as the most frequently killed raptor species in wind farms (0.41 deaths/turbine/year)[15]. This high mortality rate, combined with their low annual productivity and slow maturity, is thought to undermine the population viability of this species and of vultures in general [5]. The foreseen global expansion of onshore wind farms and their associated electric grid, particularly nearby vulture colonies and foraging grounds [16], is therefore expected to increase mortality in many vulture populations [17][18]. This risk is particularly concerning for the conservation of European vulture populations, as Europe emerged as a stronghold for the guild after the large declines of Asian and African vulture populations that pushed some species to the brink of extinction.

Maps of existing and planned wind turbines represent the first crucial information needed to evaluate collision risk, and thus to design conservation strategies and mitigation measures [19] for vultures as well as any other species. Nevertheless, while several studies already tested different methods to perform fine-scale risk assessment [20][21], or generate risk maps for vultures at large spatial scales [19][22][23] no study considered to what extent differences between available data sources on wind turbine locations can affect these results. This gap is considerable, because in many countries the proliferation of wind turbines has not been coupled with the implementation of maps complying with well-established standards of quality [24][25]. Therefore, risk assessments often rely on maps of wind energy "potential" - representing areas with the most suitable wind conditions for the construction of wind farms [12] - or on maps of existing wind turbines of unknown quality [19][23]. This heterogeneity in the accuracy and type of wind turbines data sources is expected to hinder the comparability of risk assessments and challenge their reliability. Recently, Cerri *et al.* (2024) [26] found that some of these data sources severely underestimate the number of wind turbines that are effectively present in the environment, at least in areas of intensive wind energy development. However, the extent to which these differences affect the collision risk estimates are yet to be investigated.

In this study, we used a combination of movement data from Griffon Vultures and three different wind turbine data sources, to assess how these affect collision risk assessments. Sardinia is the second largest island in the Mediterranean sea, it is highly suitable for wind power development and is facing an increase in onshore wind farms (Fig. S1)[26], with 102 projects submitted to the Ministry of the Environment for development in the next few years. Sardinia also hosts a stable population of Griffon Vultures, and therefore represents an interesting study area for the evaluation of the impact of wind farms on this species, as already demonstrated by recent studies [26]. In particular, here we used GPS and accelerometer data from 6 adult Griffon Vultures freely roaming on the island. Because of their foraging behaviour, the foraging grounds of Griffon Vultures are considered as the areas of highest collision risk. To quantify this risk, we thus estimated the overlap between Griffon Vultures' foraging grounds and wind turbines, whose locations were obtained from three different sources: namely Open Street Maps (*i*), a map available from a publication by Smeraldo *et al.* (2020) [27] (*ii*) and a dataset recently developed from aerial pictures, representing turbines that are effectively present in the study area, from a publication by Cerri *et al.* (2024) [26]. Finally, given the high number of new wind turbines planned for this area in the coming years, we used information obtained from the projects submitted to the Ministry of the Environment to evaluate upcoming changes in collision risk.

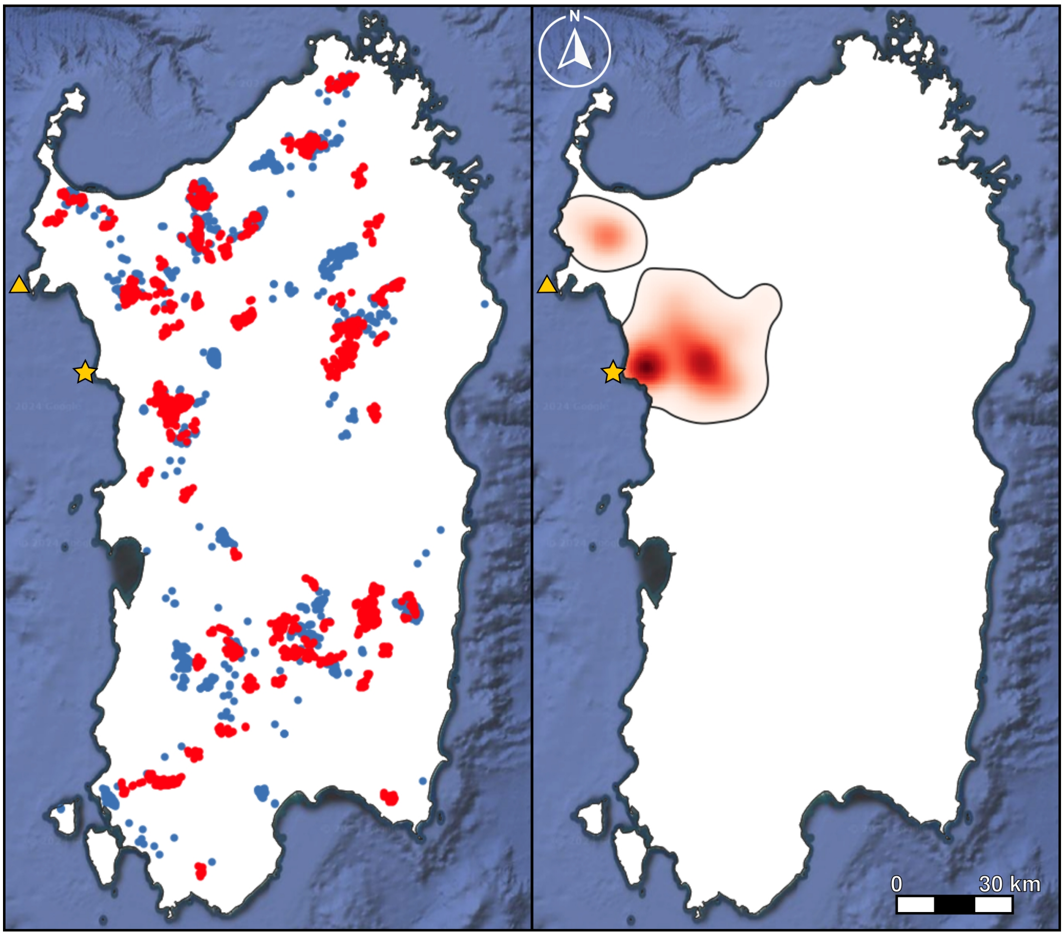

Figure 1: Left: location of wind turbines that were present in Sardinia in 2023 (blue dots) and that were planned (red dots), according to Cerri et al., 2024. Right: UD representing the foraging grounds of Griffon Vultures in Sardinia, resulted from our analysis of feeding events. Darker areas correspond to those portions of the foraging grounds with the highest density of feeding events. The location of the colony in Punta Cristallo is represented by a triangle, whereas the colony in Bosa by a star.

Materials and methods

Study area

The study area includes the northwestern portion of Sardinia (Italy, Fig. 1). Sardinia hosts a population of approximately 420-470 Griffon Vultures (Berlinguer et al., 2025 in prep.), which concentrate their movements between two main colonies in the northwestern part of the island [28].

In Italy, planned wind farms are subjected to a preliminary environmental impact assessment, but there is no mandatory standard about the design of monitoring protocols [29]. Moreover, a post-construction impact assessment is not mandatory and, even if carried out, there is no standard protocol to be followed for an accurate estimation of the number of animals killed by the turbines. Therefore, best practices, such as the use of trained dogs [30], or the estimation of carcass removal by scavengers [31], are not implemented. Finally, in case an impact is highlighted by the non-mandatory assessment, there is no legal obligation to implement mitigation measurements, such as selective stopping [32] or blade painting [33]. Despite the lack of monitoring schemes at wind farms, in the study area at least 3 Griffon Vultures mortality events due to collision with wind turbines have been documented since 2014.

Wind turbines data sources

To our knowledge, no officially recognised map of wind turbines is publicly available for the study area. We therefore relied on three unofficial but publicly available datasets of wind energy infrastructures in Sardinia: (*i*) OpenStreetMap (`OSMhttps://www.openstreetmap.org`), an open-source GIS where infrastructures are georeferred by volunteers, which is widely used in ecology and conservation [23][34][35][36][37][38][39][40]; (ii) a map published by Smeraldo et al. (2020)[27], who validated multiple pre-existing datasets through satellite images and created a map of wind turbines operating in Italy in 2019-2020; (*iii*) a map recently published by Cerri et al. (2024)[26], representing wind turbines that were effectively present in the study area in September/October 2023, according to the most recent high-resolution aerial images available on Google Satellite. Despite its widespread use, we decided not to include data from AtlaImpianti (`https://www.gse.it/dati-e-scenari/atlaimpianti`). This dataset includes wind turbines in Italy that receive economic incentives for renewable energy production, but it was recently found to be severely biased [26].

Finally, to appreciate the potential increase in wind turbines in the study area, across the next few years, we used another dataset from Cerri et al. (2024)[26]. This dataset was constructed by querying projects that, in March 2024, were undergoing the mandatory preliminary impact assessment procedure by the Italian Ministry for the Environment (`https://va.mite.gov.it/it-IT/Ricerca/ViaTipologia`). For each project, the authors of the study downloaded the impact assessment report and manually georeferenced each wind turbine. Although several years could pass from project submission to the construction of a certain wind farm, this dataset contains the maximum number of turbines which could be built in the study area in the near future, in the case all wind farm projects are approved (n = 1,026). Collision risk estimates obtained from this dataset therefore represent a worst-case scenario.

Identification of feeding events and foraging grounds

To define foraging grounds we first identified feeding events using a combination of GPS and accelerometer (ACC) data. We used GPS-ACC data from 6 Griffon Vultures that had been translocated within the "LIFE Under Griffon Wings" (LIFE14 NAT/IT/000484) and "LIFE Safe for Vultures" (LIFE19 NAT/IT/000732) projects. Griffon Vultures were equipped with Ornitela 3G_50g GPS/GSM devices with accelerometer, attached with a Teflon leg-loop harness constituted by three assembled strings (round silicone cord 2mm + tubular teflon ribbon 0.2500 and 0.4400) as recommended by Hegglin *et al*. (2004)[41]. Transmitters and rings did not exceed 3% of the birds' body mass [42]. GPS-ACC devices were fitted by following the best practice in animal welfare - the heads of the birds were covered to guarantee minimal stress and the transmitter placement time was reduced to less than ten minutes. ACC recorded gravitational and inertial acceleration in three axes, corresponding to the anterior–posterior (surge), dorso-ventral (heave) and lateral (sway) axis (Fig. 2). When the battery level was higher than 70%, ACC data were collected every minute, in bursts of 10 consecutive seconds, at a frequency of 20 Hz. For the following analysis, we associated each ACC burst to the GPS coordinates closest in time, with a time tolerance of 300 seconds.

We obtained evidence of feeding events both in the wild with camera traps and direct observation of a captive individual in the aviary of a wildlife recovery center, that had been equipped temporarily with a Ornitela tag with accelerometer. We also collected direct observation in the wild of other behaviors. We made a validation by considering the exact time of feeding events and of the other behaviors and then visually inspecting the ACC patterns of 4 different behaviors (feeding, soaring flight, flapping flight, standing) with the software Firetail [43]. Since the pattern of every behavior is quite recognizable on Firetail, starting from the validated behavior we performed a visual classification of feeding events, also using information on speed and altitude, and then we constructed a labeled dataset of feeding events that we then used to train a classification random forest [44], calculating summary statistics from the ACC data for each burst (Table 2) and using them as predictors for the model. Random forests were tuned with 10-fold cross validation, by using 80% of the dataset as training set for the model and 20% of the dataset as test set. Once trained on our labeled dataset, random forests were used to classify new data and identify other feeding events. To minimize the potential error we kept only those feeding events that lasted at least 5 minutes. For each burst, we calculated the mean of GPS coordinates to identify the centroid of a specific feeding event.

In order to map foraging grounds from the feeding events identified above, we used Kernel Density Estimators (KDEs)[45]. Given the high spatial overlap in the location of feeding events, both across individuals and across years, we applied KDEs on all feeding events' centroids to obtain an overall utilization distribution (UD) of the feeding events. Considering the gregarious habits of Griffon Vultures while foraging [46][47], and the fact that only two colonies occur in northwest Sardinia, as well as the fact that feeding events were stable across years and between individuals (Fig. S2, S3), we assumed that the UD of feeding events from our 6 Griffon Vultures represents the foraging grounds of the entire population of Griffon Vultures in Sardinia.

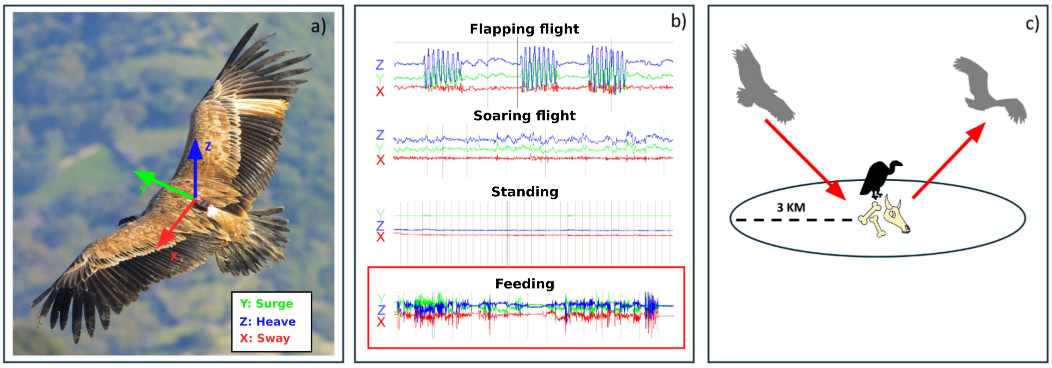

Figure 2: Overview on how collision risk was calculated: accelerometers recorded triaxial acceleration of Griffon Vultures (panel a), whose patterns were visually analyzed with the software Firetail to identify feeding events (b). Finally by combining GPS, flight altitude values and accelerometer patterns, we identified a 3 km radius around feeding events, corresponding to the distance at which griffon vultures landed, fed and left again (c). In this 3 km radius, Griffon Vultures were deemed to be susceptible to intercept and collide with rotating blades.

Estimation of collision risk

We estimated collision risk in the foraging grounds based on their overlap with the location of the wind turbines present in the area, as identified by the different data sources used. In this study we assumed that Griffon Vultures were more prone to collide with wind turbines while foraging [14], particularly when descending or departing from the ground, as they would fly at the same height of the rotor of most wind turbines (15 – 210m)[19]. We therefore identified a buffer around each turbine, constituting an area of potential risk. To define the buffer radius, we checked existing literature on the biomechanics of flight in vultures, but could not find any clear information about the distance that Griffon Vultures need to land and take off, relative to their food source. To estimate these distances, we conducted a visual analysis of ACC patterns using the software Firetail. For each identified landing and take-off event, we recorded the altitude, speed, and coordinates at the moment of flight and the corresponding data when the individual was on the ground (for landing; vice versa for take-off). We then used Google Earth to determine approximate flight altitudes by subtracting the position altitude from the altitude recorded by the GPS tag, and we measured the linear ground distance between the airborne and ground points. This allowed us to estimate the distance required for both landing and take-off. Due to the GPS settings and ACC data configuration, which provided a 2-minute fix rate only when the battery level exceeded 70%, we were limited in the number of individuals analyzed.

We manually identified a total of 29 landings and 28 take-offs. Griffon Vultures required 2,355 $\pm$ 561 m (mean $\pm$ standard deviation) for their landings and 2,524 $\pm$ 527 m to take-off. Therefore, we quantified collision risk associated with wind turbines by: *i*) generating a 3 km buffer around each turbine, according to the different data sources *ii*) calculating which percentage of the UD of foraging grounds fell into the buffers and finally *iii*) summing these obtained percentages across the wind turbines

Table 1: Table. 1. Characteristics of the released Griffon Vultures

Name	Sex	Country of origin	Year of birth	Release	N. feeding events
Artis3	F	Netherlands	2018	25/06/2019	518
Artis4	M	Netherlands	2018	25/06/2019	26
Artis6	F	Netherlands	Unknown	30/11/2022	212
Artis7	F	Netherlands	Unknown	30/11/2022	421
Cristina	Unknown	Sardinia (local, recovered)	2021	03/10/2021	124
Doglia	M	Spain	2018	22/10/2019	262

that were deemed to occur in the study area according to the different sources: OSM, Smeraldo et al. (2020)[27] and Cerri *et al*. (2024)[26]. Finally, we also calculated the percentage of the foraging UD that is expected to become at risk of collision by considering the wind turbines which could be built in the near future (n = 2,221)[26]. Statistical analyses were carried out through the statistical software R [48].

Results

The random forest model based on the ACC summary statistics identified 1,563 feeding events across the 6 vultures between May 2020 and March 2024 (random forest accuracy = 0.99, precision = 0.99, recall = 0.99, Fig. S4).

When considering predictors that affected model accuracy, if excluded, the most important ones were the mean ACC value on the x axis (mean_acc_x_g), the skewness of ACC value on the y axis (skewness_acc_y_g) and the difference between the maximum and the minimum pitch value calculated for each burst (PitchAmpl_burst). When considering predictors that contributed to the homogeneity of nodes and leaves in the random forest, the most important variables were the maximum ACC value on the y axis (max_acc_y_g), the range of ACC value on the y axis (ampl_acc_y_g) and the variance of ACC values on the x axis (var_acc_x_g, Fig. S5). Foraging grounds, delimited by the 95% of the Kernel UD, covered an area of approx. 2,286 km2. The highest density values of the UD were located in the backcountry of the main colony in Bosa, but areas with a lower density of feeding events also encompassed the backcountry of the secondary colony, in Punta Cristallo (Fig. 1).

The three data sources showed different numbers of turbines, with Cerri *et al*. (2024)[26] having the highest number (n = 1,155), followed by Smeraldo *et al*. (2020, n = 914)[27][27] and by OSM (n = 744). Therefore buffers applied on the wind turbines obtained from these different datasets resulted in very different percentages of the foraging UD being at risk of collision (Fig. 3, Fig. S6). The buffers around the turbines from OSM overlapped with 8.7% of the foraging grounds UD, while turbines that were effectively present in 2023, according to aerial pictures, overlapped with 18.7% of the UD. Even turbines mapped from satellite imagery by Smeraldo *et al*. In 2020 [27], only four years before this study, underestimated collision risk, as they involved 15.3% of the UD.

When pooling together turbines that were present in the study area in late 2023, with those contained in the wind farms projects under evaluation by the Ministry for the Environment (representing the worst case scenario of wind energy development in the study area) we found that, should all projects be approved, 31.4% of the foraging UD would soon be at risk of collision. Under this scenario, the foraging grounds in the backcountry of the main colony in Bosa would be completely surrounded by wind turbines (Fig. 4).

Discussion

Our findings show that the data source used to estimate and map the potential collision risk generated by wind farms significantly impacts the resulting risk assessment, and potentially the decision-making process governing the implementation of new energy infrastructures.

Risk estimates obtained from a frequently used dataset, Open Street Map, can substantially diverge from, and particularly underestimate, those obtained from datasets that objectively quantify wind turbines in the environment (e.g. from aerial images)[26]. Therefore, studies relying on datasets whose accuracy is not verified can seriously underestimate collision risk, sometimes across large spatial scales [19] or in critical conservation areas such as migratory routes [23][34]. Moreover, our risk estimates are conservative. In fact, we only considered single wind turbines, without including the associated electric grid, which constitutes itself a major source of mortality for vultures [49][50].

Moreover, due to global differences in digitalization [51], this underestimation can vary across countries, and it is expected to be highest in developing countries with a good potential for wind energy production. Some of these countries are considered conservation hotspots for sensitive species, such as African Vultures [12][52] or bustards [53][54][55], while others intersect major migratory routes [56] or even represent migration bottlenecks [57].

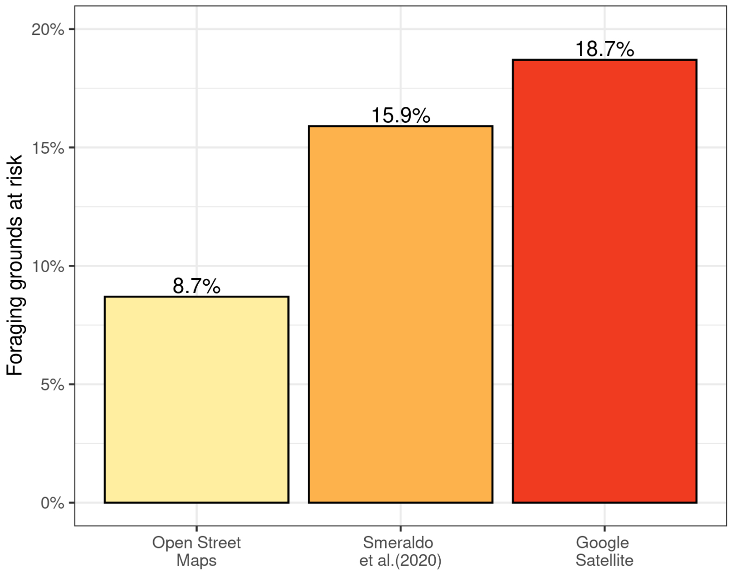

Figure 3: Percentage of foraging grounds where Griffon Vultures can be at risk of collision with wind turbines, when considering wind turbines that are mapped on Open Street Maps, turbines that were mapped by Smeraldo et al. (2020), and turbines that were detected through aerial images on Google Satellite by Cerri et al, 2024. See Fig. S2 for a map of the three different datasets.

At the policymaking level the underestimation of collision risk can mislead spatial planning and zonation, as well as bias population viability analyses. If authorities underestimate the number of turbines in the environment, they can potentially authorize the construction of new wind farms in areas where turbines are already abundant. For vultures this could increase the already high mortality rate from collisions with turbines [49][50][58], potentially beyond critical "tipping points". This could for instance disrupt density-dependent foraging strategies [46] and lead to widespread numerical declines, especially in regions where vultures are already facing other important threats, such as electrocution [50], food shortages [59], disease outbreaks [60], as well as accidental or deliberate poisoning [61][62]. From an analytical perspective, if researchers underestimate the number of turbines, flawed mortality estimates might bias demographic models and population viability analyses, a critical tool for vulture conservation [17][63][64]. Although it is possible that in the long term vulture mortality from collisions might be reduced by their avoidance of wind farms [65], empirical support for this behavior is currently scarce [66].

At the meta-population level, our results also raise serious concerns about how current wind energy development in the Mediterranean basin can affect the viability of insular vulture populations. All the largest islands in the Mediterranean sea host small vulture populations, which are isolated from mainland Europe and probably unable to compensate for increased mortality. As in the case of Sardinia, by adding the turbines that are planned in the next few years to the number of turbines that were present in our study area in 2023, our risk estimates increased by 63%, involving around one third of total foraging grounds, since their development is planned in an area where Griffon Vultures forage on a daily basis. In absence of adequate mitigation measures, this increase could lead to a mortality rate which would undermine the viability of this population [67].

Our findings bear two clear implications for policy. First, the creation of high-quality and publicly available datasets of wind turbine locations is a priority for environmental agencies. While maps with the exact location of each turbine can be developed only for high-risk areas, such as migration bottlenecks [23] or vulture colonies [16], aerial pictures and spatially-balanced sampling schemes [68] might be a cost-effective solution to produce large-scale interpolations of turbine densities. These interpolations could be useful to identify overlaps between wind energy development and biodiversity hotspots or strongholds of sensitive species, with a potentially significant improvement from current estimates, based on untested data. Their creation and periodic update could be further facilitated by automatically identifying turbines from satellite images through machine learning algorithms [69]. Periodically updating maps is also crucial, as our findings showed that even high-quality maps [27] accumulate significant bias in the span of a few years, due to the rate of wind energy development.

Finally we emphasize the need to rapidly implement post construction impact assessment schemes and mitigation measures, such as selective stopping [32] and periodic field surveys to detect and remove undisposed livestock carrion around wind turbines [70]. Practical evidence indicates that in most Mediterranean countries, outside the Iberian peninsula, post construction impact assessment and mitigation measures are seldom implemented. Without accurate zonation policies and the implementation of the above-mentioned mitigation strategies, the current magnitude of wind energy development will likely result in the large-scale proliferation of ecological traps and increased mortality for many vulture populations.

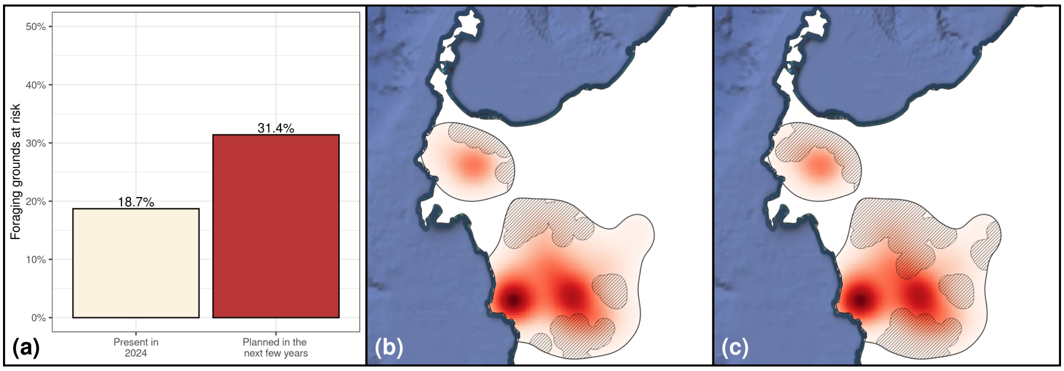

Figure 4: Percentage of foraging grounds where Griffon Vultures can be at risk of collision with wind turbines. Panel (a): comparison between existing wind turbines and turbines that will be built in the next few years, according to Cerri et al, 2024. Panel (b): portion of foraging grounds where vultures are currently at risk of collision, when considering existing turbines (highlighted). Panel (c): portion of foraging grounds where vultures will be at risk of collision in the next few years (highlighted). Darker areas in panel (b) and (c) represent those sections of the foraging grounds with the highest density of feeding events. Projections about future wind turbines consider the worst-case scenario, where all wind farms projects that have been submitted to the Italian Ministry for the Environment are approved (see the Methods section).

Table 2: Summary statistics used in the random forest analysis as predictors for the classification of the acceleration data.

Covariates	Overview and calculation
Static acceleration (Xst_g, Yst_g, Zst_g)	Calculated on each axis in g using a smoothing window of 2 second (40 samples) to identify postural change
Vedba (vedba_g)	Calculated as the square root ((total acc x – static acc x)^2 + (total acc y – static acc y)^2 + (total acc z – static acc z)^2)
Mean Vedba (meanVedba_burst)	Mean of Vedba for each burst
Cumulative Vedba (cumVedba_burst)	Sum of Vedba for each burst
Standard deviation of Vedba (sdVedba_burst)	Calculated for each burst
Pitch (Pitch)	In degrees, rotation on heave-surge axis, calculated as atan^2(-y, sqrt(x*x + z*z))*180/pi
Pitch difference (PitchDiff)	Maximum pitch value – minimum pitch value
Pitch amplitude (PitchAmpl_burst)	Maximum pitch value – minimum pitch value calculated for each burst
Roll (Roll)	In degrees, rotation on yaw axis, calculated as atan^2(x, sqrt(z*z + x*x))*180/pi
Mean (mean_acc_x_g, mean_acc_y_g, mean_acc_z_g)	Value on each axis
Variance (var_acc_x_g, var_acc_y_g, var_acc_z_g)	Value on each axis
Minimum (min_acc_x_g, min_acc_y_g, min_acc_z_g)	Value on each axis
Maximum (max_acc_x_g, max_acc_y_g, max_acc_z_g)	Value on each axis
Amplitude (ampl_acc_x_g, ampl_acc_y_g, ampl_acc_z_g)	Range of values on each axis
Skewness (skewness_acc_x_g, skewness_acc_y_g, skewness_acc_z_g)	Skewness of values on each axis
Kurtosis (kurtosis_acc_x_g, kurtosis_acc_y_g, kurtosis_acc_z_g)	Kurtosis of the distribution of values on each axis

Acknowledgements

We are grateful to the Vulture Conservation Foundation for its support, particularly Dr. Franziska Lörcher, who provides guidance about GPS harnessing. We are also deeply grateful to the Artis Royal Zoo, the Selwo Aventura Zoological Park, the Dresda Zoo, Acción por el Mundo Salvaje and the Los Hornos Wildlife Rescue Centre which provided the 76 Griffon Vultures that were subsequently released under the project LIFE "Under Griffon Wings". We are deeply grateful to Dr. Hannah Williams and Prof. Kamran Safi for their precious help with accelerometer analysis. We also thank the Corpo Forestale e di Vigilanza Ambientale della Regione Sardegna, the Municipality of Bosa, the Porto Conte Regional Park, the Centro di Educazione Ambientale e Sostenibilità di Monte Minerva for their support with field and communication activities. Finally, our deep appreciation also goes to all those who helped us with monitoring and management activities within the LIFE "Under Griffon Wings" project.

Data availability statement

The reproducible data and software code are available at: https://osf.io/v9pdt/

Funding

The following study was co-financed by the European Commission through the LIFE "Under Griffon Wings" (LIFE14 NAT/IT/000484) and the LIFE "Safe for Vultures" (LIFE19 NAT/IT/000732) projects. Chiara Costantino was supported by the Italian Ministry of Education, University and Research, through the National Recovery and Resilience Plan (PNRR) - "Budget di ricerca borse 118 - Pianificazione territoriale integrata, finalizzata a massimizzare la compatibilità tra lo sviluppo delle energie rinnovabili e le comunità faunistiche della Regione Sardegna". Grant number: UA2003DOTTRIC39_118. Ilaria Fozzi was supported by the Italian Ministry of Education, University and Research—PON ricerca innovazione 2014-2020, Azione IV.5 "Dottorati su tematiche Green", Grant number: DOT1629893-2

CRediT authorship contribution statement

Conceptualization: FB, DDR, DS, FB, IF, JC **Methodology**: CC, FB, IF, JC, MM, MS **Software**: CC, IF, JC, MS **Validation**: CC, DAB, DDR, IF, JE, LP, MS **Formal analysis**: CC, DAB, IF, JC, JE, LP, MS **Investigation**: CC, DAB, IF, JC, JE, LP **Resources**: DS, FB, MM **Data curation**: CC, DAB, DDR, IF, JE, LP **Writing - original draft**: IF, JC, MS **Writing- review and editing**: CC, DDR, FB, IF, JC, MS **Visualization**: CC, DDR, FB, IF, JC **Supervision**: DDR, DS, FB, MM **Project administration**: DS, FB, MM **Funding Acquisition**: DS, FB

Conflict of interest

The authors declare no conflict of interest.

References

1. Katzner, T. E., *et al*. (2019). Wind energy: An ecological challenge. *Science*, 366(6470), 1206-1207. https://doi.org/10.1126/science.aaz9989
2. Diffendorfer, J. E., *et al*. (2019). Geographic context affects the landscape change and fragmentation caused by wind energy facilities. *PeerJ*, 7, e7129. https://doi.org/10.7717/peerj.7129
3. Tolvanen, A., *et al*. (2023). How far are birds, bats, and terrestrial mammals displaced from onshore wind power development?–A systematic review. *Biological Conservation*, 288, 110382. https://doi.org/10.1016/j.biocon.2023.110382
4. Marques, A. T., *et al*. (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.2023.110382
5. Thaxter, C. B., *et al*. (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), 20170829. https://doi.org/10.1098/rspb.2017.0829

6. Voigt, C. C. (2021). Insect fatalities at wind turbines as biodiversity sinks. *Conservation Science and Practice*, 3(5), e366. https://doi.org/10.1111/csp2.366
7. Venter, O., *et al.* (2016). Global terrestrial Human Footprint maps for 1993 and 2009. *Scientific data*, 3(1), 1-10. https://doi.org/10.1038/sdata.2016.67
8. Ramírez-Fráncel, L. A., *et al.* (2022). Bats and their vital ecosystem services: a global review. *Integrative zoology*, 17(1), 2-23. https://doi.org/10.1111/1749-4877.12552
9. Donázar, J. A., *et al.* (2016). Roles of raptors in a changing world: from flagships to providers of key ecosystem services. *Ardeola*, 63(1), 181-234. https://doi.org/10.13157/arla.63.1.2016.rp8
10. Monteagudo, N., *et al.* (2023). Avian regulation of crop and forest pests, a meta-analysis. *Pest Management Science*, 79(7), 2380-2389. https://doi.org/10.1002/ps.7421
11. Whelan, C. J., *et al.* (2008). Ecosystem services provided by birds. *Annals of the New York academy of sciences*, 1134(1), 25-60. https://doi.org/10.1196/annals.1439.003
12. Santangeli, A., *et al.* (2019). Priority areas for conservation of Old World vultures.*Conservation Biology*, 33(5), 1056-1065. https://doi.org/10.1111/cobi.13282
13. Carucci, T., *et al.* (2022). Ecosystem services and disservices associated with vultures: A systematic review and evidence assessment. *Ecosystem Services*, 56, 101447. https://doi.org/10.1016/j.ecoser.2022.101447
14. Martin, G. R., *et al.* (2012). Visual fields, foraging and collision vulnerability in *Gyps* vultures. *Ibis*, 154(3), 626-631. https://doi.org/10.1111/j.1474-919X.2012.01227.x
15. de Lucas, M., *et al.* (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
16. Carrete, M., *et al.* (2012). Mortality at wind-farms is positively related to large-scale distribution and aggregation in griffon vultures. *Biological Conservation*, 145(1), 102-108. https://doi.org/10.1016/j.biocon.2011.10.017
17. Bounas, A., *et al.* (2025). Cumulative collision risk and population-level consequences of industrial wind-power plant development for two vulture species: A quantitative warning. *Environmental Impact Assessment Review*, 110, 107669. https://doi.org/10.1016/j.eiar.2024.107669
18. Serrano, D., *et al.* (2020). Renewables in Spain threaten biodiversity. *Science*, 370(6522), 1282-1283. https://doi.org/10.1126/science.abf6509
19. Morant, J., *et al.* (2024). Fine-scale collision risk mapping and validation with long-term mortality data reveal current and future wind energy development impact on sensitive species. *Environmental Impact Assessment Review*, 104, 107339. https://doi.org/10.1016/j.eiar.2023.107339
20. Khosravifard, S., *et al.* (2020). Identifying birds' collision risk with wind turbines using a multidimensional utilization distribution method. *Wildlife Society Bulletin*, 44(1), 191-199. https://doi.org/10.1002/wsb.1056
21. Péron, G., *et al.* (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
22. Cervantes, F., *et al.* (2023). A utilization distribution for the global population of Cape Vultures (*Gyps coprotheres*) to guide wind energy development. *Ecological Applications*, 33(3), e2809. https://doi.org/10.1002/eap.2809
23. Gauld, J. G., *et al.* (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*, 59(6), 1496-1512. https://doi.org/10.1111/1365-2664.14160
24. Selva, N., *et al.* (2023). FAIR data would alleviate large carnivore conflict. *Science*, 382(6673), 893-894. https://doi.org/10.1126/science.adl6080
25. Sequeira, A. M., *et al.* (2021). A standardisation framework for bio-logging data to advance ecological research and conservation. *Methods in Ecology and Evolution*, 12(6), 996-1007. https://doi.org/10.1111/2041-210X.13593
26. Cerri, J., *et al.* (2024). Widely used datasets of wind energy infrastructures can seriously underestimate onshore turbines in the Mediterranean. *Biological Conservation*, 300, 110870. https://doi.org/10.1016/j.biocon.2024.110870
27. Smeraldo, S., *et al.* (2020). Modelling risks posed by wind turbines and power lines to soaring birds: The black stork (*Ciconia nigra*) in Italy as a case study. *Biodiversity and Conservation*, 29, 1959-1976. https://doi.org/10.1007/s10531-020-01961-3
28. Cerri, J., *et al.* (2023). Griffon Vulture movements are concentrated around roost and supplementary feeding stations: implications for wind energy development on Mediterranean islands. *Global Ecology and Conservation*, 47, e02651. https://doi.org/10.1016/j.gecco.2023.e02651
29. Christie, A. P., *et al.* (2019). Simple study designs in ecology produce inaccurate estimates of biodiversity responses. *Journal of Applied Ecology*, 56(12), 2742-2754. https://doi.org/10.1111/1365-2664.13499
30. Nilsson, A. L. K., *et al.* (2023). Estimating mortality of small passerine birds colliding with wind turbines. *Scientific Reports*, 13(1), 21365. https://doi.org/10.1038/s41598-023-46909-z
31. Ravache, A., et al. (2024). Monitoring carcass persistence in windfarms: Recommendations for estimating mortality. *Biological Conservation*, 292, 110509. https://doi.org/10.1016/j.biocon.2024.110509

32. Ferrer, M., *et al*. (2022). Significant decline of Griffon Vulture collision mortality in wind farms during 13-year of a selective turbine stopping protocol. *Global Ecology and Conservation*, 38, e02203. https://doi.org/10.1016/j.gecco.2022.e02203
33. May, R., *et al*. (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
34. Assandri, G., *et al*. (2024). Assessing exposure to wind turbines of a migratory raptor through its annual life cycle across continents. *Biological Conservation*, 293, 110592. https://doi.org/10.1016/j.biocon.2024.110592
35. Boggie, M. A., *et al*. (2023). Forecasting suitable areas for wind turbine occurrence to proactively improve wildlife conservation. *Journal for Nature Conservation*, 74, 126442. https://doi.org/10.1016/j.jnc.2023.126442
36. Dunnett, S., *et al*. (2022). Predicted wind and solar energy expansion has minimal overlap with multiple conservation priorities across global regions. *Proceedings of the National Academy of Sciences*, 119(6), e2104764119. https://doi.org/10.1073/pnas.2104764119
37. Dunnett, S., *et al*. (2020). Harmonised global datasets of wind and solar farm locations and power. *Scientific data*, 7(1), 130. https://doi.org/10.1038/s41597-020-0469-8
38. Ibisch, P. L., *et al*. (2016). A global map of roadless areas and their conservation status. *Science*, 354(6318), 1423-1427. https://doi.org/10.1126/science.aaf7166
39. Marques, A. T., *et al*. (2022). Individual variability in space use near power lines by a long-lived territorial raptor. *Ecology and Evolution*, 12(4), e8811. https://doi.org/10.1002/ece3.8811
40. Palacín, C., *et al*. (2023). Detailed mapping of protected species distribution, an essential tool for renewable energy planning in agroecosystems. *Biological Conservation*, 277, 109857. https://doi.org/10.1016/j.biocon.2022.109857
41. Hegglin, D., et al. (2004). Satellite tracking of Bearded Vultures-the project '"Bearded Vultures on the Move."' Annual Report of the Foundation for the Conservation of the Bearded Vultures, 52–55. https://www.beardedvulture.ch/
42. Bodey, T. W., *et al*. (2018). A phylogenetically controlled meta-analysis of biologging device effects on birds: Deleterious effects and a call for more standardized reporting of study data. *Methods in Ecology and Evolution*, 9(4), 946-955. https://doi.org/10.1111/2041-210X.12934
43. Berger, M., et al. (2023). Firetail – a fast and versatile software for the visualization and analysis of tagged animal data, Schäuffelhut Berger GmbH, Version 11, Jun. 2023. https://www.firetail.de
44. Breiman, L. (2001). Random forests. *Machine learning*, 45, 5-32. https://doi.org/10.1023/A:1010933404324
45. Kie, J. G. (2013). A rule-based ad hoc method for selecting a bandwidth in kernel home-range analyses. *Animal biotelemetry*, 1, 1-12. https://doi.org/10.1186/2050-3385-1-13
46. Cortés-Avizanda, A., *et al*. (2014). Bird sky networks: how do avian scavengers use social information to find carrion?. *Ecology*, 95(7), 1799-1808. https://doi.org/10.1890/13-0574.1
47. van Overveld, T., *et al*. (2020). Integrating vulture social behavior into conservation practice. *The Condor*, 122(4), duaa035. https://doi.org/10.1093/condor/duaa035
48. R Core Team (2024). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/
49. Arrondo, E., et al. (2020). Landscape anthropization shapes the survival of a top avian scavenger. *Biodiversity and Conservation*, 29, 1411-1425. https://doi.org/10.1007/s10531-020-01942-6
50. Serratosa, J., *et al*. (2024). Tracking data highlight the importance of human-induced mortality for large migratory birds at a flyway scale. *Biological Conservation*, 293, 110525. https://doi.org/10.1016/j.biocon.2024.110525
51. Billon, M., *et al*. (2010). Differences in digitalization levels: a multivariate analysis studying the global digital divide. *Review of World Economics*, 146, 39-73. https://doi.org/10.1007/s10290-009-0045-y
52. Buechley, E. R., *et al*. (2022). Priority areas for vulture conservation in the Horn of Africa largely fall outside the protected area network. *Bird Conservation International*, 32(2), 188-205. https://doi.org/10.1017/S0959270921000228
53. Collar, N. J., Wacher, T. (2023). The conservation status of the Nubian Bustard *Nubotis nuba*: a review and prognosis. *Bird Conservation International*, 33, e76. https://doi.org/10.1017/S095927092300028X
54. Dolman, P. M., *et al*. (2021). Captive breeding and the conservation of the threatened houbara bustards. *Endangered Species Research*, 46, 161-173. https://doi.org/10.3354/esr01151
55. Palacín, C., *et al*. (2016). Assessing the extinction risk of the great bustard *Otis tarda* in Africa. *Endangered Species Research*, 30, 73-82. https://doi.org/10.3354/esr00726
56. Briedis, M., *et al*. (2020). Broad-scale patterns of the Afro-Palaearctic landbird migration. *Global Ecology and Biogeography*, 29(4), 722-735. https://doi.org/10.1111/geb.13063
57. Panuccio, M., et al. (Eds.). (2021). Migration strategies of birds of prey in Western Palearctic. CRC press. https://www.amazon.com/Migration-Strategies-Birds-Western-Palearctic/dp/0367765438
58. Pérez-García, J. M., Serrano, D. (2023). ¿ Cuántas aves mueren en España debido a la colisión en parques eólicos y qué medidas preventivas y correctoras se pueden aplicar para evitarlas? Energía Eólica: *Preguntas y respuestas*. Pp, 282-294. https://www.researchgate.net/publication/375765445_Cuantas_aves_mueren_en_Espana_debido_a_la_colision_en_parques_eolicos_que_medidas_preventivas_y_correctoras_se_pueden_aplicar_para_evitarlas

59. Almaraz, P., *et al*. (2022). Long-term demographic dynamics of a keystone scavenger disrupted by human-induced shifts in food availability. *Ecological Applications*, 32(6), e2579. https://doi.org/10.1002/eap.2579
60. Duriez, O., *et al*. (2023). Highly pathogenic avian influenza affects vultures' movements and breeding output. *Current Biology*, 33(17), 3766-3774. https://doi.org/10.1016/j.cub.2023.07.061
61. Daboné, C., *et al*. (2023). Trade in vulture parts in West Africa: Burkina Faso may be one of the main sources of vulture carcasses. *Bird Conservation International*, 33, e8. https://doi.org/10.1017/S095927092100054X
62. Sanz-Aguilar, A., *et al*. (2015). Action on multiple fronts, illegal poisoning and wind farm planning, is required to reverse the decline of the Egyptian vulture in southern Spain. *Biological Conservation*, 187, 10-18. https://doi.org/10.1016/j.biocon.2015.03.029
63. Carrete, M., *et al*. (2009). Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. *Biological Conservation*, 142(12), 2954-2961. https://doi.org/10.1016/j.biocon.2009.07.027
64. Vasilakis, D. P., *et al*. (2017). A balanced solution to the cumulative threat of industrialized wind farm development on cinereous vultures (*Aegypius monachus*) in south-eastern Europe. *Plos one*, 12(2), e0172685. https://doi.org/10.1371/journal.pone.0172685
65. Farfán, M. Á., *et al*. (2023). Wind farms and Griffon Vultures: Evidence that under certain conditions history is not-always turbulent. *Global Ecology and Conservation*, 48, e02728. https://doi.org/10.1016/j.gecco.2023.e02728
66. Sassi, Y., *et al*. (2024). Empirical and simulation data reveal a lack of avoidance of wind turbines by *Gyps fulvus* (Griffon Vulture). *Ornithological Applications*, duae019. https://doi.org/10.1093/ornithapp/duae019
67. Aresu, M., *et al*. (2021). Assessing the effects of different management scenarios on the conservation of small island vulture populations. *Bird Conservation International*, 31(1), 111-128. https://doi.org/10.1017/S0959270920000040
68. Kermorvant, C., *et al*. (2019). Spatially balanced sampling designs for environmental surveys. *Environmental monitoring and assessment*, 191(8), 524. https://doi.org/10.1007/s10661-019-7666-y
69. Hoeser, T., *et al*. (2022). DeepOWT: A global offshore wind turbine data set derived with deep learning from Sentinel-1 data. *Earth System Science Data*, 14(9), 4251-4270. https://doi.org/10.5194/essd-14-4251-2022
70. Fernandez-Gomez, L., *et al*. (2022). Vultures feeding on the dark side: current sanitary regulations may not be enough. *Bird Conservation International*, 32(4), 590-608. https://doi.org/10.1017/S0959270921000575

Supplementary figures

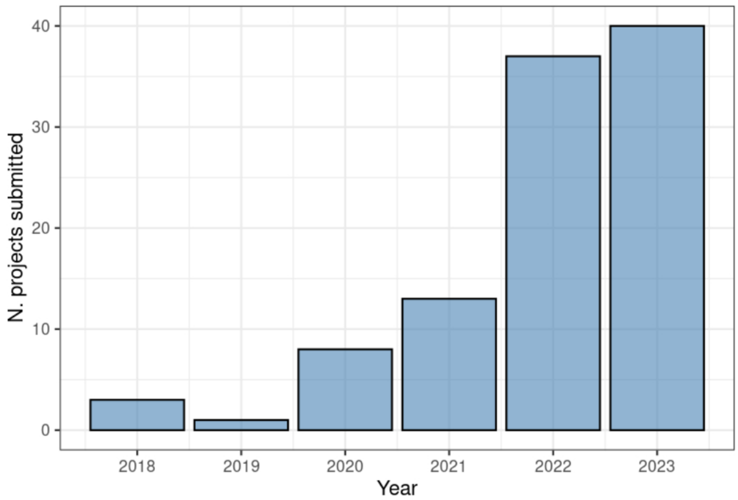

Figure S1: Increase in the number of projects about new wind farms, submitted to the Italian Ministry for the Environment, since 2018

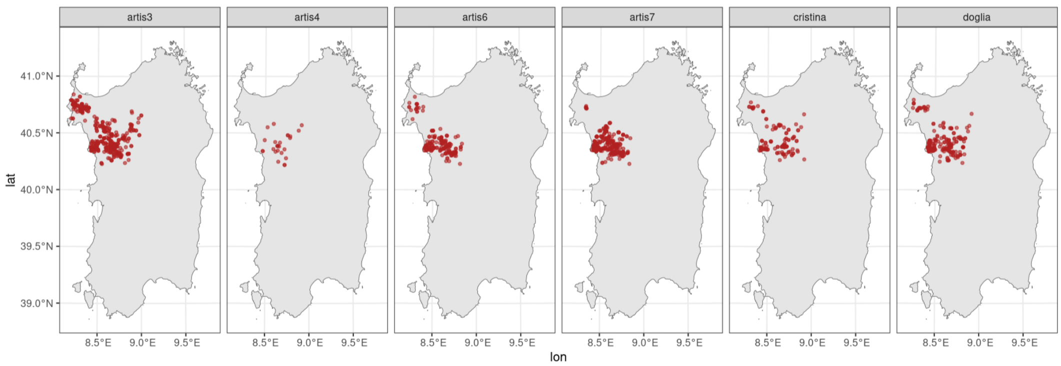

Figure S2: Spatial distribution of feeding events between different individuals

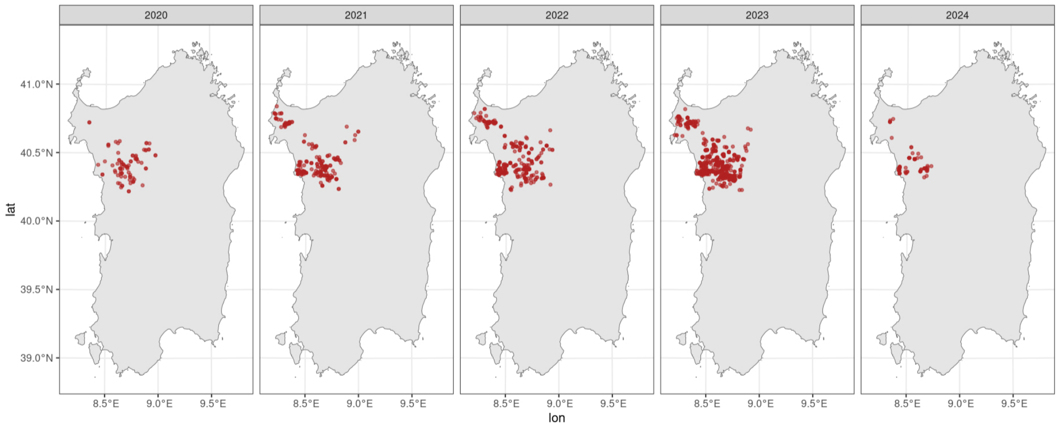

Figure S3: Spatial distribution of feeding events across different years

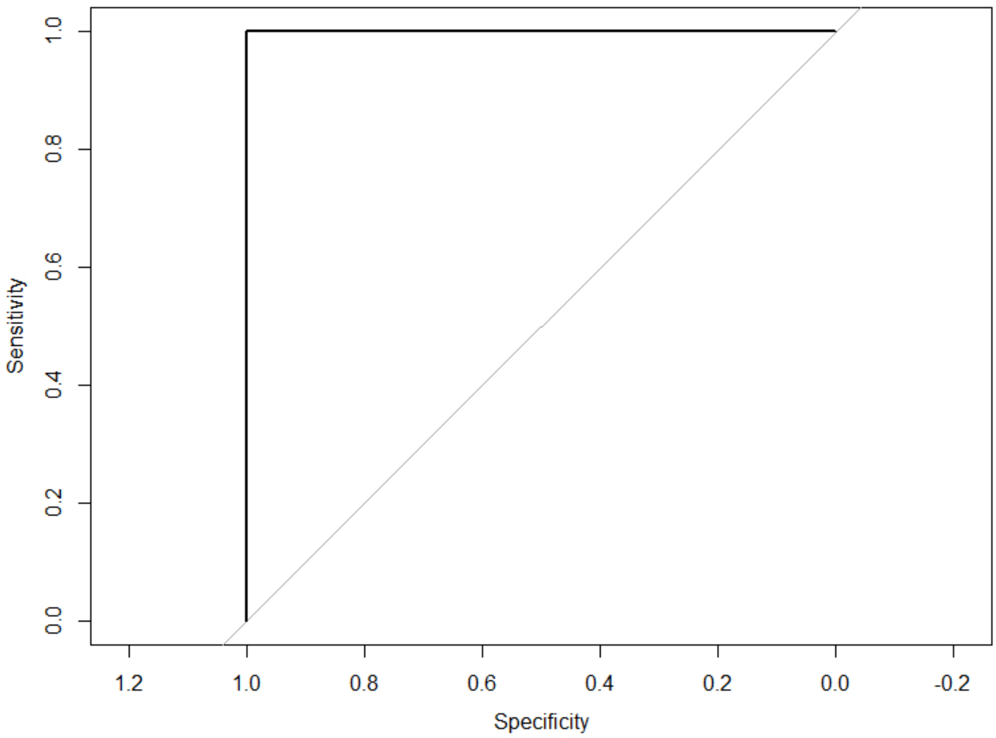

Figure S4: ROC curve from the random forest model used to identify feeding events from ACC data

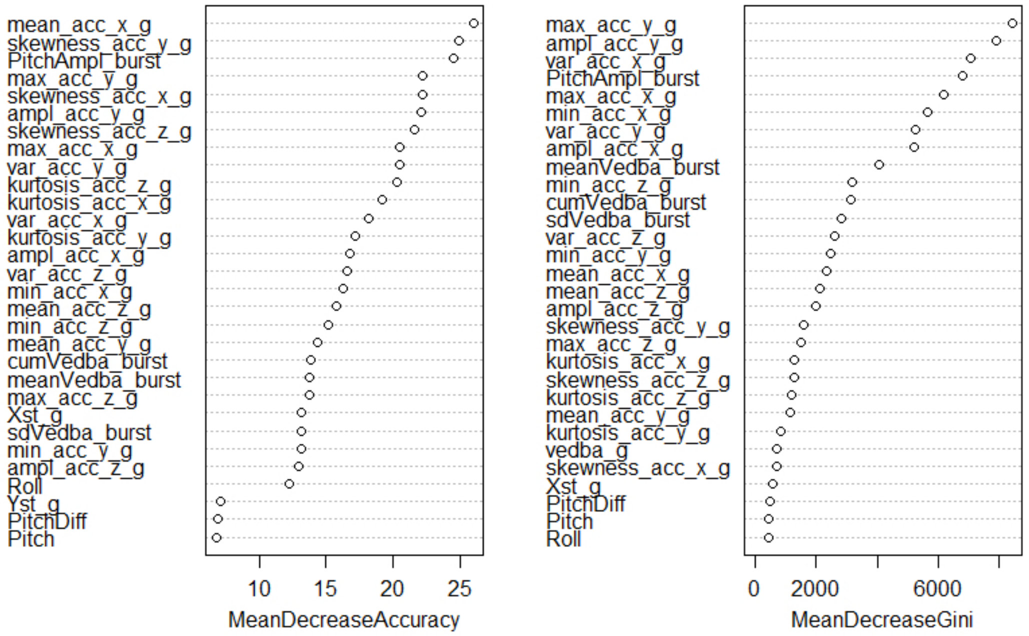

Figure S5: Importance of covariates in the random forest model, in terms of how much accuracy was lost by the model in case they were excluded (left) and in terms of the mean decrease in Gini coefficient, representing how each variable contributed to the homogeneity of the nodes and leaves of the random forest (right).

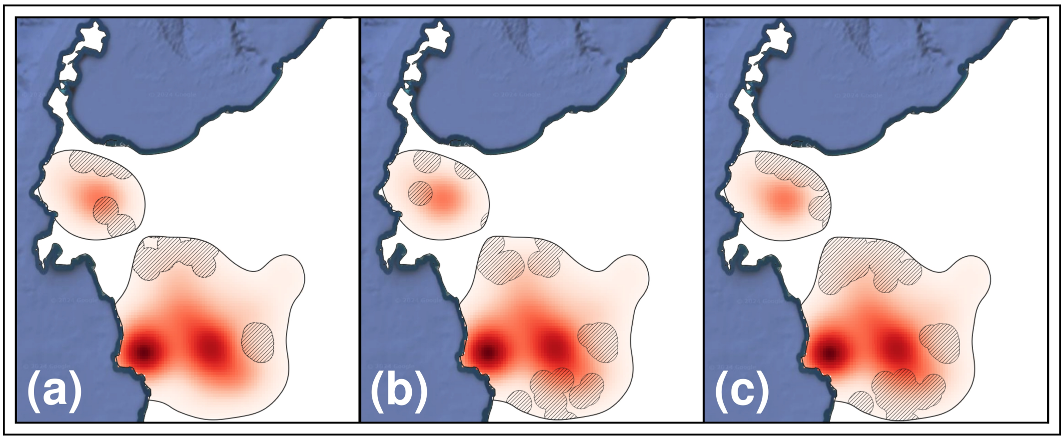

Figure S6: Portion of foraging grounds where vultures are currently at risk of collision (highlighted), according to wind turbines from OSM (a), from Smeraldo et al. (2020, b), as well as according to wind turbines effectively present in the study area in 2023 (c).