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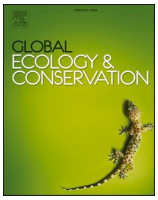

Griffon Vulture movements are concentrated around roost and supplementary feeding stations: implications for wind energy development on Mediterranean islands

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ABSTRACT

Griffon Vulture (*Gyps fulvus*) populations occur on Mediterranean islands, where wind energy is developing fast. As griffons are subjected to collisions with wind turbines while foraging, it is necessary to understand which factors affect their movements to minimize the potential impact of wind farms. We assessed habitat use of 37 griffons (n. GPS locations = 130,218) and their overlap with wind farms in Sardinia (Italy), an island where both Griffon Vulture population and wind energy are significantly expanding. Griffons in Sardinia cover smaller areas (95% isopleth = 956.3 ± 677.7 km^2, 50% isopleth = 73.8 ± 48.2 km^2) than in mainland Europe, restricting most of their movements within 5–10 km from colonies and roosts. Supplementary feeding stations throughout these areas (n = 37) provide approximately 20 tons of carrion each year, suggesting that griffon movements are strongly determined by food availability. Overall, 6 wind farms (101 turbines) out of the 29 present in Sardinia were built in areas used by foraging griffons. Two of them were positioned near roosts and supplementary feeding stations. As griffon movements concentrate around nesting/roosting sites and feeding stations, wind farms should be excluded around these highly utilized areas, and mitigation measures, including the removal of livestock carrion, should be adopted for those that are built at greater distances. There is also an urgent need for updated data about wind energy location. The creation of supplementary feeding stations could be used to shape the enlargement of the foraging grounds of an increasing Griffon Vulture population on Mediterranean islands and to exclude wind farm areas to mitigate their impacts.

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1. Introduction

Wind energy production is expanding worldwide. Nowadays offshore and onshore wind farms account for approx. 25% of renewable energy globally (https://ourworldindata.org/renewable-energy). However, wind farms can threaten wildlife by fragmenting and/or reducing habitats, disrupting animal behavior, altering trophic cascades or increasing mortality through collisions with rotating blades and distribution lines (Bennun et al., 2021).

Large soaring raptors, characterized by a low aerial maneuverability and a reduced frontal vision (Martin et al., 2012), are particularly prone to collide with rotating blades when turbines occur on areas regularly used by resident individuals (Fielding et al., 2021; Martín et al., 2018), such as foraging grounds (Katzner et al., 2012), slopes generating updrafts (Péron et al., 2017) or roosts (Carrete et al., 2012). For many species, collisions with blades can become a relevant source of mortality (Bellebaum et al., 2013; Grainger Hunt et al., 2017) capable of jeopardizing endangered populations (Carrete et al., 2009; Cervantes et al., 2022). This is the case for many Old World Vultures for which collision with wind turbines is considered a main threat (Ives et al., 2022).

The Griffon Vulture (*Gyps fulvus*, hereinafter "griffon") is a gregarious vulture that congregates in large numbers around rocky cliffs, often used either as roosts or breeding sites (Bildstein, 2022). Griffons are central-place foragers relying on social foraging to increase their chance to detect carrions, their only trophic resource (Harel et al., 2017). Their gregarious habits make them susceptible to mass poisoning and to reduced foraging success whenever population densities are reduced by repeated mortality events (Harel et al., 2017).

In the mainland griffon colonies are capable to compensate for extra-mortality through immigration, when occurring in a well-connected metapopulation (Le Gouar et al., 2008). Island populations are incapable of doing so, since griffons display a scarce capacity to cross the sea and thus immigration is significantly reduced. This is the case of many griffon populations inhabiting islands in the Central and Eastern Mediterranean (Terraube et al., 2022), where they deliver valuable ecosystem services (Berlinguer et al., 2021) but where any increase in mortality can rapidly impact their conservation status.

Assessing the risks posed to griffons by wind farms (Carrete et al., 2012; Ferrer et al., 2022), and more generally by man-made structures (Arrondo et al., 2020), is particularly urgent for these insular populations. In the Mediterranean wind energy development is occurring at an unprecedented pace (Gauld et al., 2022) and a careful zonation of wind farms is necessary.

However, important insights about the movement ecology of griffons living on Mediterranean islands are still missing to develop adequate zonation policies. First, although the home range and core area of griffons living on the mainland were estimated by various studies (see Table S1 for an overview), only Xirouchakis et al. (2021) did so for insular griffons in Crete. However, Xirouchakis et al. (2021) used low-resolution VHF telemetry and range distribution to estimate their distribution. This method is unsuitable to reveal fine-scale patterns of space use, such as flyways, which are particularly precious to identify potential collision hotspots but which require the estimation of the occurrence distribution (Alston et al., 2022).

Moreover, considering that griffons are susceptible to collisions when foraging, there is a need to understand the extent to which supplementary feeding (Cortés-Avizanda et al., 2016) affects space use, also with respect to its distance from colonies (van Overveld et al., 2020). On Mediterranean islands griffon colonies often occur on coastal cliffs and foraging could be constrained by the effect of wind over leaving or arriving at the nest (Shepard et al., 2019).

So, although the effect of supplementary feeding has already been considered for the mainland, with sometimes contrasting conclusions (Arkumarev et al., 2021a,b; Dobrev and Popgeorgiev, 2021; Duriez et al., 2012; Fernández-Gómez et al., 2022a,2022b; Fluhr et al., 2017; Genero et al., 2020; Monsarrat et al., 2013; Zuberogoitia et al., 2013, see Table S2 in Appendix S1), there is a need to quantify its role over space use by griffons for a Mediterranean island, preferably through high-resolution GPS-telemetry which could reveal small-scale patterns around coastal areas.

In this study we aim to quantify *i*) space use; *ii*) its overlap with existing wind farms and *iii*) to assess how the presence of supplementary feeding stations, altogether with landscape and topographic attributes, affects resource use by griffons in Sardinia, an island in the Central Mediterranean. Based on the obtained results, we provide realistic recommendations on the deployment of wind turbines in the flight zone of a Griffon Vulture colony.

2. Materials and methods

2.1. Data collection and pre-processing

Contrary to mainland Italy, where griffon populations originate from reintroductions after their extinction, in Sardinia griffons have always beenpresent. However, their population was severely reduced between the 1950s and early 2000s (Aresu et al., 2021, 2022). Between 2016 and 2021, the project LIFE Under Griffon Wings (LIFE14 NAT/IT/000484) was implemented to increase Griffon Vulture conservation status in Sardinia, through a restocking program that included the release of 64 individuals in North-West Sardinia. The initiative was authorized by the National Institute for Environmental Protection and Research and the Sardinian Regional Department for the Environment.

Most released griffons came from wildlife rehabilitation centers in Spain (n = 57) and captive breeding programs (n = 7). However, some of them (n = 10) came from Sardinia, after having been found and rehabilitated at a local wildlife center. Release strategies included hard release, with no acclimatization (n = 12), as well as soft release with a 3 month (n = 48) or 14 month (n = 14) acclimatization period. Before being released, griffons were fitted with PIT tags and with an engraved metal ring around one tarsus and an orange plastic ring with a black alphanumeric code on the other tarsus, containing the official identifier from the National Institute for Environmental Protection and Research. Rings were useful for long-distance identification. Moreover, remiges and rectrices were bleached, to provide individual recognition until their molt.

Environmental conditions at all release sites were comparable, with vegetation consisting mostly by holm oak (*Quecus ilex*), cork oak (*Quercus suber*) and *Pinus* sp., as well and pastures used for extensive livestock rearing. In the study area cattle and sheep are kept all year round in extensive pastures, with no seasonal movements. Wild ungulate populations are relatively limited, with wild boar (*Sus scrofa*) present all over the areas with a density lower than 15 animals/100 ha and a small population of about 300 fallow deer (*Dama dama*) localized around the aviary in Porto Conte (Berlinguer et al., 2020).

In the study area 37 supplementary feeding stations were progressively implemented since 2016. These aimed to counteract the decline of the local griffon population by maximizing reproductive success, which in griffons strongly depends upon trophic resources (Almaraz et al., 2022), and by reducing the risk of poisoning. Feeding stations were built on pastures used by livestock herders and they were fenced enclosures of about 100 m^2 made of wooden/plastic poles and a low-tension electrical fence (1.5 m height, 3–4 layers). Each station was constructed at a distance of at least 5 km from the closest wind farm, > 15 km from the closest airport and approx. 200 m from farm facilities.

Feeding stations were managed by herders. Rather than having carrion incinerated by professional companies, as disposed by the Regulation (EC) No 1069/2009 and the Regulation (EU) No 142/2011, herders occurring on Natura 2000 sites included in the vulture feeding area were allowed to dispose them at a feeding station built within their farm. This measure had the explicit goal to ensure the conservation of Griffon Vultures. Feeding stations were designed to exclude terrestrial mammals but were visited by other scavenger birds (e.g. Golden eagle, *Aquila chrysaetos*; e.g., Egyptian vulture, *Neophron percnopterus*; e.g., Common raven, *Corvus corax*). Therefore, feeding stations ensure a regular, but temporally and spatially unpredictable, provisioning of carrion (approx. 20 tons every year) to griffons (Berlinguer et al., 2020). Feeding stations occur in a radius of approx. 50 km from the main group of cliffs used by griffons as roosting and breeding sites between the villages of Pozzomaggiore (40° 23’ 49.704’’N 8° 39’ 35.208’’E), Montresta (40° 22’ 33.312’’N 8° 30’ 0.432’’E) and Monteleone Rocca Doria (40° 28’ 10.74’’N 8° 33’ 38.412’’E).

In the study area, in addition to carrion provided by feeding stations, carrion is also left on the ground by livestock herders, due to difficulties associated with their collection and disposal. Around 563,421 sheep (weighting approx. 55 kg, 8% mortality rate) and 17,487 cattle (weighting approx. 500 kg, 3% mortality rate) carcasses are generated by livestock farms located in the area where griffons move (Fig. 1). Given these numbers, and by assuming that 10% of livestock carcasses are left in the field and detected by griffons, every year around 94 tons of carrion would be available to them. By assuming that: *i*) that griffons can exploit soft tissues only (corresponding to approx. 27% of the whole carrion), *ii*) that 316–338 adult griffons live in the study area and that 55 chicks were born

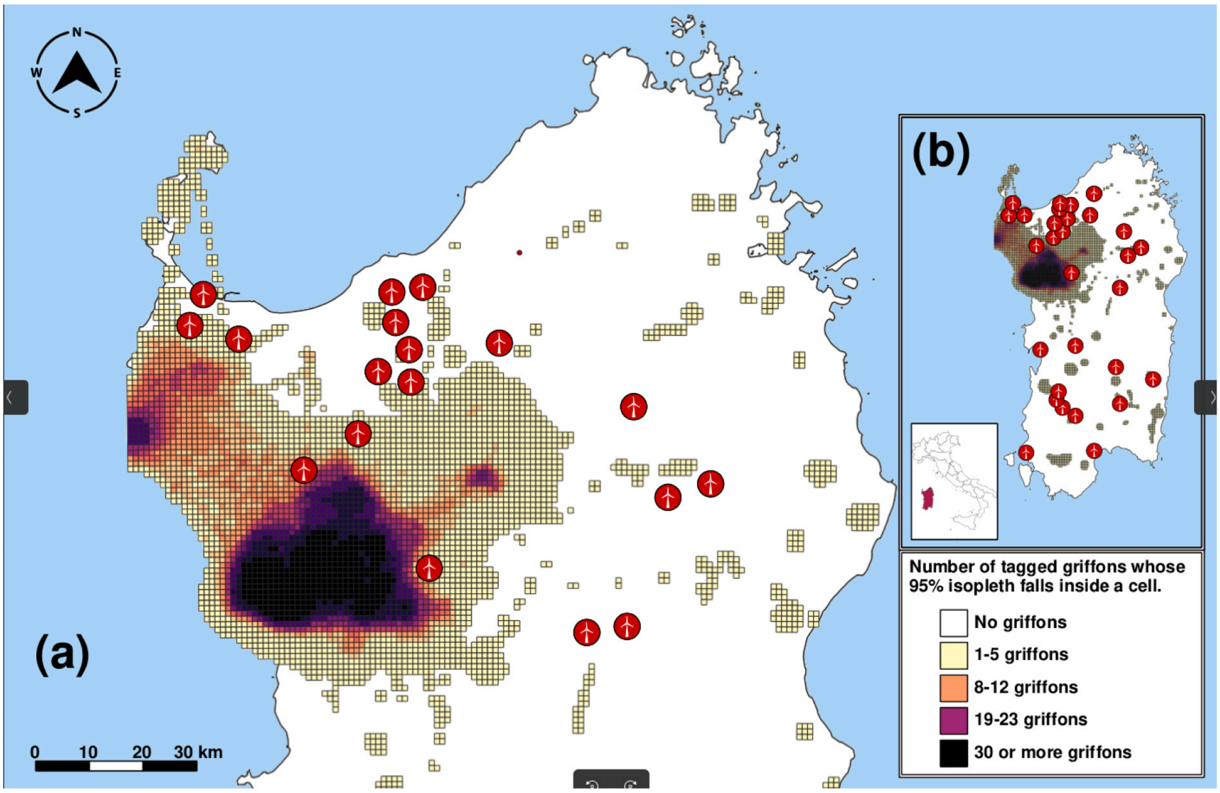

Fig. 1. Spatial distribution of areas covered by griffons and wind farms in Sardinia. Each cell of the grid (1 km x 1 km) represents the number of areas where individual vultures moved on a regular basis, delimited by 95% isopleths occurrence distributions. Darker areas were used by a higher number of griffons. Panel (a) shows a detail of North Sardinia, whereas panel (b) shows an overview of Sardinia. Individual occurrence distributions are available in the Supplementary Information (Appendix S6).

in 2022 (Berlinguer et al., 2022), *iii*) that each adult griffon needs around 500 g of meat per day and each breeding pair needs approx. 75 kg of food to rear a chick (Donázar and Fernández, 1990), then the whole population of griffons would consume between 61 and 66 tons of carrion per year. Therefore, the total biomass of 94 tons, provided by feeding stations and by carrion left on the field, would be sufficient to sustain the entire population. In the study area human infrastructures pose a major threat to griffons: out 43 released individuals that had been equipped with GPS transmitters, 4 died from electrocution, 1 from a collision with a wind turbine and 2 from collisions with powerlines (Fozzi et al., 2023; also see Table S3).

A total of 43 griffons were equipped with solar-powered GPS/GSM and VHF transmitters. Devices were mounted with a leg-loop harness made of teflon assembled in three strings (a cord of rounded silicone 2 mm + tubular teflon ribbon 025" and 0.44"), according to the recommendation of the Vulture Conservation Foundation (https://4vultures.org/). We used GPS/GSM devices from Ecotone (Ecotone Telemetry, Sopot, Poland; cDuck model, n = 3; Crex n = 28; Saker, n = 9; Skua, n = 5; all weighting 33 g) and Ornitela (Ornitela, Vilnius, Lithuania; Ornitela 3G_50g, n = 4; weight 50 g). The weight of GPS and harness did not exceed 3% of total body mass (Bodey et al., 2018).

GPS/GMS devices acquired GPS locations at different rates (Table S3) from 06:00 CET to 21:00 CET. However, in autumn and winter the frequency of data acquisition was lower, due to scarce solar charging caused by lower levels of solar radiation and diminished daylength (Fig. S1). When a griffon was still for more than 24 h, field technicians checked if it was dead. Deceased griffons were subjected to necropsy, carried out by FoReSTAS Agency and by Istituto Zooprofilattico Sperimentale della Sardegna. We discarded GPS locations from 6 griffons whose devices had stopped after a short timespan (17.5 ± 10.3 days) due to malfunctioning or the death of the individual.

Between September 2017 and June 2022, we collected a total of 130,218 GPS locations from 37 griffons (see Fig. S2 and Table S3) that had acquired on average 3038.5 ± 2525.1 GPS positions each (mean ± standard deviation) over a tracking time of 582.7 ± 462.1 days. As some individuals acquired GPS positions every 2 h, we resampled GPS locations at this rate for each individual and then interpolated missing data with the Euclidean distance method. This approach interpolated locations also at night when griffons do not fly and usually spend the time at roosting sites. Therefore, before using interpolated data, we graphically inspect them to check their plausibility and found that nocturnal GPS locations were reliable as they fell around roosts or nesting sites.

To quantify the overlap between the range distribution of griffons and existing wind farms in Sardinia we requested data about wind energy facilities from the Industrial secretariat of Regione Sardegna. The position of each wind turbine was provided in the shapefile format.

2.2. Statistical analysis

2.2.1. Estimation of the occurrence distribution

To identify the area and environmental resources used by griffons we estimated their occurrence distribution. This represents the uncertainty surrounding the observed trajectory of moving individuals over a certain time (Alston et al., 2022). We decided to estimate the occurrence distribution because griffons are a long-lived species, where juveniles and adults have different movement patterns (Bildstein et al., 2022), changing across their lifetime (Acácio et al., 2023) and can travel long distances (Delgado-González et al., 2022). Therefore, as data were collected only for 2–3 years, they could have been characterized by a low effective sample size and therefore estimators for the range distributions could have been unreliable (Silva et al., 2022).

As our GPS locations showed a significant temporal autocorrelation (Appendix S1), we fitted dynamic Brownian Bridge Movement Models (Kranstauber et al., 2012). Dynamic Brownian Bridge Movement Models were chosen as they are effective at identifying flyways (Palm et al., 2015) and they have already been successfully applied to gregarious vultures of the genus *Gyps* (Kane et al., 2022; Kmetova, Biro et al., 2021; Zvidzai et al., 2020). We selected a location error of 25 m, in line with empirical evidence and previous studies about *Gyps* vultures (Kane et al., 2022; Kmetova, Biro et al., 2021), as well as a window size and margin of 31 and 11 GPS positions respectively. However, preliminary exploration of model outputs indicated that minor changes occurred when window size and margins were changed. The occurrence distribution was estimated at a 250 m resolution.

We used the 95% isopleth of the occurrence distribution to represent areas regularly covered by griffons, and the 50% isopleth to represents areas where griffons spent most of their time, such as those around roosts and colonies (Alston et al., 2022).

2.2.2. Resource utilization function

The occurrence distribution did not allow us to test for habitat selection, as use-availability approaches require the use of the range distribution (Alston et al., 2022; Northrup et al., 2013). However, it allowed us to test which environmental features were associated to the use of landscape patches, through resource utilization functions (Marzluff et al., 2004).

We tried to predict the intensity of utilization of landscape patches, at a 250 m resolution, from *i*) their roughness and *ii*) aspect, *iii*) the percentage of the patch that was covered by trees, the distance of each patch *iv*) from the nearest supplementary feeding station and *v*) from the nearest roosting or nesting site, *vi*) the distance of each patch from the coastline, *vii*) the number of farms occurring on each patch and the viii) latitude and *ix*) longitude of the centroid of each habitat patch.

Roughness and aspect were selected because they are associated with the generation of orographic updrafts, important for soared flight (Shepard et al., 2013). In the study area, orographic updrafts are usually caused by Western winds, that come from the Mediterranean Sea and hit on the coastal cliffs, where griffon colonies are also located (Fig. 1). Roughness and aspect were generated from a Digital Elevation Model, freely available from Amazon AWS Terrain Tiles (https://registry.opendata.aws/terrain-tiles/).

The percentage covered by trees was also included to predict space use, as *Gyps* vultures detect carrion through eyesight (Bildstein, 2022) and tree cover could undermine their foraging success. Therefore, we expected them to avoid forest patches where foraging is impeded. This value was measured through the MODIS/Terra Vegetation Continuous Fields (https://lpdaac.usgs.gov/products/mod44bv006/).

As some studies emphasized that griffons concentrate foraging movements around colonies and roosts, especially when supplementary food is nearby (Dobrev and Popgeorgiev, 2021; Fluhr et al., 2017; Zuberogoitia et al., 2013), we also included distance from colonies and the nearest supplementary feeding station as covariates. The distance from supplementary feeding stations was also deemed to capture traditional foraging patterns of gregarious *Gyps* species, where individuals use interdependent foraging (Harel et al., 2017) and feeding stations are likely to be regularly selected. Moreover, we also used the number of farms occurring on a habitat patch as a proxy for carcass availability, as livestock often graze not far away from the main farm. The location of colonies was obtained from long-term population monitoring programs (Berlinguer et al., 2020), while the location of supplementary feeding stations has been recorded during the LIFE Under Griffon Wings project. The location of livestock farms was provided by the Regional Veterinary Epidemiological Observatory (Regional Department of Health, Veterinary services, Region of Sardinia).

The distance from the coastline was also included, as griffons are soaring fliers which are well-known to avoid flying over the sea, unless necessary (Bildstein, 2009). The coastline was obtained from official administrative boundaries downloaded from the Italian National Institute for Statistics (https://www.istat.it/it/archivio/222527), after having checked its plausibility against a satellite image of the study area.

We predicted space utilization through regression random forests (James et al., 2013). The random forest algorithm averages multiple regression trees and was used as we had no prior expectations about the functional forms of our covariates, and about their possible interactions. Moreover, random forests allow to control for spatial trends in the data by including the latitude and longitude of GPS locations as covariates, as we did with the centroids of each cell of the occurrence distribution. We did not use multilevel modeling (Ripari et al., 2022), as our considerable amount of data allowed for individual models, which for large samples attain a higher degree of accuracy than partial pooling (Liu et al., 2017). Instead, we fitted one random forest to each individual, and then calculated the total decrease in node impurities, through the residual sum of squares, and the R^2, to assess the overall predictive accuracy of our models. Finally, we used partial dependence plots to highlight the relationship between each covariate and space utilization by griffons, as well as interactions between covariates. Statistical analyses were carried out with the statistical software R (R Core Team, 2023) and a completely reproducible software code, and a dataset, are available at the following link https://osf.io/urbpv/.

3. Results

During the time of the study, griffons moved across an area of 956.3 ± 677.7 km^2 (95% isopleth) but restricted most of their

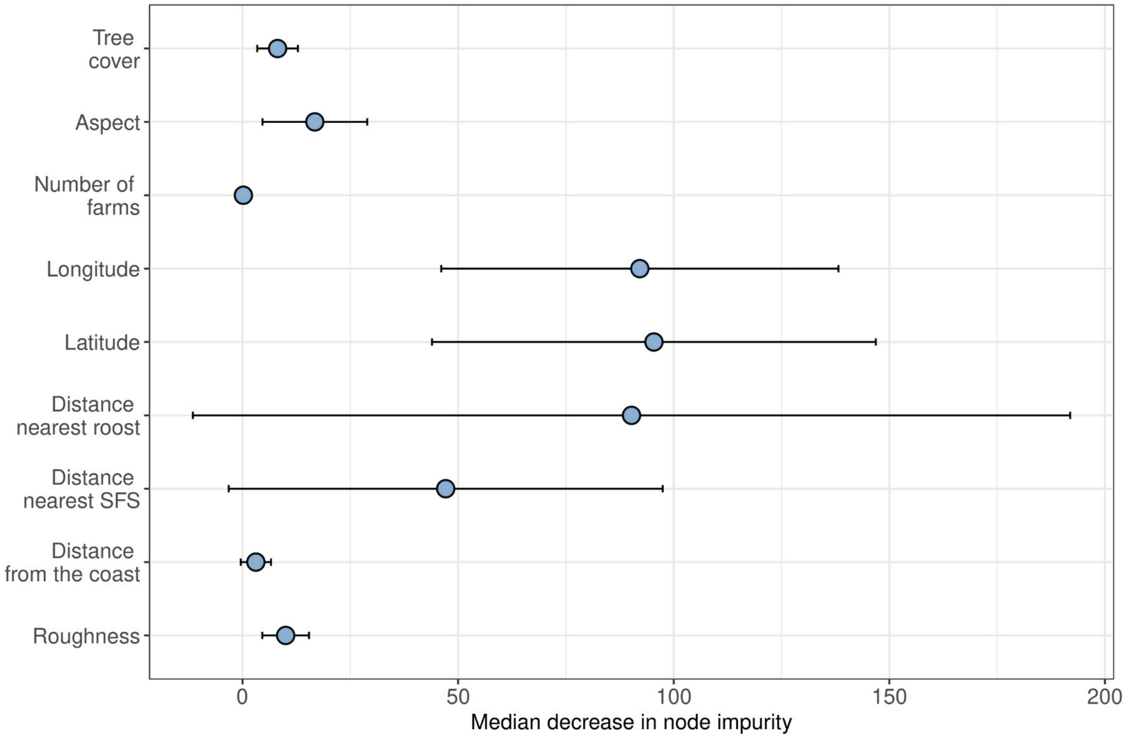

Fig. 2. Importance of the various predictors, expressed as the decrease in node impurities through the residual sum of squares. This value tells how well trees can split variables (the higher the better). Values were averaged for all 37 random forests: points represent median increase in node purity, and error bars standard deviation.

activities over an area of 73.8 ± 48.2 km^2 (50% isopleth). There were no clear differences in the size of covered areas between male and female vultures (Fig. S3). The size of both the 95% and the 50% isopleth increased with the length of data acquisition, indicating that griffons in our sample have not stabilized their movements yet (Fig. S4).

The occurrence distribution of griffons highlighted two areas with a very high spatial utilization (Fig. 1). The first one corresponded to colonies, roosts and foraging grounds distributed between the villages of Pozzomaggiore (40° 23' 49.704''N 8° 39' 35.208''E), Montresta (40° 22' 33.312''N 8° 30' 0.432''E) and Monteleone Rocca Doria (40° 28' 10.74''N 8° 33' 38.412''E), the stronghold of the species in Sardinia (approx. 69 territorial pairs, distributed over approx. 9 cliffs). The second area corresponded to colonies and roosts in Punta Cristallo (40° 37' 10.452''N 8° 8' 42.432''E, approx. 5 territorial pairs at one single cliff; Berlinguer et al., 2022).

As for wind turbines, the most recent data referred to those that had been built or authorized by 2019. We found 29 sites subjected to wind energy development, with a total of 649 turbines, mostly in Northwest and Southwest Sardinia (Fig. S5). Overall, 101 wind turbines were located within the occurrence distribution of griffons. Of these, 48 turbines were located at three sites just outside the most used area, at a distance of approx. 5 km (n. turbines = 37), 8.6 km (n. turbines = 10) and 3.7 km (n. turbines = 1). This last site was also located on the flyway connecting the two main colonies (Fig. 1).

Covariates predicted a significant amount of the occurrence distribution ($R^2 = 0.91 \pm 0.12$, Fig. S6). The median increase in node purity indicates that the distance from the nearest roost/colony and the distance from the nearest supplementary feeding station were the most important predictors (Fig. 2). For the majority of griffons, the areas used the most occurred within 5 km from roosting sites or colonies and within 10 km from the nearest supplementary feeding station (Fig. 3).

However, some individuals (n = 6) also had a non-monotonic relationship between space utilization and distance from roosts and colonies, increasing again their space utilization at distances greater than 5 km. And some other individuals (n = 4) had a non-monotonic relationship with distance from supplementary feeding stations increasing again their space utilization at distances greater than 20 km. There was no clear interaction between these two variables (Appendix S2) and the effect of supplementary feeding stations over space utilization did not vary according to their distance from colonies.

The aspect of habitat patches also seemed to affect their use by griffons. Griffons used more of those terrains that were oriented westward, between 180 and 300 degrees from North. The distance from the coastline, tree cover in each habitat patch and terrain slope did not seem to be important for predicting space utilization and did not have any clear pattern (Fig. S7).

4. Discussion

To the best of our knowledge this study is the first to assess space utilization by Griffon Vultures with high-resolution GPS telemetry on a Mediterranean island well disconnected from the mainland and characterized by both supplementary feeding and the availability of undisposed carrion.

Overall, we found that griffons' distribution range in Sardinia is smaller compared to those living in mainland Europe, like in the Iberian Peninsula, but also to those living in islands like Crete. These differences were sometimes quite impressive, with areas identified by our 95% isopleth being one order of magnitude smaller (Table S2). The fact that griffons in Sardinia move across relatively

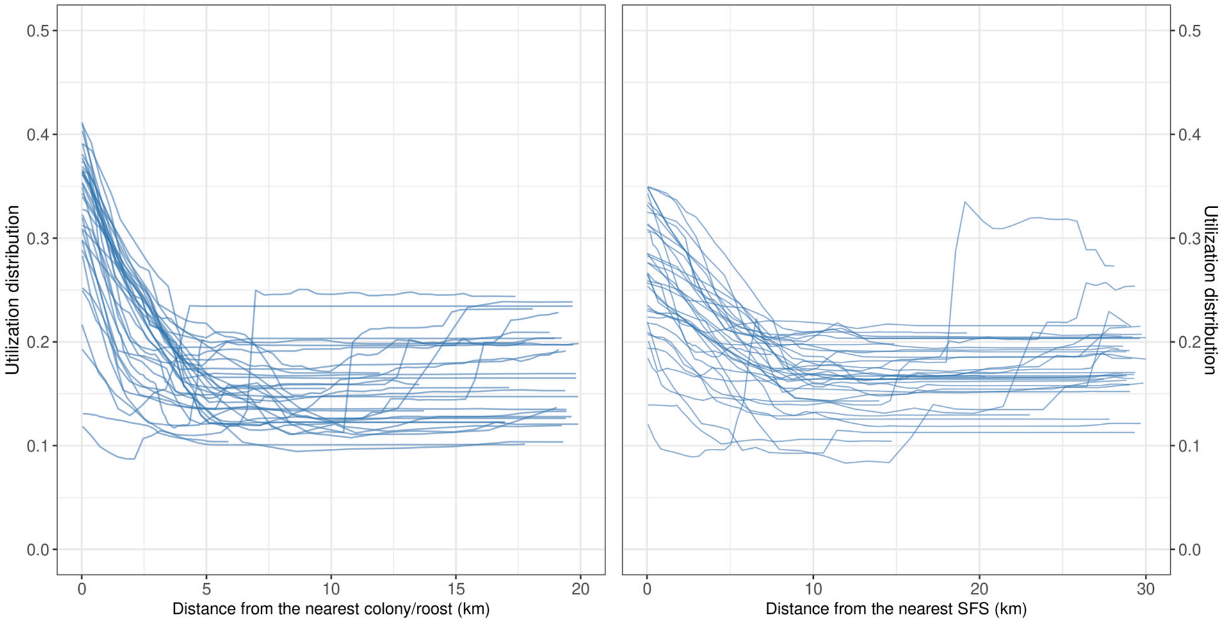

Fig. 3. Partial dependence plot of random forests, showing how the intensity of the occurrence distribution varied in function of the distance from roosts/colonies (panel on the left) and the distance from the nearest supplementary feeding stations (SFS, panel on the right).

small areas could be motivated by the proximity of trophic resources to roosts and colonies and possibly also by long-term mechanisms that reduced vagrancy in the Sardinian population.

As for the spatial distribution of roosting sites and trophic resources, these two factors were the most predictive of space utilization by griffons (Fig. 2), with most vulture movements occurring within 5–10 km from colonies and roosts (Fig. 3). In this area, supplementary feeding stations provide griffons with nearly 20 tons of carrion per year, approx. 21% of total biomass available. Griffons are gregarious (van Overveld et al., 2020) and their colonies grow through time, becoming subjected to strong density dependent competition for optimal breeding sites (Zuberogoitia et al., 2019) before experiencing increased emigration. Considering that cliffs in Punta Cristallo and around Bosa are still capable of hosting new breeding pairs and given the considerable availability of trophic resources around existing roosts and colonies, where griffons can rely on highly efficient group foraging, griffons may have limited reasons to expand their distribution.

Another explanation might also lie in the fact that in Sardinia griffons could have progressively lost their migratory habits, that implied sea crossings, due to selective pressure (Sanz-Aguilar et al., 2015). Although most of the GPS-tagged griffons from this study were wild-caught individuals recovered in Spain (n = 64), griffons are gregarious and have complex interdependent behaviour (van Overveld et al., 2020). Therefore, by not having contacts with movement-prone individuals, they may have adapted their movements to those of the sedentary local population.

From a conservation viewpoint our findings have three clear implications. First, since griffon movements concentrate around nesting/roosting sites and feeding stations, wind farms should not be built in these highly utilized areas. This recommendation aligns with Carrete et al. (2012), who showed that distance from roosts and aggregations was a major predictor of collisions between griffons and wind turbines and that setback distances are a crucial tool to reduce mortality. According to our findings, we believe that a setback distance for wind farm development of at least 15 km from the most used areas (Fig. 4) should be enforced as soon as possible. A similar

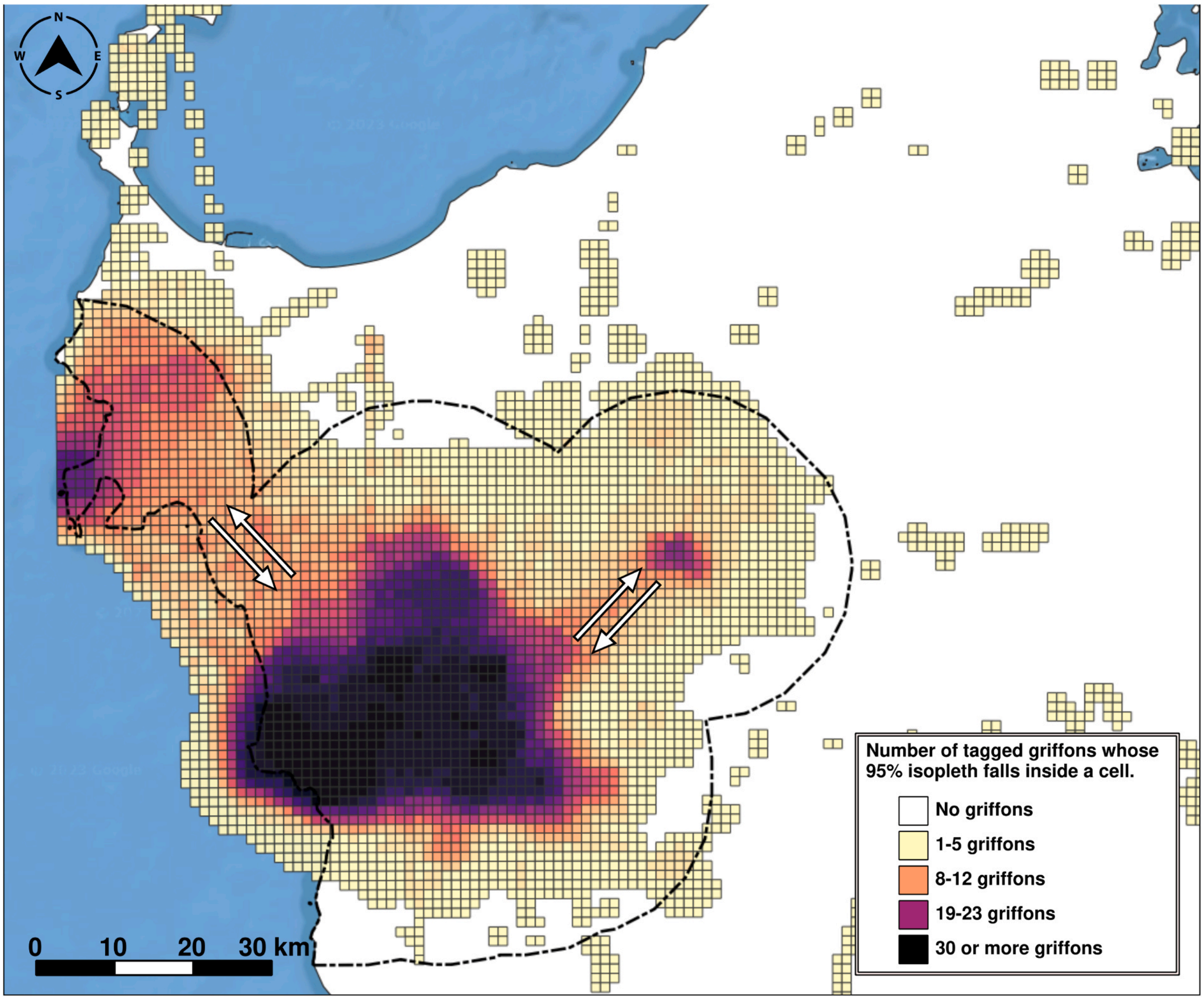

Fig. 4. Area delimited by the setback distance of 15 km, where onshore wind turbines should not be built (dashed line). Similarly to Fig. 1, darker areas of the grid were used by a higher number of griffons. Flyways between highly utilized areas are represented by bi-directional arrows.

measure would avoid construction of wind turbines around colonies and roosts, on main foraging grounds, as well as on flyways between colonies. Moreover, provided that a careful zonation of wind farms remains the most desirable management option, mitigation measures like selective stopping protocols, where wind turbines are halted whenever griffons fly around them (Ferrer et al., 2022), should be enforced on a compulsory basis. This measure should be implemented particularly along flyways connecting the two most utilized areas at the Southernmost and Northernmost portion of the study area (Fig. 4). Considering the presence of extensive animal husbandry, and the fact that wind farms areas can be used as pastures, monitoring carrion occurring on the field would also be important. Vultures have blind spots ahead and cannot detect the rotating blades of wind turbines when foraging (Martin et al., 2012), hence the presence of carrion around them could result into the death of multiple foraging individuals. These measures are needed, as wind farms have already been built around the area the most used by Griffon Vultures, well within the occurrence distribution of the species. Furthermore, among griffons that were tagged with GPS devices, one already died from collisions with wind turbines in 2017 (Table S3).

Adaptive supplementary feeding has been suggested as a measure to divert vultures away from wind turbines (Brink et al., 2020). In Sardinia feeding stations are located in the EU network of protected area – so called Natura 2000 sites - comprised within the vulture feeding area (Fig. S8), as approved by the Ministry for the Environment and by the regional environmental and sanitary authorities. The Region of Sardinia has determined Natura 2000 sites to be ineligible for wind farm development despite European legislation (Directives no. 92/43/CE and no. 79/409/CE) that does not exclude wind farm developments. However, vultures move outside the network of protected area and wind farms are present near their borders and in the flyways connecting them. Roosts are natural sites selected by vultures and several of them fall outside the protected areas. Therefore, wind farm development should be limited in the core area of priority species to ensure them the same level of protection as in protected areas, according to the Habitat Directive of the European Union (Directive no. 92/43/CE).

Moreover, our study emphasizes the need to understand how to regulate wind energy development, considering that griffons are expected to progressively disperse across the island. To enlarge the occupancy area a new release site is now being created in Southeast Sardinia, within the LIFE Safe for Vulture project (LIFE19 NAT/IT/000732). Moreover, supplementary feeding stations will be constructed to create a corridor between Southeast and Northwest Sardinia, across which griffons could move. Even if we did not monitor feeding events (Fernández-Gómez et al., 2022a), the intensity to which griffons use habitat patches also depends upon their distance from supplementary feeding stations. It is crucial that these are not placed in areas where wind farms occur or where their development has already been authorized. Given that no updated map of wind turbines is publicly available for Sardinia, it will be crucial to rapidly map wind energy facilities across the island and to use models based on thermal uplifts (Eisaguirre et al., 2020) or landscape connectivity (D'Elia et al., 2019) to predict the main routes that will be used by griffons to optimize mitigation measures.

Finally, by identifying under which weather conditions and at which time of the year griffons perform exploratory sallies (Jacobsen et al., 2020) and then select specific landscape patches (Hooven et al., 2023), it would also be possible to tailor mitigation measures across specific temporal windows, optimizing their efficacy.

Considering that up to approx. 6700 turbines could be built in Sardinia by 2030 (https://www.anev.org/wp-content/uploads/2022/07/Anev_brochure_2022.pdf), there is an urgent need for the zonation of wind energy, as well as the adoption of compulsory mitigation measures by wind farms. Griffon mortality could otherwise reach a magnitude capable of triggering severe density-dependent dynamics, undermining the viability of the whole population (Tsiakiris et al., 2021).

Griffon Vultures play an important role in the ecosystems of Mediterranean islands where they remove livestock carrion and ensure valuable ecosystem services. Nevertheless, fast onshore wind energy development is threatening their conservation. There is an urgent need for zonation and mitigation policies, co-designed by multiple stakeholders, to safeguard griffon population, as well as their ecosystem services and to ensure a truly sustainable development of onshore wind energy.

Nowadays, the main challenges posed by wind energy to Old World vultures are well known (Ives et al., 2022). However, significant progresses were also made in estimating collisions (Korner-Nievergelt et al., 2013), implementing mitigation measures (Ferrer et al., 2022) and developing zonation policies (Vasilakis et al., 2017). Mediterranean islands could translate this knowledge into effective conservation actions, showing a possible way to conjugate the development of green renewable resources with large raptor conservation.

CRediT authorship contribution statement

Fiammetta Berlinguer, **Jacopo Cerri** and **Marco Apollon**io conceived the ideas and designed methodology; **Fiammetta Berlinguer**, **Davide De Rosa**, **Ilaria Fozzi** and **Mauro Aresu** collected the data; **Jacopo Cerri** analysed the data; **Jacopo Cerri** and **Fiammetta Berlinguer** led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jacopo Cerri reports financial support was provided by European Commission. Ilaria Fozzi reports financial support was provided by European Commission. Davide De Rosa reports financial support was provided by European Commission. Fiammetta Berlinguer reports financial support was provided by European Commission. Marco Apollonio reports financial support was provided by European Commission.

Data Availability

Data have been archived on the Open Science Framework repository at https://osf.io/urbpv/.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02651.

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