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The Wind of Change: Mapping Wind Energy Growth and Multi-Species Vulnerability in Sardinia, Mediterranean

Chiara Costantino[1] | Jacopo Cerri[1,2] | Ilaria Fozzi[1] | Davide De Rosa[1] | Fiammetta Berlinguer[1]

[1]Dipartimento di Medicina Veterinaria, Universita Degli Studi di Sassari, Sassari, Italy | [2]Mammal Research Institute, Polish Academy of Sciences, Białowieża, Poland

Correspondence: Chiara Costantino (c.costantino1@studenti.uniss.it)

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ABSTRACT

The rapid expansion of wind energy across the Mediterranean region calls for more advanced tools to assess and mitigate its impacts on biodiversity. In this study, we present an innovative approach combining 13-year satellite imagery analysis and ecological modelling to assess the spatiotemporal overlap between wind energy development and habitat suitability for multiple vulnerable raptor species. We reconstructed a spatio-temporal trajectory of wind turbine distribution using high-resolution satellite images, meaning we quantified how and where turbines were installed over time to capture the progressive transformation of the landscape. This trajectory was then spatially compared with habitat suitability maps derived from species distribution models for seven raptor species of conservation concern, while for the Griffon Vulture (*Gyps fulvus*), we used GPS telemetry data. Our analysis revealed an overall 118% increase in wind energy infrastructure over the 13-year period. A substantial spatial overlap emerged between wind installations and suitable areas for raptors: specifically, we found that 50.5% of suitable areas fall within historically active wind zones (with wind farms operating for at least 13 years), and 73.3% of suitable areas overlap with new wind expansion zones. Although the degree of overlap varied among species, these values indicate that a considerable proportion of suitable habitat for the studied raptors now lies within areas potentially affected by wind turbines. This approach highlights the potential of combining geospatial data, predictive modelling, and a multi-species perspective to complement traditional assessment methods. Our results offer useful insights for identifying priority areas for monitoring and mitigation and propose a transferable framework that could support more biodiversity-informed energy planning in Mediterranean ecosystems.

1 | Introduction

Over the past decade, wind energy has grown rapidly, establishing itself as a key source of renewable energy and reaching a global capacity of 651 GW in 2019 (Global Wind Energy Council 2020). In the Mediterranean region, Southern European countries such as Spain, Italy, and Greece have significantly expanded wind energy capacity. By the end of 2023, Spain added 0.76 GW, Italy 0.53 GW, and Greece 0.54 GW of new onshore wind, with further growth continuing into 2024 (Spain +1.2 GW H1 2024; Italy +0.685 GW H1 2024), underscoring the region's growing contribution to the EU's 220 GW total wind capacity (WindEurope 2024 reports). This positive trend, reinforced by the agreement reached at the 2015 United Nations Climate Change Conference (COP 21) in Paris, underscores the crucial role of renewable energy in the global energy transition, with wind power standing out as one of the key contributors.

While providing crucial environmental benefits, chiefly the reduction of greenhouse gas emissions, wind turbines can negatively impact wildlife, particularly flying vertebrates such as birds and bats (Marques et al. 2014; Jonasson et al. 2024). Specifically, impacts include direct mortality from collisions with rotor blades and power lines (Rydell et al. 2010; Garvin et al. 2011; Huso et al. 2016) and indirect impacts such as habitat loss and disturbance, which can lead to species displacement and reduced population viability (Drewitt and Langston 2006; Madders and Whitfield 2006; Zimmerling et al. 2013; Arnett and May 2016; Frick et al. 2017). In addition, wind-power plants may act as barriers to movement, with the severity of these effects varying depending on site-specific and species-specific factors. However, birds can exhibit behavioural adaptations to mitigate these impacts, such as fleeing, shifting activity patterns, or modifying habitat utilisation; these responses are collectively termed avoidance (May 2015).

Among avian species, those that use soaring flight, such as raptors, are particularly vulnerable to the impacts of wind farms. The latter, in fact, cause high mortality among them due to collisions with turbine blades, recorded in various areas (Hunt 2002; Barrios and Rodriguez 2004; de Lucas et al. 2008). Their vulnerability can be attributed to three principal factors: low reproductive rates and delayed sexual maturity, which make populations incapable of compensating for additional mortality (Duriez et al. 2023); limited visual capacity in the direction of movement, primarily due to the lateral placement of their eyes, which restricts the frontal binocular field of view. During soaring flight, when the head remains relatively stable, this visual configuration reduces their ability to detect vertical obstacles such as turbine blades (Martin et al. 2012); and the overlap between wind farm locations and geomorphological features, such as ridges and updrafts, which are attractive for raptor activities (Katzner et al. 2012; Poessel et al. 2018; Rushworth and Krüger 2014). Other factors may also influence collision risk. For example, species with high wing loading and weak-powered flight, like Griffon Vultures (*Gyps fulvus*), rely on uplift winds to stay aloft. In poor uplift conditions, they are forced to fly lower, increasing their risk of collision with turbine blades (de Lucas et al. 2008; Pennycuick et al. 1975; Pennycuick 1998; Janss and Ferrer 2000). Moreover, species that habitually fly at dawn, dusk, or during the night may have a lower ability to detect and avoid turbines (Larsen and Clausen 2002).

In Europe, the precautionary principle is widely adopted to mitigate the impacts of wind turbines on threatened species (Braunisch et al. 2015; Kriebel and Tickner 2001). One of the most common applications of this principle is the buffer zone approach, which excludes wind turbines from areas around sensitive locations such as nesting sites. Buffers are typically based on expert knowledge or the estimated home range size of sensitive species (Bright et al. 2008; Janss et al. 2010; Venter et al. 2019), and generally range from 500 m to 3 km depending on species-specific ecology and sensitivity. This method is relatively easy to implement and avoids the uncertainties inherent in complex risk models, which often rely on multiple parameters with unknown distributions or inaccurate spatial data. However, it has notable limitations. Buffer zones are typically defined based on habitat use during a single life stage, most commonly the reproductive phase, without accounting for the spatial and temporal variability of species movements and habitat utilisation. Furthermore, as a static approach, buffer zones lack predictive capacity, making them insufficient for anticipating future conflicts, especially in dynamic systems where populations are expanding, declining, or shifting their distributions (Hirzel et al. 2004; Krüeger et al. 2014; Braunisch et al. 2015). Rather than abandoning buffer zones entirely, a more effective strategy would be to enhance them by integrating predictive tools. This combination would allow buffer zones to account for ecological dynamics, improving their adaptability to changes in species distribution and movement patterns. As a result, conservation measures would be not only scientifically robust but also more practical and effective in the long term.

To fill this gap, this study provides a novel spatiotemporal assessment of wind energy expansion over the past 13 years and its impact on the vulnerability of eight species of raptors of conservation concern. Unlike previous studies that rely on static assessments, we reconstruct the spatial and temporal patterns of wind farm development using repeated historical aerial imagery. This approach allows us to track changes in turbine distribution over time and identify areas where cumulative impacts are likely to be most significant. Despite the recognised importance of cumulative impacts (Willsteed et al. 2018), spatiotemporal analyses of wind turbine expansion remain largely unexplored in the literature. Moreover, while most studies focus on single species, our work assesses the effects of wind energy on multiple vulnerable species simultaneously. This broader perspective is crucial, as wind energy impacts extend beyond direct mortality and can also alter ecological interactions between species, such as predation and competition (Sergio and Hiraldo 2008). By integrating species distribution models (SDMs), we identify high-risk areas where these effects may be particularly relevant, providing a more comprehensive understanding of the ecological consequences of wind energy.

Our case study in Sardinia, Italy, exemplifies this approach by combining spatiotemporal wind energy mapping with a multi-species assessment. While Sardinia's wind energy expansion has specific local characteristics, the methodology we adopt provides a transferable and reproducible framework applicable to other regions. It may be applied to other Mediterranean insular contexts that share comparable ecological and development dynamics, thereby supporting broader efforts in conservation-oriented spatial planning. These insights contribute to more effective conservation strategies and the sustainable development of renewable energy.

2 | Methods

2.1 | Study Area

Sardinia, the second-largest island in the Mediterranean Sea, spans 24,094 km^2, approximately 8% of Italy's land area, and hosts a diverse range of Mediterranean habitats of conservation

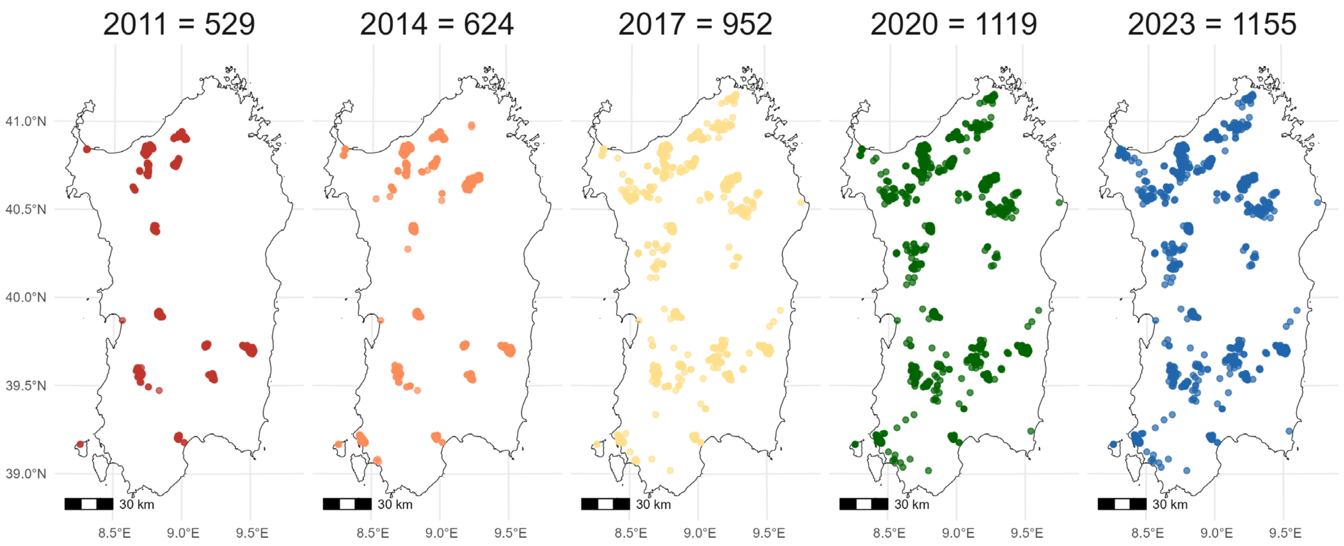

FIGURE 1 | Spatial distribution of wind turbines installed in Sardinia between 2011 and 2023, grouped by year of installation. Each panel shows the cumulative number and geographic spread of turbines for a given year, highlighting the progressive expansion of wind energy infrastructure over time.

concern. These ecosystems are safeguarded by a network of Natura, 2000 sites covering 8646 km^2 (35.9% of the island) and regional and national parks extending over 1273 km^2 (5.3%). In recent years, the island has experienced a significant expansion of wind energy, with a steady increase in installed capacity (Cerri et al. 2024). While playing a strategic role in renewable energy development, Sardinia's landscapes also reflect a long-standing pastoral tradition that has shaped local ecosystems and contributed to biodiversity conservation.

The island is home to several species of high conservation value, including the Griffon Vulture (*Gyps fulvus*), currently the focus of the LIFE Safe for Vultures project, which aims to support its protection and population recovery (https://lifesafeforvultures.eu/). Other vulnerable species include the Golden Eagle (*Aquila chrysaetos*) and the Red Kite (*Milvus milvus*). Sardinia also harbours Italy's last remaining population of the Little Bustard (*Tetrax tetrax*), along with two species of conservation concern: the Sardinian Long-eared Bat (*Plecotus sardus*), endemic to Sardinia, and the Sardinian Goshawk (*Accipiter gentilis arrigonii*), a subspecies endemic to Sardinia and Corsica. Other vulnerable raptors, such as Bonelli's Eagle (*Aquila fasciata*), are being reintroduced on the island through the EU-funded LIFE ABILAS project (LIFE23-NAT-IT, 2024–2030). With growing pressure from wind energy infrastructure and the presence of multiple vulnerable species, Sardinia represents a key area for assessing the balance between renewable energy expansion and biodiversity conservation.

2.2 | Temporal and Spatial Distribution of Wind Turbines

This study incorporates the dataset developed by Cerri et al. (2024), updated to 2023, which served as the reference for analysing temporal and spatial variations in the distribution of wind turbines in Sardinia. The dataset was constructed by comparing three pre-existing datasets and validating them through satellite imagery, with the latest update conducted using Google Earth (https://www.google.it/intl/it/earth/index.html). A grid of 1-km^2 cells was employed, covering an area of 8123 km^2, and each cell was checked against historical satellite images to ensure consistency within a 5-km buffer around each turbine. The cell selection protocol and spatial extent are described in detail in Cerri et al. (2024) research paper. To complement this, satellite images from 2011, 2014, 2017, and 2020 were used for a manual count of turbines visible in each time interval (Figure 1). These years were chosen because 2020 marked a peak in applications for new wind farm projects in Sardinia, while the preceding years showed a gradual increase in installations. The selection of these specific time windows also provided a temporally distributed sampling framework. The dataset primarily includes the geographic position of turbines, as identified through satellite imagery. The analysis of historical images allowed us to trace the evolution of wind energy infrastructure back to 2011, starting from the 2023 dataset and working retrospectively. These results provide a detailed spatial and temporal perspective on wind energy development in Sardinia, offering insights into the factors driving turbine placement and their implications for land-use changes.

To identify the spatiotemporal patterns of wind energy expansion on the island, we compared normalised wind turbine density rasters from 2011 and 2023. Raster cells were classified into two categories. Historically active areas include cells where wind energy activity was already present in 2011 and remained active in 2023 (value > 0 in 2011). As wind farms are a permanent alteration of the landscape, once wind turbines are built, these areas of the island are arguably those where sensitive species experience the highest cumulative impacts. Expansion zones include cells where wind energy activity was present in 2023 (value > 0) but absent in 2011 (value $= 0$), representing new wind farm developments established over the past decade.

2.3 | Data Selection

For this study, we selected seven raptor species based on specific criteria defined prior to model calibration, to ensure ecological and statistical robustness. Species were included in the analysis only if they met three key conditions:

- Raw occurrence records were subjected to expert-based spatial screening, during which two ornithologists from our research team (DDR, IF) verified that each record fell within areas ecologically consistent with the species' known range and habitat preferences;
- Following spatial thinning, a minimum of 40 unique and valid occurrence points remained, ensuring sufficient data density for reliable modelling;
- The species had to be ecologically relevant to the study area, particularly in terms of known or potential interactions with wind energy infrastructure (e.g., de Lucas et al. 2008), as supported by scientific literature and existing conservation knowledge.

These criteria ensured the development of statistically robust and ecologically meaningful species distribution models (SDMs; Stockwell and Peterson 2002). Additionally, the Griffon Vulture (*Gyps fulvus*) was treated separately due to its reintroduction history and ongoing management (see below). For this species, we used GPS telemetry data and dynamic Brownian bridge movement models (dBBMM) to delineate its spatial use, reflecting its current distribution more accurately than habitat-based models. The species analysed using SDMs were: Golden Eagle (*Aquila chrysaetos*), Little Owl (*Athene noctua*), Western Marsh Harrier (*Circus aeruginosus*), Peregrine Falcon (*Falco peregrinus*), Common Kestrel (*Falco tinnunculus*), Red Kite (*Milvus milvus*), and Common Buzzard (*Buteo buteo*). Table 1 provides an overview of the IUCN status at different levels and key information on the habitat preferences of these species. Species selection also considered conservation status. Only those with recognised conservation importance were considered, with priority given to species listed in Annex I of the Birds Directive or included in international conservation agreements. All selected species are indeed protected under the Birds Directive (2009/147/EC), with several listed in Annex I, which mandates the establishment of Special Protection Areas (SPAs) to safeguard their populations. Additionally, many of these species are included in the annexes of key international agreements, such as the Bern Convention (Annex II) and the Bonn Convention, highlighting their conservation priority at both European and global scales.

Notably, the Bonelli's Eagle (*Aquila fasciata*) was not included in the dataset. This exclusion is due to the temporal scope of our analyses, which date back to 2011, when the species had not yet been reintroduced to the island. The reintroduction project, known as Aquila a-Life, commenced between 2018 and 2023, during which 39 Bonelli's Eagles were released in Sardinia (Raganella Pelliccioni et al. 2024). Species for which limited data were available, such as Eleonora's Falcon (*Falco eleonorae*) and the Little Bustard (*Tetrax tetrax*), were also excluded. The scarcity of observations and reliable ecological records for these species prevented the development of robust models, which could have led to biased or unrepresentative outcomes.

TABLE 1 | Median values of the True Skill Statistic (TSS) and Area Under the ROC Curve (AUC) for the species included in the species distribution models (SDMs). The table also reports the predominant habitat type and the conservation status based on the IUCN Red List at the Sardinian (Shenk 2009), national (Italy), and global levels. The number of occurrence records used in the analysis is indicated for each species as sample size. IUCN categories follow the official classification: Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CE).

Species	Median TSS	Median ROC (AUC)	Habitat	Italian IUCN status	Global IUCN status	Sardinian IUCN status	Sample size (*n*)
Golden Eagle (*Aquila chrysaetos*)	0.75	0.94	Mountains, hills, grasslands, cliffs and open areas	NT	LC	VU	80
Little Owl (*Athene noctua*)	0.68	0.94	Agricultural areas, pastures, forest edges. Close to human's settlement	LC	LC	LC	169
Western Marsh Harrier (*Circus aeruginosus*)	0.76	0.95	Wetlands, marshes, lakes, extensive reed beds	VU	LC	NT	247
Peregrine Falcon (*Falco peregrinus*)	0.70	0.91	Cliffs, mountains and urban areas	LC	LC	NT	125
Common Kestrel (*Falco tinnunculus*)	0.80	0.96	Open, urban, and rocky areas	LC	LC	LC	437
Red Kite (*Milvus milvus*)	0.75	0.94	Semi-open areas with forests, agricultural areas, pastures and hillsides	VU	LC	CR	49
Common Buzzard (*Buteo buteo*)	0.80	0.97	Open woodland, grassland, hills and farmland	LC	LC	LC	440

2.4 | Species Distribution Models

The models were constructed using four algorithms commonly used in SDMs studies, using the package *Biomod2* (ftp://137.208.57.37/pub/R/web/packages/biomod2/biomod2.pdf) in RStudio: Random Forest (RF), Generalised Linear Models (GLM), Generalised Boosting Models (GBM), and Generalised Additive Models (GAM). These algorithms were selected to represent a complementary set of modelling paradigms, statistical (GLM, GAM), machine learning (RF), and boosting-based (GBM), that together allow capturing both linear and complex non-linear relationships, as well as interactions among predictors (Guisan et al. 2017). Their combined use enhances model robustness and minimises bias associated with individual algorithms. To ensure a reliable spatial representation, models were developed at a 1 km resolution (Seo et al. 2009), balancing ecological relevance and computational efficiency. Species presence data were obtained through a data-sharing agreement with *Ornitho* (https://www.ornitho.it/), ensuring access to high-quality occurrence records for the study area. Subsequently, an expert-based evaluation was conducted to identify and remove potentially unreliable records, ensuring the robustness of the dataset, as explained in 'Data Selection' section.

From the models generated using the four algorithms, the best-performing model for each species was selected based on the best-performing model. The best model was selected using an aggregated score derived from sensitivity and specificity metrics. Subsequently, the True Skill Statistic (TSS) and Receiver Operating Characteristic (ROC) scores were calculated (Segurado and Araújo 2004; Elith et al. 2006; Prasad et al. 2006). For each species, 10,000 pseudo-absences were generated. This choice is supported by Barbet-Massin et al. (2012), who demonstrated that large numbers of pseudo-absences improve the predictive accuracy of regression-based models (e.g., GLM, GAM) by better characterising unfavourable conditions. Furthermore, in ensemble models, the use of a single, unified set of pseudo-absences across algorithms ensures comparability and consistency, and the adoption of 10,000 pseudo-absences provides a robust compromise between predictive performance and computational cost. To further minimise spatial biases in presence data, the *spThin* package in R was used to perform spatial thinning, applying a minimum distance of 1 km between retained occurrences, in accordance with the spatial resolution of the environmental predictors. This ensured independent sampling by removing occurrence records violating a specified minimum nearest-neighbour distance (Aiello-Lammens et al. 2015). Additionally, to ensure that the model accounted for a realistic accessibility margin for the species, we applied a 5 km buffer around occurrence points. This choice is based on the concept of the accessible area described by Barve et al. (2011), which emphasises that the spatial extent of the model should reflect the species' ability to explore the landscape over time, thereby reducing the risk of bias in model outcomes. All environmental variables were standardised and centred at a spatial resolution of 1 km^2. The selection of environmental variables (shown in Table 2) was further refined by means of a Variance Inflation Factor (VIF) analysis, using *usdm* package in RStudio with an exclusion threshold of 5, in line with the study conducted by Shrestha in 2020, aimed to exclude multicollinearity among the predictors in the regression model (Shrestha 2020). A threshold value of 0.50 was applied to retain only areas with habitat suitability scores equal to or above this value, thereby excluding areas of lower suitability from the analysis. After testing several thresholds ranging from 0.30 to 0.70, the 0.50 cut-off was selected as a consistent and interpretable criterion to differentiate suitable from unsuitable areas. The species included in the analysis, along with ROC, TSS, and other relevant model performance metrics, are presented in Table 1. Finally, a cumulative habitat suitability map (Figure 2) was created by summing all individual species' raster layers. This approach allowed for the identification of areas with overlapping high suitability for multiple raptor species. The resulting map highlights zones that are not only suitable for several species but also those most impacted by wind energy development.

2.5 | Griffon Vulture Range Delineation

Unlike other species analysed using the SDMs approach, the Griffon Vulture required a different methodological approach due to its unique demographic and management context. In particular, its population has been extensively restocked and is still under active conservation management, making habitat-based modelling (SDMs) less appropriate. The current population derives from repopulation programs carried out in two key areas of Sardinia: the northwest (Bosa area) and the southeast (Villasalto area). Between 2016 and 2021, the LIFE Under Griffon Wings project (LIFE14 NAT/IT/000484, https://www.lifeundergriffonwings.eu/it/index.html) was implemented to improve the conservation status of the species, with a restocking program that included the release of 64 individuals in northwestern Sardinia.

To date, the species is currently part of the LIFE Safe for Vultures project (LIFE19 NAT/IT/000732, https://www.lifesafeforvultures.eu/), which aims at securing population growth and at enlarging its distribution. The delineation of the species' range was based on known colony location data, which allows us to define the spatial distribution. The area of presence was defined using a Dynamic Brownian Bridge Movement Model (dBBMM, Kranstauber et al. 2012), which estimates the cumulated occurrence distribution based on temporally autocorrelated GPS data. In this study, we used GPS data collected from 45 Griffon Vulture individuals over 8 years (2015–2023), totalling 174,184 fixes. The dBBMM was parameterised with window size = 31 and margin = 11, following standard practices for movement ecology. The 95% isopleth was used as a presence/absence cutoff, defining the core activity range of the species. This threshold includes 95% of the estimated movement, effectively delineating areas of regular use while excluding exploratory and occasional movements (Figure S2).

3 | Results

In 2011, there were 529 wind turbines installed across Sardinia. Over the following 13 years, this number more than doubled, reaching 1155 turbines by 2023. The growth was uneven, with distinct phases of more intense development. Between 2011 and 2014, the number of turbines increased moderately, rising to 624 turbines. A significant expansion occurred between 2014 and 2017, with the number of turbines growing to 952, marking the most substantial increase within the study period. From

TABLE 2 | Description of the environmental datasets used for species distribution models (SDMs).

Variable	Description	Source	References	Spatial resolution
BIO5	Maximum temperature of the warmest month	CHELSA	https://doi.org/10.16904/envidat.332	1000 m
BIO12	Annual precipitation	CHELSA	https://doi.org/10.16904/envidat.332	1000 m
BIO18	Precipitation of the warmest quarter	CHELSA	https://doi.org/10.16904/envidat.332	1000 m
DEM	Digital Elevation Model	CGIARCSI	https://csidotinfo.wordpress.com/data/srtm-90m-digital-elevation-database-v4-1/	90 m
Distance to lakes	Euclidean distance from lakes	Hydro SHEDS	https://doi.org/10.1038/ncomms13603	1:250.000
Slope	Terrain slope derived from DEM	CGIARCSI	https://csidotinfo.wordpress.com/data/srtm-90m-digital-elevation-database-v4-1/	90 m
Aspect	Terrain exposure derived from DEM	CGIARCSI	https://csidotinfo.wordpress.com/data/srtm-90m-digital-elevation-database-v4-1/	90 m
GHS	Global human settlement density	Copernicus JRC Data Catalogue	https://human-settlement.emergency.copernicus.eu/download.php	100 m
Crops and Pastures	Land cover classification	LP DAAC	https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD44B?hl=es-419	250 m
Tree Percentage Cover	Percentage of tree coverage	LP DAAC	https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD44B	250 m
Wetlands	200 m buffer around rivers	HydroSHEDS	https://www.hydrosheds.org/products/hydrorivers	1:500.000

2017 to 2020, the construction of new turbines continued at a slower pace, reaching 1119 turbines. Finally, between 2020 and 2023, turbines increased up to 1155 units (Figure 1). Historically active areas (Figure 3a) are primarily distributed across the north-western part of the island, with additional concentrations in central and southern sectors. Their spatial pattern tends to form contiguous clusters of varying extent. Expansion zones (Figure 3b) appear more fragmented in comparison with historically active areas, affecting different and partly new portions of the island, including eastern, southern, and central sectors. In some cases, the new cells are located near areas already active in 2011, while in others, they occur as isolated cells, distant from the main previous developments.

Species Distribution Models (SDMs) developed for the seven raptor species showed a good level of predictive accuracy. Performance metrics, including the Area Under the Curve (AUC) and the True Skill Statistic (TSS), are summarised in Table 1. All models achieved AUC values above 0.90, indicating strong model discrimination capabilities. TSS values ranged between 0.68 and 0.80, further supporting the robustness of the models in distinguishing suitable from unsuitable habitats. The habitat suitability maps, shown in Figure 4, highlight areas across Sardinia with varying degrees of suitability for each of the seven raptor species. A summary of the number of turbines located within suitable habitats for each species is provided in Table S2. Mountain specialists, such as the Golden Eagle (*Aquila chrysaetos*) and Peregrine Falcon (*Falco peregrinus*), show high habitat suitability in central and northern Sardinia, as well as along rugged coastal cliffs and rocky outcrops. In 2023, 443 turbines overlapped with suitable habitat for the Golden Eagle, up from 274 in 2011. Similarly, the number of turbines in Peregrine Falcon suitable areas rose from 153 to 368, representing 31.86% of turbines installed by 2023. The Red Kite, a species favouring open and hilly landscapes, particularly in central and northern Sardinia, also experienced an increase in turbine overlap. In 2011, 169 turbines were located in its suitable areas, rising to 383 in 2023, accounting for 33.16% of the turbines installed that year. Generalist species, including the Common Buzzard and Common Kestrel, exhibit the broadest distributions across the island, thriving in open agricultural and mixed landscapes. By 2023, 94.89% and 83.20% of wind turbines were in areas suitable for the Buzzard and Kestrel, respectively. The Little Owl, while more restricted to lowland agricultural areas, also showed a marked increase in turbine overlap, from 337 in 2011 to 803 in 2023 (69.52%). Wetland-associated species, such as the Marsh Harrier, are mostly confined to coastal wetlands and lowland zones in western and southern Sardinia. Despite this narrower range, overlap with turbines increased from

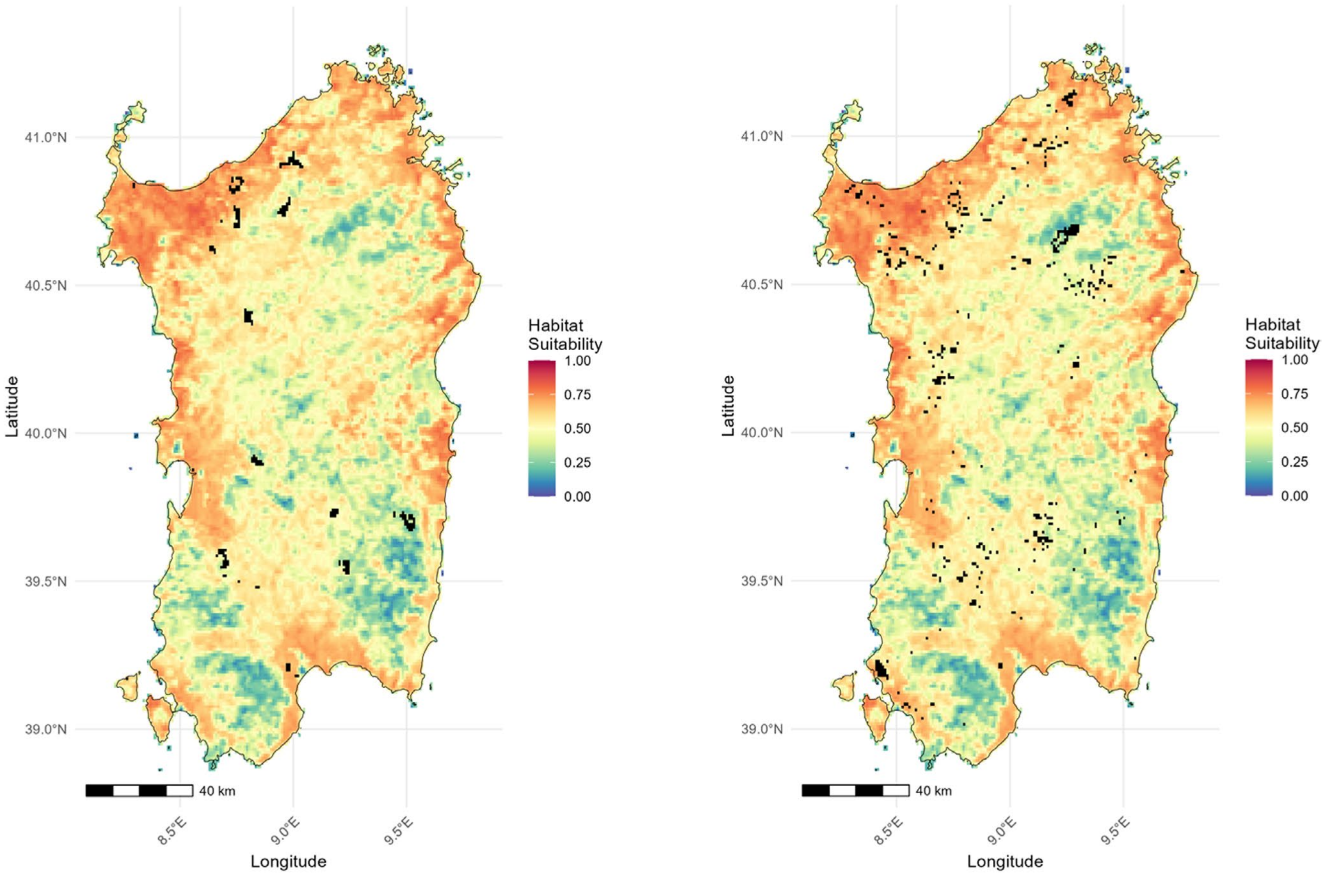

FIGURE 2 | Cumulative habitat suitability map for seven raptor species in Sardinia, based on species distribution models (SDMs), overlaid with historically active areas (left side) and expansion zones (right side). The overlay reveals a substantial increase in the overlap with high-suitability areas (≥ 0.50) in expansion zones (73.3%) compared to historically active areas (50.5%). This difference was statistically significant ($\chi^2 = 31.18$, df = 1, $p < 0.000001$), indicating a growing spatial conflict between wind energy development and raptor conservation priorities.

148 in 2011 to 456 in 2023. The Griffon Vulture, whose range was modelled using GPS telemetry rather than SDMs, shows a contrasting spatial pattern. While southeastern Sardinia remains free of wind development, the core activity range in the northwest experienced a substantial increase, from 25 to 90 turbines between 2011 and 2023 (Figures 5 and S6). Of critical conservation concern, turbines within Griffon Vulture core habitat increased 3.6-fold over the study period. The overlay with the cumulative habitat suitability raster for raptors (Figure 2) revealed that a total of 100 km^2 within historically active areas falls within zones with suitability values equal to or greater than 0.50, accounting for 50.5% of the total area classified as historically active.

In the case of the expansion zones, 335 km^2 falls within areas with suitability values equal to or greater than 0.50, representing 73.3% of the total area identified for expansion.

4 | Discussion

4.1 | Key Findings and Conservation Implications

This study offers a novel perspective about the added value of combining the spatially and temporally variable assessment of turbine expansion with habitat suitability modelling. Our approach allowed us to: (1) identify spatial and temporal patterns in wind farm expansion, and (2) quantify the overlap between installed wind turbines and areas of high cumulative suitability for multiple species of vulnerable raptors. Our results reveal three major patterns with important implications for raptor conservation and wind energy planning in Mediterranean ecosystems. First, wind energy development in Sardinia expanded by 118% between 2011 and 2023, following a spatially and temporally uneven trajectory, with new turbines increasingly clustered in certain areas. Second, this expansion led to a substantial increase in the overlap between installed turbines and highly suitable habitats for multiple raptor species, from 50.5% (100 km^2) in 2011 to 73.3% (335 km^2) in 2023. Third, this overlap disproportionately affected threatened and endemic species, suggesting an uneven distribution of potential impacts across the raptor community. Together, these findings highlight the need for spatially explicit, species-informed planning to prevent escalating biodiversity risks from poorly coordinated wind energy expansion.

4.2 | Spatial and Temporal Trends in Turbine Development

While the number of turbines in Sardinia increased by 2.18 times between 2011 and 2023, their construction did not occur uniformly across the island but was clustered in space and time

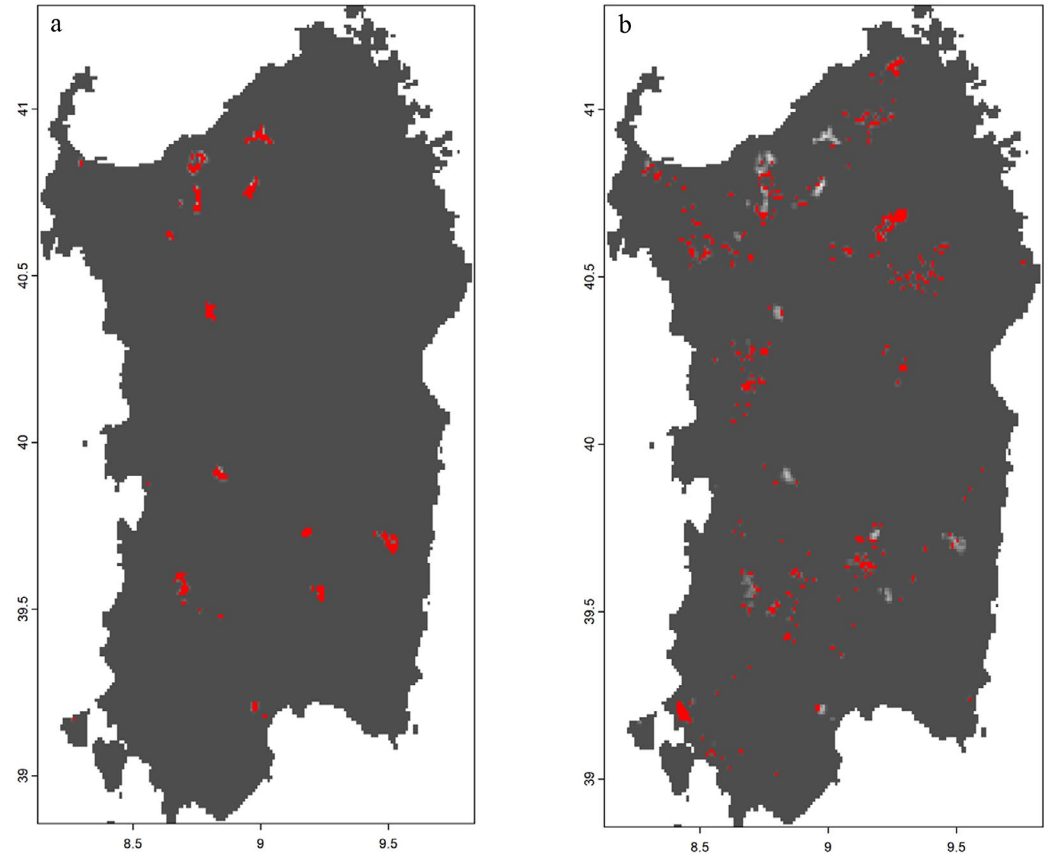

FIGURE 3 | Spatiotemporal patterns of wind energy development on the island based on normalised wind turbine density rasters from 2011 and 2023. Historically active areas (panel a) indicate cells where wind energy infrastructure was already present in 2011 and remained active in 2023. Expansion zones (panel b) correspond to cells where wind energy activity emerged in 2023 but was absent in 2011, representing areas of recent wind farm expansion during the past decade.

(Figures 1 and S1). Spatial analysis using the Nearest Neighbour Index (NNI) confirmed this pattern, with a value of 0.145, indicating a highly aggregated distribution of turbines. This clustering likely reflects underlying planning dynamics, whereby new projects tend to expand near already authorised wind farms, forming spatially consolidated development zones. While some areas have hosted wind turbines since at least 2011, others foresaw a more recent expansion of wind farms. The distinction between historically active areas and expansion zones highlights two different phases in the development of wind energy in Sardinia, with important implications for (1) environmental impact assessment, (2) mitigation measures aimed at reducing collisions between raptors and wind turbines, (3) spatial planning and (4) future research on how wind energy development can affect biological communities in the Mediterranean. In terms of environmental impact assessment, the distinction between historically active areas and expansion zones calls for two different assessments aimed at filling two different knowledge gaps. Historically active areas correspond to the island's earliest wind energy installations and have remained operational for over 13 years. This long-term presence implies that several sensitive species of birds and bats have been exposed to prolonged disturbance and/or mortality. This could in turn have resulted in a long-term reduction of their fitness, due to behavioural changes, stress and/or mortality (Duriez et al. 2023; May 2015), and in the creation of source-sink systems (Grainger Hunt et al. 2017) or in the permanent alteration of entire assemblages of species (Fernández-Bellon et al. 2019).

Environmental impact assessment for wind farms in historically active areas should therefore focus on quantifying the long-term impact of wind turbines on individual fitness and population viability dynamics. Conversely, raptors in expansion zones, particularly those living in areas where wind farms developed after 2020, are still probably affected by increased disturbance and habitat modifications associated with the construction phase of wind farms (Schöll and Nopp-Mayr 2021). Environmental impact assessment for wind farms in expansion zones should therefore prioritise the detection of short-term impacts on vulnerable species. In this context, historically active areas should represent the highest priority for monitoring, as they provide the ideal conditions to assess the prolonged impact of wind energy infrastructure on habitats and wildlife. Data gathered from these areas can also serve as a reference for predicting the future impact of wind turbines, for those areas where their construction was more recent. Expansion zones, while more recent in origin, also warrant attention, particularly when located near historically active clusters. In such cases, the cumulative effect may be amplified by the spatial overlap of pressures. Expansion zones situated farther from existing developments may offer opportunities to assess wind energy impacts in previously undisturbed environmental contexts.

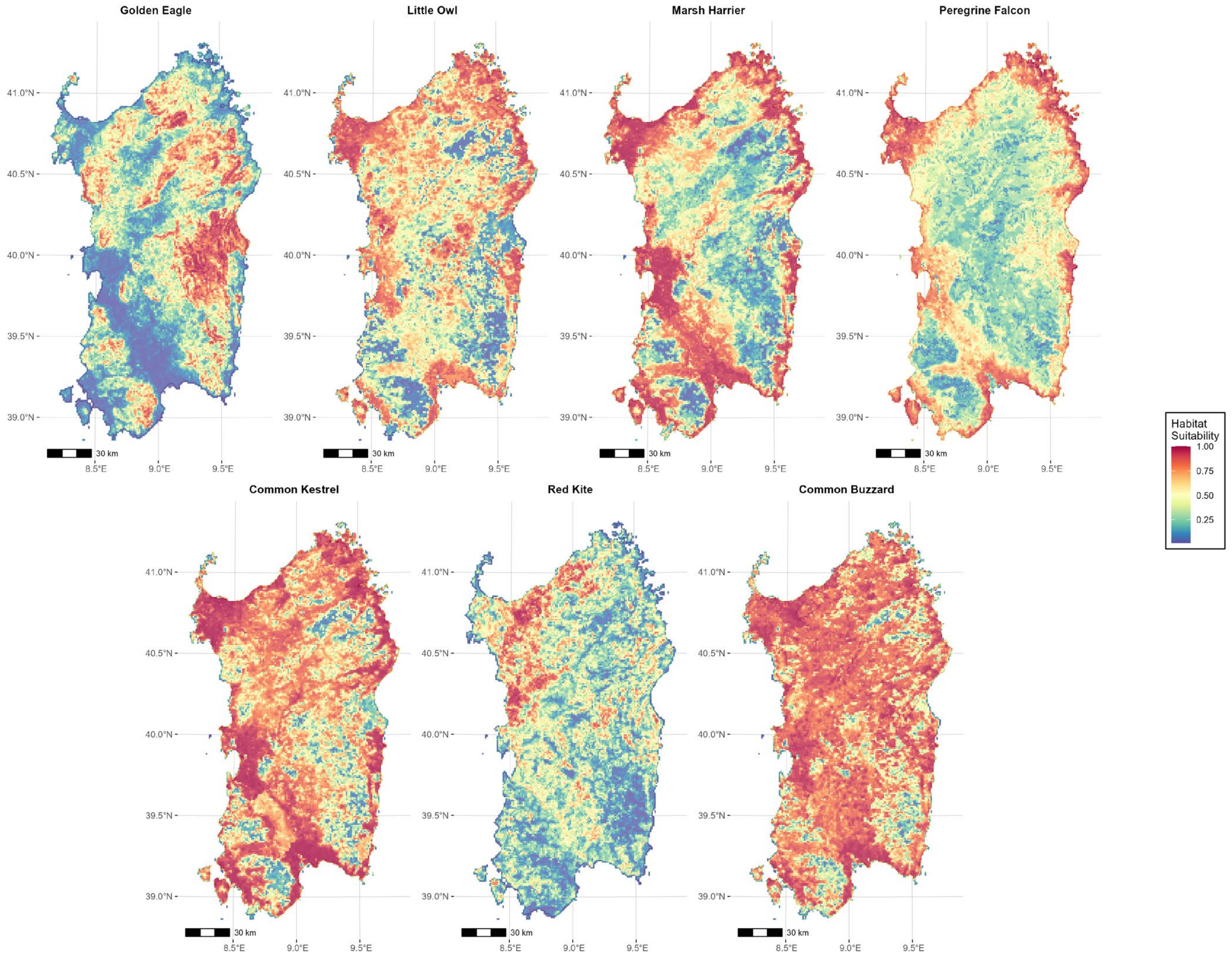

FIGURE 4 | Habitat suitability maps for seven raptor species in Sardinia based on species distribution models (SDMs). Each panel represents the spatial distribution of habitat suitability for a single species, with values ranging from low (blue) to high (red).

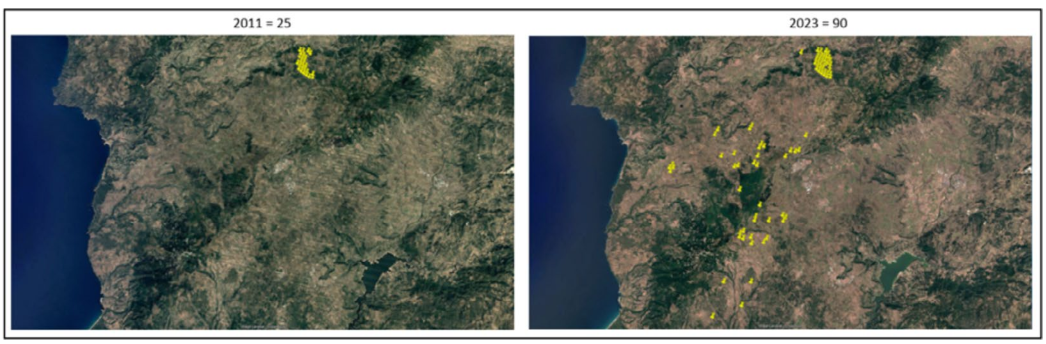

FIGURE 5 | Side-by-side comparison of historical satellite imagery used to assess wind turbine development through time-lapse analysis. The left panel shows an older satellite image where few turbines were present (2011), while the right panel displays a more recent image where wind turbines have been installed at the same locations (2023). A total of 65 new turbines were added over the period, increasing from 25 in 2011 to 90 in 2023.

4.3 | Increasing Overlap With Suitable Habitats

The overlap between these areas and the cumulative habitat suitability raster showed that a significant proportion of new wind farm installations falls within zones of high suitability for raptors. This finding is particularly relevant from a risk management perspective, as it suggests increasing exposure of sensitive species to potential interference from wind energy infrastructure. Within this framework, the multi-species approach adopted represents a key element. Integrating the spatial suitability of multiple raptor species allows for the identification of areas that are potentially more sensitive, overcoming the limitations of single-species assessments. The resulting cumulative output provides a synthetic map of areas with the highest ecological vulnerability, which can serve as an operational tool to guide monitoring efforts and further investigation. In particular, zones where wind energy expansion overlaps with high multi-species suitability should be considered priority targets for further assessments of collision risk and for the design of site-specific mitigation measures. From an operational perspective, we recommend a graduated monitoring strategy, prioritising among the suitable areas: (1) historically active areas, (2) expansion zones adjacent to these areas, and (3) expansion zones located further away. This approach would optimise the use of available resources while enabling data collection across a spatio-temporal gradient of wind energy impact.

4.4 | Species-Specific Vulnerabilities

Species-specific analyses underscore the urgency of these findings. The Red Kite shows a marked preference for areas increasingly affected by wind energy development. This spatial overlap raises major concerns: due to their soaring flight and foraging behaviour, medium-sized raptors like the Red Kite are highly susceptible to collisions (Mattsson et al. 2022). Collision risk models suggest that even moderate mortality rates can threaten the viability of small, declining populations (Schaub 2012) such as the Critically Endangered Red Kite in Sardinia. The Red Kite was considered common and resident in Sardinia until the end of the nineteenth century, but since the second half of the last twentieth century the species has experienced a progressive contraction of its habitat declined until the period 1990–1995 when it bred, population was 8–15 pairs (Schenk 1995), concentrated in the northwest of the island. Comparing the current distribution with the historical one, the Red Kite has completely disappeared as a breeder from the east and south of the island (De Rosa et al. 2021). The Golden Eagle is vulnerable to both collisions and habitat displacement. In places like California's Altamont Pass, turbine collisions kill dozens of individuals annually (Smallwood and Thelander 2008), and similar risks have been reported in Europe (Fielding et al. 2021). In Sardinia, increasing turbine density since 2011 has intensified threats. Even a few collisions can reduce foraging efficiency and reproductive success, compromising long-term survival (Grainger Hunt et al. 2017). Generalist species such as the Common Buzzard and Common Kestrel, although listed as Least Concern, show broad overlap with wind turbines. The Common Buzzard, for instance, occupies areas with over 90% turbine coverage. Evidence from Italy and Germany points to both behavioural avoidance and high mortality rates (De Lisio et al. 2011; Grünkorn et al. 2017), suggesting potential long-term effects.

The Griffon Vulture represents a particularly critical case. This large, soaring scavenger depends on thermal currents and often flies in groups through high-risk areas near turbines (Arrondo et al. 2020). In Sardinia, the impact of wind energy development varies markedly by region. The south-eastern area remains currently turbine-free, offering a low-risk context. In sharp contrast, the north-western area, which hosts the species' core population, has experienced a dramatic expansion of wind infrastructure, with the number of operational turbines increasing from 25 in 2011 to 90 in 2023 (Figure 5). This sharp rise substantially elevates the likelihood of turbine-vulture interactions, raising serious concerns about cumulative collision risk for this recovering population. As such, this area emerges as a priority for implementing mitigation measures and refining spatial planning to prevent future conflicts.

4.5 | Current Gaps and Mitigation Strategies

In some European regions, advanced strategies are already in place to mitigate bird collision risk with wind turbines, such as on-demand turbine shutdown in the presence of vulnerable species. In Andalusia, for example, a year-round surveillance system allows for the temporary shutdown of turbines when hazardous situations are detected, reducing Griffon Vulture mortality by around 50% with a negligible energy loss (de Lucas et al. 2012). Alongside human observers, automated systems such as radar and smart cameras are increasingly used to detect birds in real time and trigger immediate responses. In Sardinia, where there is significant overlap between areas of high suitability for soaring raptors and zones targeted for wind energy expansion, active mitigation strategies of this kind are still lacking. Risk management largely relies on static, pre-construction assessments, with no dynamic monitoring during turbine operation. Currently, neither real-time surveillance nor automated detection technologies are in place. Overall, this study underscores the necessity of integrating spatial and temporal data on wind energy development with multi-species habitat models to inform conservation strategies. The clear spatial clustering of turbines in areas of high cumulative suitability, coupled with uneven temporal dynamics, highlights the need for more proactive and adaptive management approaches. Periodic updates to turbine databases, regular monitoring of raptor populations, and the adoption of avoidance-based siting criteria are essential steps to mitigate long-term impacts. As renewable energy continues to expand across the Mediterranean, Sardinia emerges as a critical case study, illustrating both the risks of poorly planned development and the value of biodiversity-informed decision-making.

This study presents an unprecedented spatiotemporal assessment of wind energy development over a 13-year period, focusing on eight raptor species of conservation concern. Unlike previous research, which has often examined shorter timeframes or single species, our approach offers a more comprehensive understanding of spatial and temporal trends, revealing how wind energy expansion can proceed in a non-uniform manner and potentially conflict with biodiversity conservation goals. The combination of a long-term perspective and a multi-species framework represents a significant methodological advancement, providing more robust insights for spatial planning and for evaluating the cumulative risks associated with wind energy development. Our findings reinforce the urgent need for regularly updated data, rigorous environmental assessments, and the integration of ecological monitoring into decision-making processes to support genuine coexistence between energy transition and nature conservation. In this context, our work provides a solid scientific foundation for the development of more effective mitigation strategies that address not only the siting of new wind farms but also the adaptive management of risks for the most vulnerable species.

4.6 | Policy Implications and Strategic Environmental Assessment

The findings of this study provide valuable insights for enhancing strategic planning processes and supporting the implementation of Strategic Environmental Assessment (SEA) in the context of renewable energy development. By identifying spatial and temporal patterns of wind energy expansion alongside multi-species habitat suitability, our approach offers a technical basis for proactively evaluating the ecological risks associated with new developments. These tools can be integrated into SEA procedures to anticipate cumulative impacts, identify ecologically sensitive areas, and steer wind farm siting towards zones with lower potential for environmental conflict. Furthermore, the cumulative habitat suitability map offers a replicable and operational instrument to align renewable energy policies with biodiversity conservation goals. The integration of up-to-date data on species distribution and existing infrastructure improves the effectiveness of mitigation and prevention strategies, promoting a more adaptive and precautionary planning approach. In this regard, the study supports the implementation of the European SEA Directive (2001/42/EC), reinforcing the alignment between ecological transition and the protection of natural ecosystems.

4.7 | Broader Applications, Limitations, and Future Directions

This study presents a reproducible approach that can be extended to other regions undergoing rapid expansion of renewable energy infrastructure. By integrating habitat suitability modelling with spatiotemporal analyses of wind energy development, our framework enables a multi-species and landscape-level assessment of ecological risk. Although our analysis focuses on Sardinia, the methodology is transferable to other Mediterranean insular and continental contexts that host biodiversity of conservation concern. However, the interpretation of our results requires some caution. The overlap between suitable habitat and wind energy infrastructure represents a proxy for potential vulnerability but does not automatically equate to actual collision risk. The real impact also depends on behavioural and ecological factors such as flight altitude, duration of use of the area, and probability of interaction with turbines. In addition, the habitat suitability models used are static and do not account for potential interannual or seasonal variations in habitat use. Nevertheless, this limitation is partially mitigated by the fact that all species considered in this study are breeding residents in Sardinia, with relatively stable spatial distributions over time. Another potential source of uncertainty lies in the use of a uniform threshold to binarise habitat suitability, which may not fully capture the ecological specificities of each species. Finally, the study does not directly incorporate demographic or behavioural parameters, such as survival rates, reproductive success, age structure, or avoidance capacity. However, for the Griffon Vulture, GPS telemetry data are available and offer valuable insight into spatial dynamics, which could be more fully integrated in future analyses.

In light of these considerations, we emphasise the importance of developing more integrated approaches that combine habitat suitability modelling with behavioural, demographic, and operational data. The integration of satellite telemetry, mortality rates, and automated bird detection systems represents a promising frontier for enhancing the effectiveness of mitigation strategies. Although some limitations exist, this study lays a robust foundation for supporting spatial planning, adaptive monitoring, and the prioritisation of mitigation measures aimed at enabling the coexistence of renewable energy development and biodiversity conservation.

Author Contributions

Conceptualization: C.C., J.C., F.B.; Methodology: C.C., J.C., D.D.R., I.F.; Data curation: C.C., D.D.R., I.F., J.C.; Formal analysis: C.C., J.C.; Writing – original draft: C.C.; Writing – review and editing: C.C., J.C., I.F., D.D.R., F.B.; Supervision: J.C., D.D.R., F.B.; Funding acquisition: F.B.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data supporting the results of this study is available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** acv70043-sup-0001-Supinfo.docx.