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RESEARCH ARTICLE

# GPS-tracked vultures indicate a relaxation of conservation commitments in renewable energy development

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## Abstract

1. Strategic and well-informed environmental planning tools are instrumental to achieve the 2030 Sustainable Development Goals. Given the boost in renewable energy facilities, different planning tools are being proposed to identify low-sensitive areas for the installation of these infrastructures, where environmental impact assessment procedures are simplified. However, the effectiveness of these tools is rarely scrutinized and, therefore, if they are fit for purpose remains unsolved.
2. We used data from 90 GPS-tracked griffon and bearded vultures to assess the level of spatial agreement between vultures' space use at heights with a risk of collision with wind turbines and the environmental sensitivity to wind energy identified by official planning tools.
3. Despite relatively high agreements (>0.6 out of 1), these tools still misclassified up to ~88% of vultures' home ranges, with strong disagreements observed in foraging grounds, movement corridors and near breeding colonies. Furthermore, the spatial agreement decreased when considering the legally binding categories (>0.6 out of 1) in contrast with the non-statutory categories (>0.9 out of 1).
4. *Synthesis and applications*. Our results highlight the need to evaluate and improve official spatial planning tools developed to minimize environmental impacts such as those of renewable energies. GPS-tracking data from vulnerable species help in identifying risk areas misclassified by the planning tools, which should also be founded in a proper legal background (e.g., constraining development in the most sensitive areas) to avoid limiting their effectiveness in practice.

KEYWORDS
biologging, environmental impact assessment, environmental policy, legal downgrading, movement ecology, renewable energy, scavengers, spatial planning

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## 1 | INTRODUCTION

The increasing implementation of laws and policies dedicated to reducing the impact of humans on nature illustrates the foremost role that these tools can play in nature conservation (UNEP, 2019). Among them, Environmental Impact Assessments (EIAs; in their broadest sense, see Morgan, 2012) are used worldwide to pursue the so-called 'sustainability' by assessing the negative impacts that human actions may have on nature, and identifying appropriate actions to halt or reverse them (Morgan, 2012). This is essential for infrastructures that are rapidly expanding worldwide, such as renewable energies, and can have negative impacts on nature (e.g. the increased mortality of vulnerable species due to collision or electrocution; Duriez et al., 2023; Thaxter et al., 2017).

Given the importance of achieving 'carbon neutrality' and aligning with main international commitments on climate change (e.g. the Kyoto Protocol of 1997 or Paris Agreement of 2015), from China to the United States, renewable energies are booming across the globe, with the European Union leading the way. Here, the recently adopted European Union (EU) Directive 2023/2413 requires EU Member States to identify, by February 2026, 'renewable acceleration areas' characterized by their low environmental sensitivity, where the deployment of renewable energies can be enhanced by simplifying EIA procedures. In this situation, environmental planning emerges as a key tool with the potential of balancing renewable energy development to combat climate change with nature conservation. Both challenges are identified as priorities by authorities; for example, in Europe, by their inclusion in the EU Biodiversity Strategy 2030 or the EU Climate Change Adaptation Strategy (European Parliament, 2021a, 2021b). As the Intergovernmental Panels on Climate Change (IPCC) and Biodiversity (IPBES) have stated in a joint declaration, it is essential to compatibilize both challenges, without the former prevailing over an effective conservation of nature (Pörtner et al., 2021). This compromise is even more relevant due to the rapid and decentralized expansion of renewable energies in remote, rural and natural areas (Poggi et al., 2018). The fundamental role that spatial planning plays in the current scenario is further illustrated by continuous calls for the improvement of EIA procedures for assessing the impacts of renewable energies on nature (e.g., Ferrer et al., 2012; Gibson et al., 2017; Laurance, 2022; Smart et al., 2014).

Accompanying the acceleration of the implementation of renewable energies, different landscape planning tools have been proposed to minimize potential negative consequences to nature, either by governments (e.g. across EU countries; Wingenbach et al., 2024), the scientific community (Cervantes et al., 2023; Morant et al., 2024; Sassi et al., 2025; Vignali et al., 2022) or conservation groups (SEO/BirdLife, 2023). However, criteria and procedures used are heterogeneous across and within countries (Wingenbach et al., 2024), and although some authorities have recommended the inclusion of wildlife-sensitive mapping as a criterion (European Commission, 2024), the official planning tools have grounded their environmental criteria using outdated or insufficient data (Wingenbach et al., 2024). For example, only protected areas are considered in the Spanish sensitivity map (Royal Decree-Law 20/2022), even though these areas might prove insufficient for many species (Bolonio et al., 2024; Lambertucci et al., 2014). Therefore, official planning tools should be thoroughly evaluated to determine their effectiveness in capturing sensitive areas for vulnerable species across space and to guide the necessary modifications for improvement (Bolonio et al., 2024).

GPS-tracked wildlife has the potential to inform conservation and management tools and policies by, for example, identifying shortcomings in compliance with the law (Mateo-Tomás et al., 2023) or improving the effectiveness of conservation actions (Rodríguez-Pérez et al., 2025). Accordingly, the information provided by GPS-tracked wildlife can be leveraged to improve renewable energy planning with the objective of reducing its impacts on biodiversity. While several works have analysed space use by wildlife to inform renewable development (Bolonio et al., 2024; Cervantes et al., 2023; Morant et al., 2024; Vignali et al., 2022), to the best of our knowledge, GPS-tracking data have not been used to evaluate official planning tools for renewable energy. Here we exemplify how the information provided by GPS-tracked wildlife, using griffon *Gyps fulvus* and bearded *Gypaetus barbatus* vultures (both species highly vulnerable to collision with wind turbines; Thaxter et al., 2017), can be used to assess the reliability of planning tools. As a case study, we focused on the wind energy sensitivity tools released by competent authorities in Spain, the fifth-largest country in total wind power, representing 3% of global onshore capacity (30.6 GW installed; Costanzo & Brindley, 2024; Lee & Zhao, 2024), and Portugal, the twelfth country in Europe with more wind energy installed capacity (i.e., 5.8 GW; Costanzo & Brindley, 2024). By confronting the spatial use of GPS-tracked vultures with existing planning tools, we expected to find more disagreement for the griffon than for the bearded vulture, as the former has larger home ranges that often extend beyond protected areas. We also focused on legally binding aspects that might limit the tools' usefulness, expecting less agreement between the legally binding tools and vultures' space use compared to the non-statutory versions. Furthermore, we demonstrate the utility of improving such tools by identifying operational and under-approval wind turbines located in highly used and misclassified areas where the environmental surveillance and the limitation of the development of the wind turbines should be respectively reinforced.

## 2 | METHODS

### 2.1 | Vultures and wind energy in northwestern Iberia

Our study covered ~30,000 km$^2$, corresponding to 95% of the space most intensively used by the GPS-tracked vultures used in this study ($n$ = 90), in northwestern Iberia. Here, griffon vultures are estimated to be ~1100 breeding pairs (i.e. ~235 in the region of Asturias and ~873 in NE Portugal; Del Moral & Molina, 2018; ICNF & SPEA, 2022). This species is listed as a (basic) protected species both in Portugal

(Decree-Law no. 140/99 and subsequent amendments) and Spain (Royal Decree 139/2011). Contrastingly, bearded vultures undergo a reintroduction programme in the north, with >40 individuals and 4 breeding pairs established since 2010 (i.e., <1% of the breeding units in Spain; FCQ, pers. comm., 2022). Accordingly, the bearded vulture is listed as Endangered in Spain (i.e. the maximum protection category; Royal Decree 139/2011), while in Portugal, it is listed as Regionally Extinct (Almeida et al., 2022) and protected by the Decree-Law no. 140/99—included in the Annex A-I as a priority species—and by the Decree-Law no. 38/2021.

This area also stands out for its elevated wind energy potential, particularly in the northwest (Davis et al., 2023), where >2200 wind turbines exist and >300 are currently planned (see Appendix A). The current and future expansion of wind energy infrastructure in these areas can directly affect large soaring scavengers as they are highly susceptible to collisions with wind turbines (Duriez et al., 2023; Ferrer et al., 2012; Thaxter et al., 2017). While bearded vultures have not been found dead due to collision in our study area, there has already been a fatality in the Maestrazgo region where a reintroduction project had to be suspended due to the risk posed by the development of wind energy facilities (FCQ, 2024). In fact, two other bearded vultures released as part of LIFE projects for the recovery of the species in Europe, died after colliding with wind turbines (VCF, 2023). Conversely, the griffon vulture is the species most frequently registered in wildlife mortality surveys at wind turbines in our study area (e.g., up to 65 griffon vultures were found dead between 2019 and 2022 in Asturias; Principality of Asturias, 2024), and elsewhere (Ferrer et al., 2012; Llorens et al., 2023). The species has shown low avoidance of wind turbines, which appears to depend on topography (Sassi et al., 2024).

## 2.2 | Spatial planning tools to inform wind energy development in Spain and Portugal

We evaluated the reliability of seven wind energy planning tools developed by official authorities in Spain and Portugal to scope EIAs (e.g. to simplify them or not), and available during the monitoring period of the tracked vultures. Four were developed at the national level (i.e., two in Spain and two in Portugal) and three at the regional level in Spain (i.e., by the autonomous regions of Asturias, Castilla y León and Cantabria; Table 1 and Appendices B and C.1). All these tools considered protected areas, vulnerable species or both as criteria to assign sensitivity categories (see Appendix B for details) which ranged from two (i.e., sensitive vs less or non-sensitive) to five categories (i.e. *low*, *moderate*, *high*, *very high* and *maximum*; Table 1).

As good conservation outcomes can be compromised if planning tools are not accompanied by a legal background (Bell-James et al., 2024), we considered two different approaches in evaluating the official planning tools depending on their legal status: (i) the non-statutory approach took into account the original categories of each tool, while (ii) the legally binding approach accounted only for the legal criteria for wind energy installation (i.e., regulatory framework that has direct effect on spatial planning). In the case of the national currently legally binding planning tools (i.e., the Portuguese Decree-Law no. 151-B/2013, and the Spanish Royal Decree-Law 20/2022), only the legally binding approach was considered (Table 1), as evaluating such tools from the non-statutory approach would result in the same categories as the legally binding one.

To facilitate comparisons across tools, we reclassified the planning tools' sensitivity categories into a maximum of four categories (i.e., *low*, *moderate*, *high* and *maximum* sensitivity). In the context of the non-statutory approach, the range extended from *low*-sensitivity for the lowest category to *maximum*-sensitivity for the highest sensitivity. For the legally binding approach, *low*-sensitivity was assigned where the development of wind energy was promoted (e.g., by simplifying EIAs); *moderate*-sensitivity where the standard EIA procedure was applied; *high*-sensitivity where the development was limited (e.g., below certain number of turbines and/or capacity) but still allowed; and *maximum*-sensitivity where the installation of wind energy facilities was not allowed (Table 1).

## 2.3 | Use of space by griffon and bearded vultures

From 2016 to 2024, 64 griffon and 26 bearded vultures were GPS-tracked in the study area. Forty-eight adults and subadult griffon vultures were captured along the Cantabrian Mountains (NW Spain) and 16 in the Douro, Sabor e Maças and Montesinho areas (NE Portugal). Griffon and bearded vultures were tagged using backpack harnesses, the former equipped with Ornitela® or Anitra® devices (1 GPS fix every 10 min) and the latter equipped with Ornitela® or e-obs devices® (1 GPS fix every 5 min, Appendix C.2). They were released as fledglings as part of a reintroduction project in Picos de Europa (NW Spain; Figure 1; FCQ, 2022), and accounted for ~65% of the population estimated in the study area. Rarefaction curves showing the increase of each population's home range when adding new individuals were used to further assess the level of representativeness of the GPS-tracked griffon and bearded vultures in each considered population (see Appendix C.3). All procedures that included the capture, handling and GPS tagging of vultures were specifically approved by the competent authorities (i.e., Principality of Asturias, Government of Castilla y León and Instituto da Conservação da Natureza e das Florestas, Res. 19-07-2017, Res. 01-03-2018, Res. 15-02-2022, 2019/007875, 886-891/2019/CAPT, 623-628/2020/CAPT, 363-369/2021/CAPT and AUES/LE/92/2020, 2020277030).

We focused on vultures' space use occurrence at heights under potential risk of collision with wind turbines (hereafter 'risk maps'), which allowed us to evaluate the planning tools with actual and precise data to accurately assess their reliability. In order to do this, we pre-processed vultures' GPS data to reduce location error (e.g., removing failed and duplicate locations, filtering by HDOP values) and selected locations where individuals were flying at heights susceptible to collision with wind turbines (i.e. below 200 m above the ground, corresponding to the maximum height

**TABLE 1** Wind energy spatial planning tools selected for the analysis within the study area, with the original and reclassified sensitivity categories, as well as the legal effect for each individual category.

| *Official spatial planning tools selected in the study area* | | | *Sensitivity categories reclassified for this study* | | *Legal effect* |
|---|---|---|---|---|---|
| **Competent authority and spatial scale** | **Tool name (reference)** | **Sensitivity categories** | **Non-statutory categories** | **Legally-binding categories** | |
| *Portuguese Government,* ***national*** | Official Portuguese tool as defined in Decree-Law nº 151-B/2013 (currently legally-binding) | Outside sensitive areas | - | Low | Simplified EIA with reduced bureaucratic processing and public consulting times |
| | | Sensitive areas | - | Moderate | - |
| | Less sensitive areas for the potential installation of solar and wind electricity generation units [Scenario E] (draft; GTAER 2024) | Less sensitive | Low | Moderate | - |
| | | Outside less sensitive | Moderate | | - |
| *Spanish Government,* ***national*** | Environmental zoning for renewable energies: Wind energy (version: 2022; superseded; MITERD 2022) | Low | Low | Low | Simplified EIA with reduced bureaucratic processing times and eliminating public consulting (From June to December of 2022) |
| | | Moderate | Moderate | Moderate | - |
| | | High | High | | - |
| | | Very high | | | - |
| | | Maximum-Not Recommended | Maximum | | - |
| | Sensitive areas as defined in Royal Decree-Law 20/2022 (currently legally-binding) | Outside sensitive areas | - | Low | Simplified EIA with reduced bureaucratic processing times and eliminating public consulting (Since December 2022) |
| | | Sensitive areas | - | Moderate | - |
| *Asturias Autonomous community,* ***regional*** | Sectorial Spatial Planning Guidelines for Wind Energy Development (Decree 42/2008) | High hosting capacity | Low | Moderate | Priority development zone. Any type of installation is allowed but EIA required equally. |
| | | Low hosting capacity | Moderate | High | Only small-scale wind devices are allowed (total capacity in the area <150MW) |
| | | Central Zone | High | | Only small-scale wind devices are allowed (total capacity in the area <100MW) |
| | | Eastern Zone | | | Only small-scale wind devices are allowed (total capacity in the area <50MW) |
| | | Exclusion | Maximum | Maximum | Wind energy development is not allowed in these locations |
| *Castilla y León Autonomous community,* ***regional*** | Environmental Sensitivity of Soaring Birds (Government of Castilla y León 2021) | Low | Low | Moderate | - |
| | | Moderate | Moderate | | - |
| | | High | High | | - |
| | | Very high | Maximum | | - |
| *Cantabria Autonomous community,* ***regional*** | Areas Incompatible with Onshore Wind Development (Government of Cantabria 2022) | Outside conditioned and exclusion areas | Low | Moderate | - |
| | | Conditioned areas | High | | - |
| | | Exclusion areas | Maximum | | - |

*Note*: The current legally binding tools that have not been evaluated using the non-statutory approach and the absence of legal effects are indicated with a dash.

of under approval wind turbines in the study area; Principality of Asturias, 2020; see details in Appendix C.4). Risk maps were calculated using the movement-based kernel density estimator (MKDE; Benhamou, 2011) with *adehabitatHR* (Calenge, 2023; Appendix C.5) in R software (R Core Team, 2023). We used the Recursion Distribution (RD) metric, which can help to identify movement corridors within the home ranges (Tétreault & Franke, 2017). The RD not only considers the GPS locations, but also the tracks between successive points, while giving more weight to the paths that are recurrently used (Benhamou, 2011; Benhamou & Riotte-Lambert, 2012; Calenge, 2023; see Appendix C.5). For each GPS-tracked vulture, a standardized raster with a resolution of 100 m was computed to obtain the probability density function (PDF) values (Benhamou, 2011). We also repeated these analyses without filtering by vultures' flight height, which allows us to assess both the sensitivity of our approach and the potential impact of larger wind turbines, whose construction is progressing (e.g., Amelang, 2024).

Each tracked vulture was assigned to a breeding area by identifying the colony(ies) and cliffs more frequently used (i.e. within the 50% core area): 31 and 17 griffon vultures belonged to the western and eastern breeding areas in the Cantabrian Mountains, respectively, and 16 griffon vultures to the NE Portugal breeding area. Only one breeding area at the east of the Cantabrian Mountains was considered for the bearded vulture. Each individual map was weighted based on the number of days the individual was tracked compared to the total tracking days for all animals in each breeding area, considering only days with at least one at-risk location. Individual weighted maps for each breeding area were then averaged to generate a risk map for each species (Figure 1).

To allow comparisons with the wind energy planning tools evaluated, each vulture species risk map was categorized into four levels based on the following isopleths (i.e. the smallest area containing a given percentage of the animal's space use): (i) areas within the 25% isopleth were classified as *maximum*-risk, (ii) above the 25%–50% as *high*-risk, (iii) above 50%–75% as *moderate*-risk and (iv) above 75%–95% as *low*-risk (Figure 1), using the *computeContourValues* function (MKDE package; Tracey et al., 2014).

## 2.4 | Agreement between planning tools and risky areas for vultures

We overlapped the sensitivity and risk maps (Appendix C.6) to calculate the reliability of each planning tool in identifying risky

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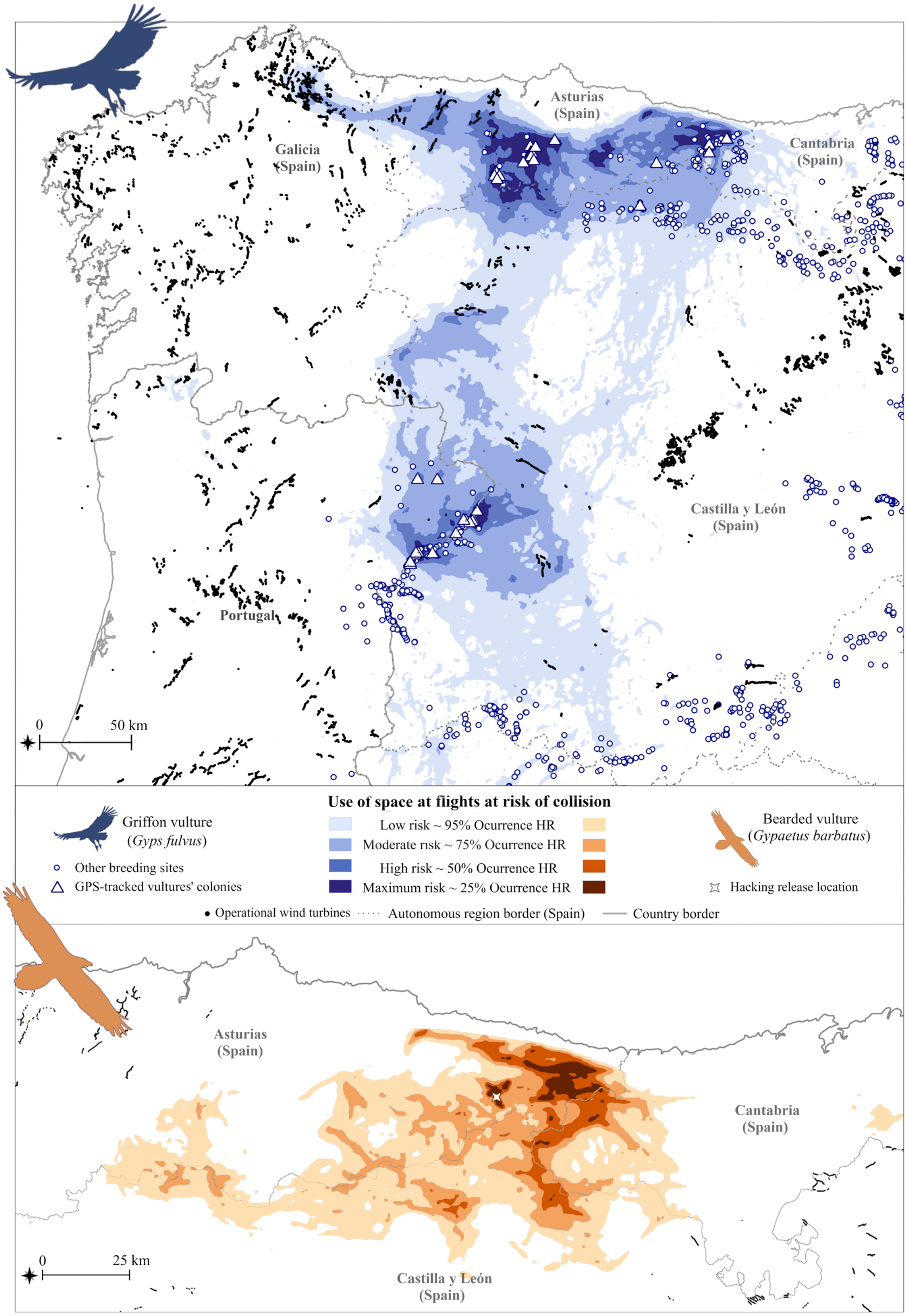



**FIGURE 1** The study area is located in the northwestern part of the Iberian Peninsula, encompassing territories within the 95% occurrence at risk of collision with wind turbines home ranges of GPS-tracked griffon (blue) and bearded (orange) vultures. This includes territories in Portugal and within four autonomous regions in Spain (indicated in light grey). The different categories of potential risk of collision are represented with different colour intensities from the darkest intensity corresponding to the *maximum risk* (~25% occurrence home range) to the lowest intensity corresponding to *low risk* (up to 95% of the occurrence home range). Griffon vultures were GPS-tracked in the north and west of the study area (light blue triangles), where the species breeds (dark blue and white dots) in Spain (Del Moral & Molina, 2018) and Portugal (based on centroids of 10×10km grid cells; EIONET, 2019; Equipa Atlas, 2022). GPS-tracked bearded vultures were released through hacking (orange-white cross) in northern Spain. Additionally, operational wind turbines are present across the study area (black dots; see Appendix A for data sources).

areas for both vultures separately. We used the proportion of agreement coefficient, which evaluates the absolute agreement between raters (e.g. classification systems) while considering the ordinal nature of the data (i.e., categories further away are more penalized; Gwet, 2014). Using the function *pa.coeff.raw* from the *irrCAC* package (*ordinal* weights; Gwet, 2019) in R software (R Core Team, 2023), we obtained values ranging from 0 (worst agreement) to 1 (perfect agreement; Gwet, 2014), separately for each planning tool, considering non-statutory and legally binding approaches. In addition, the Spanish national tools were evaluated within each autonomous region. Four agreement categories were considered: no distance between the planning tool sensitivity and the vultures' risk categories (e.g. *moderate sensitivity* and *moderate risk*) was interpreted as *good agreement*, one level of distance (e.g., *moderate sensitivity* and *high risk*) as *moderate agreement*, two levels of distance as *low agreement* (e.g., *moderate sensitivity* and *maximum risk*) and three levels of distance as *poor agreement* (e.g. *low sensitivity* and *maximum risk*). The percentage of misclassified 100-m pixels and the total misclassified area (km$^2$) within each administrative border was also calculated. As the sensitivity tools evaluated include factors beyond our vultures' populations occurrence (e.g. other vultures' populations or species' presence; see details in Appendix B), we conservatively considered as misclassifications only the 100-m pixels where planning tool sensitivity was lower than vultures' risk and excluded from the analysis the *low risk* pixels (i.e. areas with low use by vultures). For example, whereas sites with *moderate sensitivity* in the planning tools and *maximum risk* for vultures' space use were identified as *low agreement* (i.e., two levels of distance), the opposite, that is, sites with *maximum sensitivity* and *moderate risk*, were considered as *good agreement* (i.e., no distance).

Lastly, we calculated the sum and percentage of 2251 wind turbines operating or recently approved in our study area (hereafter 'operational') and 334 under-approval wind turbines (i.e., not yet authorized; Appendix A) falling in each combination of sensitivity and vultures' risk categories.

## 3 | RESULTS

Griffon vultures were observed at heights compatible with the risk of collision with wind turbines along the study area in Portugal and Spain, encompassing ca. 14,000 km$^2$ within their 75% isopleth, where 26.5% of the territory overlapped with protected areas. Meanwhile, the bearded vultures were localized between Asturias, Castilla y León and Cantabria regions in Spain, over ca. 2000 km$^2$ within its 75% isopleth (Figure 1), where 43% of the territory overlapped with protected areas. When all flight heights were considered the 75% isopleth covered ca. 20,000 km$^2$ for the griffon vultures and ca. 2200 km$^2$ for the bearded vultures (see Appendix D).

The official wind energy planning tools had generally high agreement (i.e., >0.64) with our vultures' collision risk (Figure 2). Most mismatches resulted from one level of difference between the planning tools' sensitivity and the vultures' risk categories (i.e., *moderate agreement*), with almost no mismatches caused by three levels of difference (i.e. *poor agreement*; Figure 3), except for the planning tool currently in force in Spain (Royal Decree-Law 20/2022) in which almost 6% of the territory fell into the *poor agreement* category (Appendices E and F). In total, an area between 0 and 10,000 km$^2$ (i.e., between 0 and ~88%) was misclassified depending on the planning tool, region, approach and species considered. While the most worrying mismatches were localized near the breeding sites of the GPS-tracked vultures compared to the legally binding tools, there were still *low* to *moderate agreement* areas localized up to ~117 and ~95 km from the colonies, respectively. The currently binding Spanish national tool had the lowest agreement (i.e., from 0.64 to 0.99), while the superseded Spanish national tool and the regional tools had the greatest agreement (i.e., between 0.91 and 1). The Portuguese national tools fell within an intermediate position, having the recently developed planning tool by GTAER, 2024, a higher proportion of agreement (i.e., 0.92) than the currently binding planning tool developed by the government in 2013 (i.e., 0.83). In general, the level of agreement increased when the non-statutory categories were considered for all the planning tools, but the regional tool in Asturias (Figure 2). When comparing between species, we found that the proportion of agreement was higher for the bearded vulture for all the planning tools than for the griffon vulture (except for the Cantabria region; Figure 2). Very similar results were obtained without filtering by the vultures' flight heights (see Appendix D).

Focusing on the locations of wind turbines, only griffon vultures' space use overlapped with actual ($n=2279$) and potential ($n=323$) wind turbines (Figure 1; Appendix A). Most wind turbines were in areas with *low* to *moderate risk* for griffon vultures (>90% for both operative and under approval turbines). All the turbines in areas of *high* or *maximum risk* (10%) were located in the autonomous region of Asturias, where 493 operative and 229 under-approval wind turbines overlapped with griffon vultures' space use (see Appendix G). More than 43% of these operative wind turbines were in areas of *high* and *maximum risk* for griffon vultures (this percentage decreased up to 13.5% for under-approval turbines). Considering the planning tools, between 36.3% and 91.3% of the operative turbines, and between 13.6% and 53.1% of the under-approval turbines were in misclassified areas (Appendix F).

## 4 | DISCUSSION

In a world increasingly dominated by human-made mass (Elhacham et al., 2020), strategic and well-informed landscape planning is instrumental to pursue Sustainable Development Goals, such as halting biodiversity loss. To this aim, reliable and efficient spatial planning tools are needed to properly identify sensitive areas for nature conservation. This has become essential, for instance, given the urgency to identify suitable areas for accelerating renewable energy deployment by simplifying EIA procedures (e.g. EU Directive

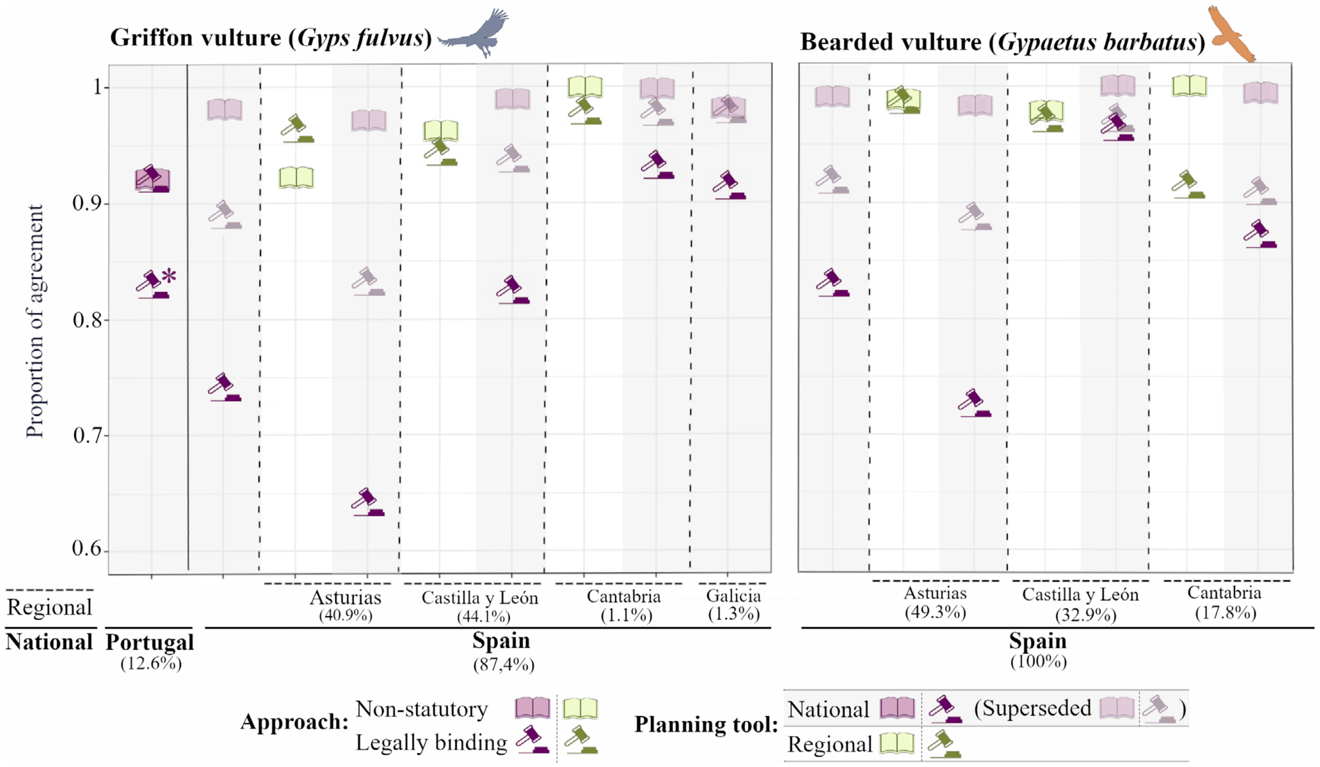
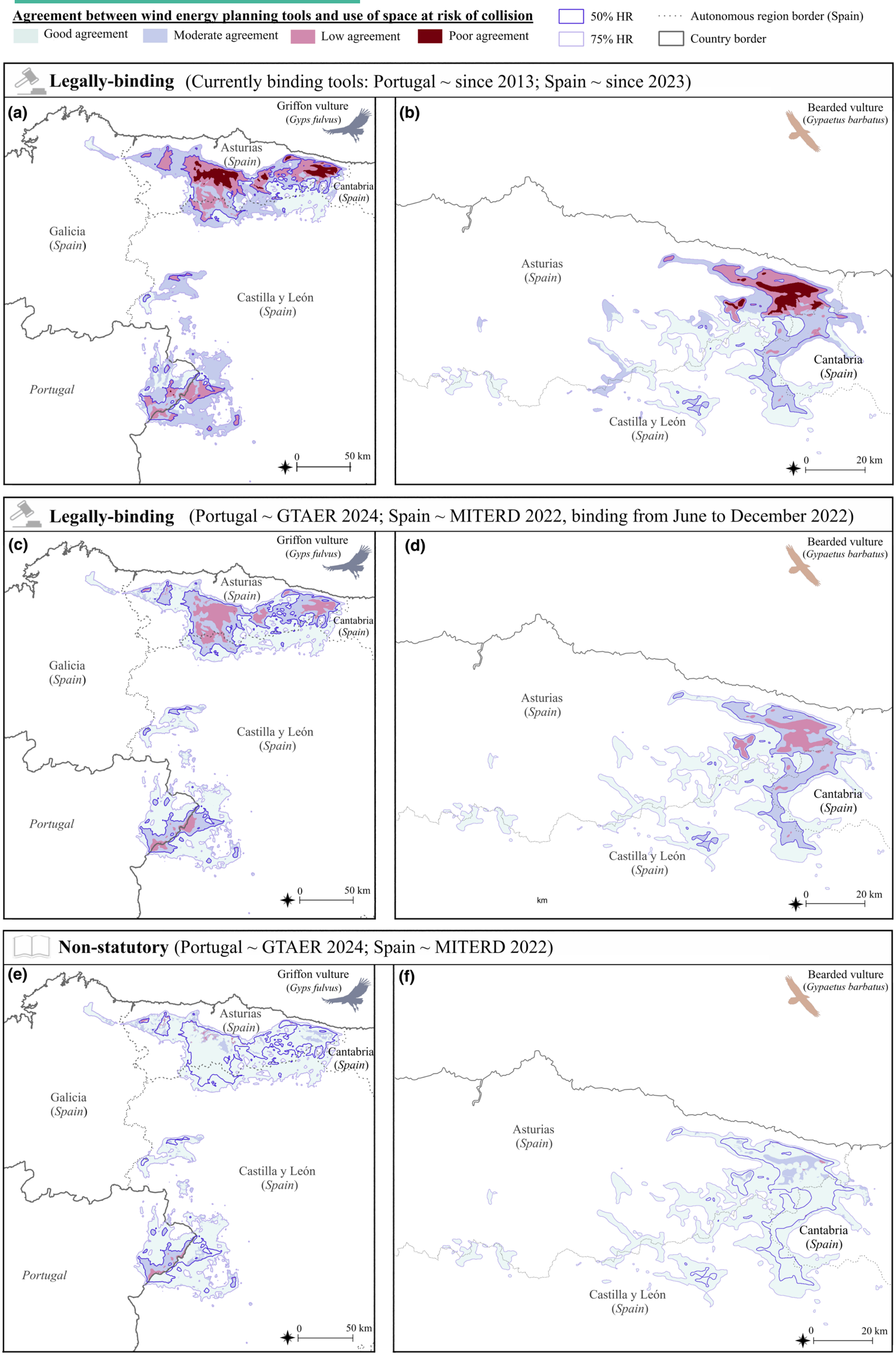



**FIGURE 2** Reliability was calculated as the proportion of agreement of each planning tool for the griffon (left) and bearded vulture (right) populations. The different approaches considered for each tool are distinguished by using a book icon for the non-statutory approach and a gavel for the legally binding approach. Those tools developed at a national level are coloured in purple with grey background, contrasting with the regional tools, in green and without any background. For each region, we compared the reliability of the autonomous region planning tool and the Spanish planning tools, shown on the right side of each region's panel. The national planning tool of Spain developed by the MITERD, 2022, is shown with transparency as it was superseded since December 2022 by the currently binding tool (Royal Decree-Law 20/2022). The asterisk (*) differentiates the national planning tool of Portugal developed by GTAER, 2024 from the planning tool defined in the Portuguese legislation* (Decree-Law no. 151-B/2013). Additional information regarding the percentage of area for each country and region is also indicated. See more details in Appendix F.

2023/2413). Here, we stress the usefulness of GPS-tracked wildlife (e.g. vultures) to assess the reliability of such spatial planning tools (i.e. sensitivity maps for renewable energy development in our case), while identifying major gaps to improve them, as requested, for example, to European countries (European Commission, 2024).

We found that the official wind energy planning tools available in Spain and Portugal have room for improvement (i.e., some areas should have higher sensitivity according to our vultures' populations occurrence). Despite the high proportion of agreement values obtained when compared with our vultures' space usage at risk of collision with wind turbines (>0.64), the assessed tools still misclassified up to ~88% of the evaluated area, highlighting the need to increase the level of sensitivity of a substantial proportion of the territory. Remarkably, some of the misclassified areas occurred in foraging and corridor sites far from vulture breeding colonies, agreeing with the insufficient land protection detected for large avian scavengers due to their large home ranges (Lambertucci et al., 2014). Accordingly, griffon vultures were worse represented in the assessed planning tools than bearded vultures, with smaller home ranges concentrated within and around protected areas (e.g., the proportion overlapping with these areas was almost twice that of griffon vultures). Cantabria was the only region showing the opposite trend, likely attributable to the absence of GPS-tracked individuals (~1% occurrence), underscoring the value of tagging vultures in untracked areas.

Even if improved, the usefulness of the planning tools to prevent negative impacts on biodiversity could still be hindered due to the absence of proper enforcement through legally binding obligations (Bell-James et al., 2024; UNEP, 2019). Our results supported such a statement, as the reliability of the official planning tools decreased when legally binding categories were considered. Likely the result of political interests in the rapid development of renewable energies to achieve energy sovereignty (i.e., European Commission, 2024). Furthermore, as shown in other contexts (e.g., top-down dilution of the protection mandate affecting breeding sites of species listed under the EU Habitats Directive *92/43/EEC*; Sazatornil et al., 2019), we identified a relaxation of conservation commitments. The most precise tools developed by authorities to guide environmental planning were mostly non-statutory (Bell-James et al., 2024). Furthermore, in the case of Spain, the national tool of MITERD (2022), which was legally binding between June and December 2022, ended up being superseded by a more permissive regulation (i.e., Royal Decree-Law 20/2022). And even though the European authorities


Agreement between wind energy planning tools and use of space at risk of collision
Good agreement
Moderate agreement
Low agreement
Poor agreement
50% HR
75% HR
Autonomous region border (Spain)
Country border
Legally-binding (Currently binding tools: Portugal ~ since 2013; Spain ~ since 2023)
(a)
Griffon vulture
(Gyps fulvus)
Asturias
(Spain)
Cantabria
(Spain)
Galicia
(Spain)
Castilla y León
(Spain)
Portugal
0
50 km
(b)
Bearded vulture
(Gypaetus barbatus)
Asturias
(Spain)
Cantabria
(Spain)
Castilla y León
(Spain)
0
20 km
Legally-binding (Portugal ~ GTAER 2024; Spain ~ MITERD 2022, binding from June to December 2022)
(c)
Griffon vulture
(Gyps fulvus)
Asturias
(Spain)
Cantabria
(Spain)
Galicia
(Spain)
Castilla y León
(Spain)
Portugal
0
50 km
(d)
Bearded vulture
(Gypaetus barbatus)
Asturias
(Spain)
Cantabria
(Spain)
Castilla y León
(Spain)
km
0
20 km
Non-statutory (Portugal ~ GTAER 2024; Spain ~ MITERD 2022)
(e)
Griffon vulture
(Gyps fulvus)
Asturias
(Spain)
Cantabria
(Spain)
Galicia
(Spain)
Castilla y León
(Spain)
Portugal
0
50 km
(f)
Bearded vulture
(Gypaetus barbatus)
Asturias
(Spain)
Cantabria
(Spain)
Castilla y León
(Spain)
0
20 km

Journal of Applied Ecology


**FIGURE 3** Agreement between the official currently binding wind energy planning tools of Spain (Royal Decree-Law 20/2022) and Portugal (Decree-Law no. 151-B/2013) evaluated using legally binding approach (a,b), the currently superseeded Spanish national tool (MITERD, 2022) and Portugal draft (GTAER, 2024) (c,d) and the proposed non-statutory approach (e,f) for the home range occurrence of 75% at flights at risk of collision with wind turbines in left panels for griffon (a, c, e) and right panels for bearded (b, d, f) vultures. Level of agreement represents the difference between the matching categories of the planning tool sensitivity maps and the vultures' risk maps: No differences are interpreted as *good agreement* (light blue), one level as *moderate agreement* (blue), two levels as *low agreement* (purple) and three levels as *poor agreement* (burgundy). The 50% and 75% isopleths of home range (HR) at risk of collision are represented by dark and light blue lines. See additional information and more details for the rest of the planning tools analysed in Appendices E and F.

have advocated for the improvement of planning tools (i.e., by considering species sensitivity maps; European Commission, 2024), no consideration has been made to include legally binding limitations in the highest sensitivity categories of such tools. Requesting more detailed EIAs or directly banning the installation of renewable energies in such areas (only observed in the regional planning tool of Asturias, out of the seven planning tools analysed), could considerably improve the effectiveness of planning tools in reducing the impacts of the expansion of renewable energies on nature conservation. In this regard, the strong disagreements shown by our results near the breeding sites of the GPS-tracked vultures when compared with the legally binding tools (Figure 2; Appendix D), would recommend the inclusion of the breeding sites of vulnerable species in legally binding categories of maximum sensitivity.

In our study area, only griffon vultures overlapped with the operational and under-approval wind turbines, being those with greater risk localized in the region of Asturias. Improving the planning tools with GPS tracking data could have avoided the proposal of installation of up to 31 wind turbines localized in *high*-risk areas for the griffon vulture but currently identified as either *moderate* or *low sensitivity* by the legally binding tools (i.e., the currently binding Spanish tool and the regional tool of Asturias; Decree 42/2008; Royal Decree-Law 20/2022). This problem could have been partially mitigated if the non-statutory national planning tool of MITERD (2022) was considered, that is, only 14 under-approval wind turbines would fall into those categories (Appendix G). Now, these wind energy proposals should be abandoned, leading to unnecessary costs and delays for promoters. For those wind turbines already operating, these improved planning tools could serve to help prioritize where mitigating and monitoring efforts should be deployed (e.g., Rodríguez-Pérez et al., 2025). In fact, according to the official records of wildlife causalities at wind energy facilities in the region of Asturias during 2019–2022, griffon vulture mortality was significantly higher at wind turbines located in areas most used by the species at low heights (estimated effect size of 1.543e+06; 95% CI: 6.58e+05 to 2.44e+06; $p$-value <0.01; Appendix H), suggesting that our maps could be useful in identifying vulnerable areas for griffon vultures. Nonetheless, as this type of mortality data could be severely biased (e.g., Camiña et al., 2023), more precise and standardized surveillance protocols would be needed to provide useful information for improving spatial planning tools. For instance, by helping refine the identification and classification of collision risk thresholds for vulnerable species based on the intensity of their space use.

Our results show how GPS-tracking data of vulnerable species can be used to evaluate and identify key aspects to improve the existing planning tools. Although the scope of our analysis is limited to the species and populations considered (e.g. agreement could be lower if the griffon vulture population of the north of Castilla y León were to be included), we decided to prioritize the reliability of the assessment over performing inference models that could virtually increase populations' coverage at the expense of precision. In addition to not relying on the quality and/or heterogeneity of the information available for inference (e.g. limited and imprecise data on livestock and carcass locations), our approach could be more easily applied by wildlife managers and policymakers, and quickly updated with data from newly GPS-tracked individuals (e.g. our results would recommend including more GPS-tracked griffon vultures in the Portuguese population; see Appendix C.3), populations or species to improve coverage and precision. To this aim, detailed scripts to replicate our approach can be found in Bravo-Chaparro et al. (2025). It is also important to note that, although we did not consider the potential avoidance behaviour of vultures towards wind turbines, our design allowed us to integrate not only the risk of collision but also the potential risk of habitat loss associated with, for example, a decreasing use of suitable areas after wind energy construction (e.g. soaring habitat loss; Marques et al., 2020). In both cases (i.e. birds' collisions or habitat loss), special attention should be paid to EIAs of renewable energies in the highest risk areas. We illustrated this approach using griffon and bearded vultures, but other species should be considered to refine collision risks (Thaxter et al., 2017) as well as other negative impacts of wind energy facilities on biodiversity (e.g. soaring habitat loss; Marques et al., 2020). Moreover, given the increasing availability of information from GPS-tagged animals (Jetz et al., 2022), our approach would also be applicable to assess a wide range of planning tools dealing with the effects of different projects on the environment (e.g. solar-energy sensitivity maps impacting steppe birds; Bolonio et al., 2024). Accurate spatial planning tools are of paramount importance, not only to reconcile biodiversity conservation and climate action but also to move forward in achieving other Sustainable Development Goals while halting environmental degradation.

## AUTHOR CONTRIBUTIONS

Elena Bravo-Chaparro and Patricia Mateo-Tomás conceived the ideas and designed the methodology; Elena Bravo-Chaparro, Jorge Rodríguez-Pérez and María Fernandez-García contributed to data analysis and visualization; Elena Bravo-Chaparro, Patricia

Mateo-Tomás and José Vicente López-Bao led the writing of the manuscript. All previously listed authors, together with José Carlos González, Gerardo Báguena, João Pedro Valente e Santos and Iván Gutierrez, collected the data, contributed critically to the drafts and gave final approval for publication.

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## CONFLICT OF INTEREST STATEMENT

Patricia Mateo-Tomás is an associate editor of the *Journal of Applied Ecology*, but took no part in the peer review and decision-making processes for this paper.

## DATA AVAILABILITY STATEMENT

The scripts to use the approach here described with other GPS data and planning tools are available at GitHub and Zenodo via https://doi.org/10.5281/zenodo.17456033 (Bravo-Chaparro et al., 2025). GPS-tracking data of griffon and bearded vultures, both protected species, will be made available upon request to the authors due to their sensitive nature.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**Appendix A.** Status of wind energy development in the study area.

**Appendix B.** Wind energy planning tools used in the analysis.

**Appendix C.** Detailed procedure of data processing for estimating space use by vultures and integration with the planning tools and wind turbine locations.

**Appendix D.** Reliability analysis considering all vultures' flying locations.

**Appendix E.** Agreement between the official wind energy planning tools and the home range occurrence of 75% at flights at risk of collision with wind turbines of griffon and bearded vultures.

**Appendix F.** Metrics of reliability for the wind planning tools analyzed.

**Appendix G.** Number and relative percentage of the wind turbines in Asturias region.

**Appendix H.** Statistical analysis of Griffon vulture mortality due to collision with wind turbines in Asturias.

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