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Use of avian GPS tracking to mitigate human fatalities from bird strikes caused by large soaring birds

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Abstract

1. Birds striking aircrafts cause substantial economic loss world-wide and, more worryingly, human and wildlife fatalities. Designing effective measures to mitigate fatal bird strikes requires an in-depth knowledge of the characteristics of this incident type and the flight behaviours of the bird species involved.
2. The characteristics of bird strikes involving aircraft crashes or loss of human life in Spain were studied and compared to flight patterns of birds monitored by GPS. We tracked 210 individuals of the three species that cause the most crashes and human fatalities in Spain: griffon and cinereous vultures *Gyps fulvus* and *Aegypius monachus* and white storks *Ciconia ciconia*.
3. All the crashes involved general aviation aircrafts, while none were recorded in commercial aviation. Most occurred outside airport boundaries, at midday, and in the warmest months, which all correspond with the maximum flight activity of the studied species.
4. Bird flight altitudes overlapped the legal flight altitude limit set for general aviation.
5. *Policy implications*. Mitigation of fatal bird strikes should especially address the conflict between general aviation and large soaring birds. Air transportation authorities should consider modifying the flight ceiling for general aviation flights above the studied species' maximum flight altitude. Moreover, policymakers should issue pilots with recommendations regarding the dates and times of peak activity of large soaring bird species to improve flight safety.

KEYWORDS

aircraft, bird strikes, cinereous vulture, GPS, griffon vulture, movement ecology, storks, wildlife conflicts

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Eneko Arrondo and Marina García-Alfonso contributed equally.

1 | INTRODUCTION

Air transportation has exponentially grown in recent decades worldwide, with >4.2 billion passengers in 2018, which is a 659% increase since 1980 (World Bank, 2019). This rapid rise in human airspace use has resulted in increased bird strikes. For example, in the United States, reported bird strikes increased from 10,896 incidents in 2012 to 15,171 in 2018 (Dolbeer et al., 2019; FAA, 2020). In Europe, where bird strike-reporting protocols are more recent, the number of bird strikes increased from 13,652 in 2015 to 16,950 in 2018. Therefore, it seems that the trend of increasing numbers of bird strikes is widespread, at least in Western countries (AESA, 2019). Bird strikes are a major concern for aviation authorities because they entail high annual economic loss, but also because they may lead to loss of human life (DeVault et al., 2013; Dolbeer et al., 2019; Thorpe, 2016). Bird strikes can also negatively affect biodiversity either directly through loss of individuals of at-risk species or indirectly through, for example, a developing negative social perception of the species involved in bird strikes, especially those with human fatalities (Margalida, 2016). Thus, the increasing number of bird strikes is an important human–wildlife conflict that not only threatens human safety and economy, but also biodiversity conservation (Lambertucci et al., 2015). Consequently, bird strikes are an issue that must be addressed to help keep air transportation safe and limit its environmental impacts.

Historically, most bird strikes have occurred at low altitude in the take-off, departure, approach or landing flight phases (Dolbeer, 2006). Consequently, most mitigation measures have focused on reducing the presence of birds and other wildlife at airports and in their close surroundings (DeVault et al., 2013; Moreno-Opo & Margalida, 2017). These wildlife management measures have succeeded in reducing damaging collisions with aircraft in airport environments, which especially benefits commercial aviation, including transport and passenger aircraft (ICAO, 2008). However, en route bird strikes are still a concern, especially for general aviation (DeVault et al., 2016; Dolbeer, 2011; Dolbeer et al., 2019), which is composed mainly of small private aircraft (ICAO, 2008). Currently, measures to mitigate en route bird strikes are largely based on risk maps built from ecological information about problem species (AESA, 2017; AHAS, 2019). Hence a growing need for information on bird flight activity to build more accurate tools that aim to minimize the en route bird strike risk (Avery et al., 2011; DeVault et al., 2005; Holland et al., 2017). GPS monitoring is a promising tool capable of characterizing bird flight details, including altitude, trajectory or daily and annual patterns (Margalida, 2016).

Our first goal was to review and quantify the characteristics of civil bird strikes in Spain, the only European country that has recorded and published the number of human fatalities caused by bird strikes in the last 18 years (AESA, 2019). We focused exclusively on bird strikes that resulted in aircraft crashes (defined as total aircraft destruction, regardless of aircraft type and excluding emergency landings) because they are the most likely to cause human fatalities. Second, we analysed the flight patterns of the species that caused aircraft crashes in Europe: griffon vulture *Gyps fulvus*, cinereous vulture *Aegypius monachus* and white stork *Ciconia ciconia*. As all the crashes registered in Europe happened in Spain, we tracked 210 GPS-marked individuals of the above-mentioned species (hereafter the study species) that regularly used Spanish air space. We specifically modelled circadian and circannual changes in the probability of flight and flight altitude. Based on our results, we offer recommendations for safe flying altitudes and time periods to reduce the risk of collisions with the studied species.

2 | MATERIAL AND METHODS

2.1 | Bird strikes

We analysed the characteristics of bird strikes that resulted in aircraft crashes in Spain from 2000 to 2018. For all these bird strikes, we recorded the bird species involved, the aircraft type (commercial or general aviation according to ICAO, 2008), altitude at which the collision occurred, date and hour of collision and distance to the nearest airport (CIAIAC, 2019a, 2019b). We finally analysed the altitude, date and hour of the collisions for all bird strikes caused by the studied species whenever available (AESA, 2019; Table 2).

2.2 | Bird tracking and modelling procedures

We recorded the GPS tracking data for individuals of the three studied species, which were the only species involved in crashes and fatal bird strikes in Spain. These species are large birds whose masses range from 2.3 kg for storks to 12 kg for cinereous vultures (Del Moral, 2017; Del Moral & Molina, 2018; Molina & Del Moral, 2005). The most recent national census in Spain recorded 30,946 and 2,400 breeding pairs of griffon and cinereous vultures, respectively (Del Moral, 2017; Del Moral & Molina, 2018), and 33,217 breeding pairs of white storks (Molina & Del Moral, 2005). Spain is also an important wintering area and part of a major migratory pathway for griffon vultures and storks from Western European populations (Bécares et al., 2019; Ramírez et al., 2019). In all, we compiled information on the movements of 210 GPS-tagged birds (Figure 1) involving 92 griffon vultures tagged in Spain, 15 cinereous vultures tagged in Spain and Portugal, and 103 white storks tagged in Spain and Germany. All the individuals were tracked between 2006 and 2018. See Table 1 for devices and tracking details.

We selected all the bird locations (i.e. GPS positions) recorded in Spain. We then classified locations as flying or non-flying according to ground speed and altitude above-ground level (AGL). To do so, we first estimated altitude AGL by a digital elevation model (cell size of 30 × 30 m; IGNE, 2019) and calculated the difference between tracking altitude and elevation model. Second, we selected 0.1% of the upper and lower values of our dataset to identify anomalous values (e.g. −8,069.4 and 47,053 m AGL in the white stork dataset), but by minimizing the risk of omitting real values. Given the known

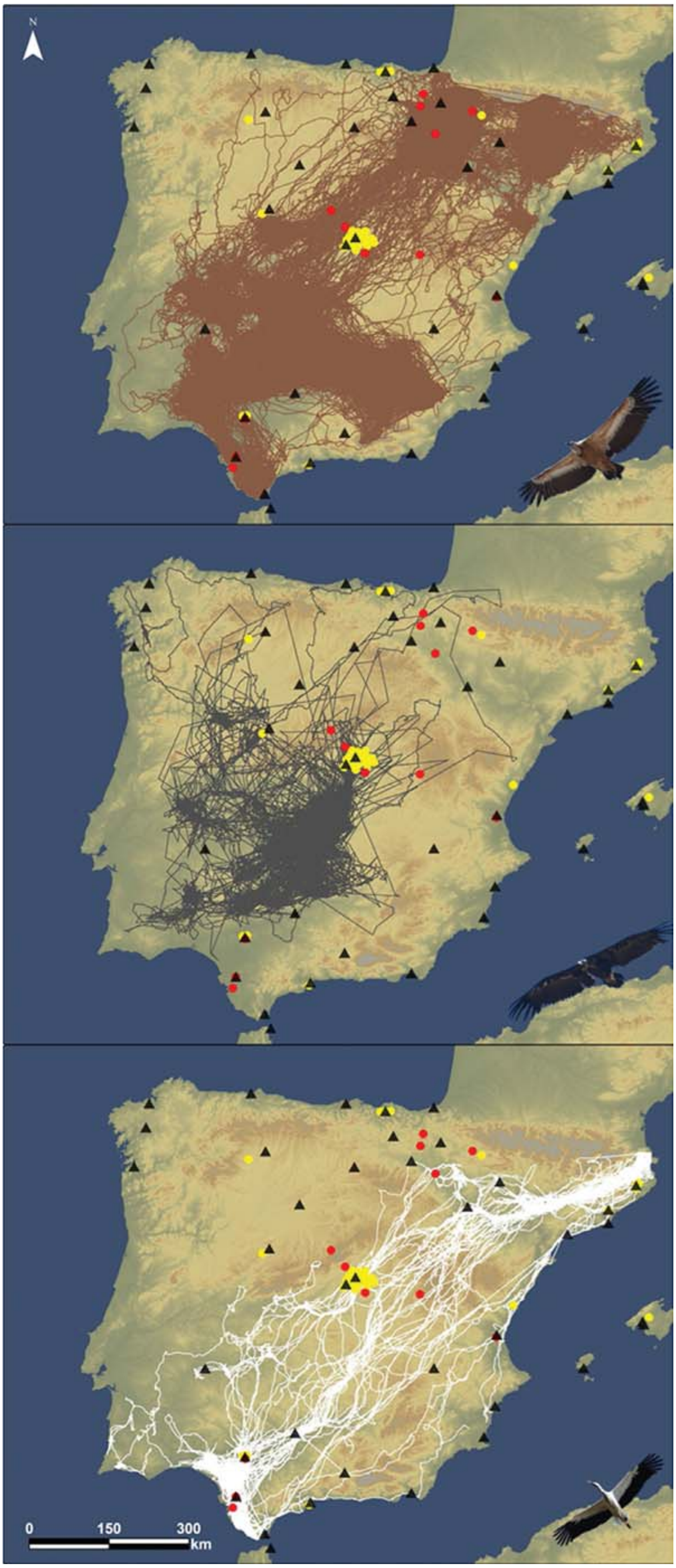

FIGURE 1 Movements of GPS-tagged individuals of the three study species: griffon vultures, cinereous vultures and white storks (respectively from top to bottom). Yellow circles show bird strikes from 2015 to 2018, red dots show crashes from 2000 to 2018, and triangles represent the largest Spanish commercial airports

TABLE 1 Details of the GPS tracking data used in this study

Species	Tagging place	No. individuals	Monitoring period	Device model	No. locations	Low performance	High performance	Reference
Griffon vulture	Cazorla Natural Park, Spain	30	Dec. 2014–Dec. 2018	GPS/GPRS-GSM, 90g. e-obs digital telemetry	1,832,729	10 min	5 min	Arrondo et al. (2018)
	Bardenas Natural Park, Spain	35	Dec. 2015–Dec. 2018	GPS/GPRS-GSM, 90g. e-obs digital telemetry	3,114,386	10 min	5 min	Arrondo et al. (2018)
	Alcornocales Natural Park, Spain	12	May. 2018–Jun. 2019	GPS/GPRS-GSM, 36g. ECOTONE telemetry	1,283,931	10 min	1 min	Unpubl. data
	Catalonian Pyrenees, Spain	15	May. 2018–Jun. 2019	GPS/GPRS-GSM, 50g. Ornitela	903,047	10 min	10 min	Unpubl. data
Cinereous vulture	Cabañeros National Park, Spain	11	Aug. 2006–Dec. 2008	Argos/GPS PTT-100s, 70g. Microwave Telemetry Inc.	30,009	3 hr	3 hr	Arrondo et al. (2018)
	Portugal	4	Jul. 2018–Jul. 2019	GPS/GPRS-GSM, 50g. Ornitela and 36g. ECOTONE telemetry	3,773,479	—	1 s	Unpubl. data
White stork	Germany	66	Feb. 2014–Dec. 2018	GPS/GPRS-GSM, 54g. e-obs digital telemetry	11,185,911	5 min	15 min (High frequency burst)	Cheng et al. (2019)
	Doñana National Park, Spain	37	Jun. 2013–Sept. 2018	GPS/GPRS-GSM, 54g. e-obs digital telemetry	4,179,763	5 min	5 min	Flack et al. (2018)

flight behaviour of the studied species, we considered these locations to be outliers and eliminated them from our analyses (Fleming et al., 2020). Third, we separated flying and perching locations by first establishing 2.5 m/s as our ground speed threshold for flying locations, which is in accordance with Schlaich et al. (2016), and then defined a second threshold using altitude. For this purpose, we calculated the cumulative histogram of altitude AGL per species (Figure S1). Using 1-m breaks, we established the value after the maximum slope for which cumulative frequency stabilized as the threshold to classify a flying location. To define the stabilization of frequencies, we calculated the relative difference (%) between consecutive cumulative frequencies. A difference of ≤0.1% was considered stabilization. Therefore, locations with ground speed ≤2.5 m/s and altitude ≤35, 60 and 90 m AGL were considered non-flight locations for griffon vultures, cinereous vultures and white storks, respectively, whereas other locations were allocated as flight locations. Finally, to gain an approximate measure of the area covered by the studied species, we calculated the 95% kernel utilization distribution (UD) with a smoothing parameter of 20 km and a grid cell size of 2.5 km using the R package adehabitatHR (Calenge, 2014) including all the available locations for each species.

Modelling procedures were followed using a unique dataset for each species that contained information on date, hour, speed and altitude AGL for each GPS location. We defined sunrise and sunset accounting to its date and geographical coordinates with the maptools package (Bivand & Lewin-Koh, 2019). Next, we divided the daylight period into 15 intervals and assigned each position to the day interval within which it was recorded. This value provided a reference for sun position and, thus, a biologically more meaningful parameter than time stamp. The duration of each interval depended on the date and geographical coordinates. As day length ranged from 8.8 to 15.6 hr, each interval lasted between 0.58 and 1.04 hr. This classification method allowed us to define a central daylight period (i.e. eighth interval) within each interval that lasted a maximum of approximately 1 hr. To accelerate the modelling process, we resampled data by randomly selecting one location per individual, date and interval during the daytime (this resulted in a maximum of 15 daily observations per individual). Resampling the original dataset was repeated 10 times to confirm the repeatability of the process.

For each studied species, we modelled two response variables: the probability of being in flight (resampling the whole database) and flight altitude. Following Pedersen et al. (2019), we used HGAM (hierarchical generalized additive model) with the R software version 3.6.1 (R Core Team, 2019) and the mgcv package version 1.8–26 (Wood, 2011). We applied binomial error with a logit link function for the variable of being in flight, and Gaussian error with an identity link function for the variable of flight altitude, and included month and day interval (see above) as predictor variables. Individual identities were fitted as random terms to avoid potential pseudoreplication. Finally, we extracted residuals and verified normality, homogeneity and independence, and checked for influential observations. To ensure the robustness of our results, we repeated the modelling procedure for the 10 resampled datasets (see above).

TABLE 2 Details of the bird strikes caused by vultures (the species are not specified in the database) and storks in Spain between 2015 and 2018. Data not reported are represented by a dash

Species	Date	Hour (UTC)	Location	Flight phase	Type of aircraft	Altitude (m AGL)
Stork	17/09/2018	—	Madrid	Take-off	Instrumental navigation	1,829
Stork	22/03/2018	—	Gerona	En route	Visual navigation	701
Stork	28/10/2017	16:35	Salamanca	Landing	Visual navigation	1,097
Stork	15/08/2017	14:38	Sevilla	Landing	Instrumental navigation	—
Stork	02/05/2017	14:34	Gerona	Take-off	Visual navigation	—
Stork	25/03/2017	13:30	Valencia	En route	Visual navigation	1,377
Stork	17/02/2017	8:46	Cadiz	—	Visual navigation	—
Stork	25/11/2016	15:40	Madrid	En route	Visual navigation	1,311
Stork	07/11/2016	17:25	Malaga	Landing	—	1,524
Stork	29/06/2016	—	Segovia	—	Visual navigation	—
Stork	31/05/2015	16:50	Cadiz	En route	Visual navigation	762
Vulture	18/09/2018	18:00	Huesca	—	—	—
Vulture	29/07/2018	10:42	Bilbao	Landing	Instrumental navigation	366
Vulture	29/07/2018	13:10	Madrid	En route	Visual navigation	152
Vulture	25/07/2018	—	—	Take-off	Visual navigation	—
Vulture	09/07/2018	16:40	Madrid	Take-off	Visual navigation	—
Vulture	16/05/2018	10:47	Madrid	Take-off	Instrumental navigation	—
Vulture	15/05/2018	15:39	Madrid	—	Instrumental navigation	—
Vulture	15/05/2018	10:04	Palma de Mallorca	Landing	Instrumental navigation	1,524
Vulture	13/05/2018	7:20	Bilbao	Take-off	Instrumental navigation	457
Vulture	06/05/2018	—	Cuenca	En route	Visual navigation	—
Vulture	30/03/2018	10:08	Madrid	Take-off	Instrumental navigation	1,250
Vulture	06/10/2017	17:30	Madrid	Landing	Instrumental navigation	457
Vulture	27/09/2017	—	Madrid	Take-off	Instrumental navigation	1,676
Vulture	13/09/2017	11:29	Madrid	Take-off	Instrumental navigation	1,524
Vulture	07/09/2017	—	Bilbao	Landing	Instrumental navigation	183
Vulture	18/08/2017	15:00	Segovia	En route	Visual navigation	610
Vulture	22/06/2017	15:00	Segovia	En route	—	—
Vulture	05/06/2017	—	Astorga	Landing	Visual navigation	—
Vulture	15/09/2016	15:30	Sevilla	Landing	Instrumental navigation	762
Vulture	27/08/2016	8:34	Madrid	Take-off	Instrumental navigation	61
Vulture	11/08/2016	16:35	Madrid	Landing	Instrumental navigation	—
Vulture	27/07/2016	12:05	Madrid	Landing	Instrumental navigation	2,438
Vulture	25/07/2016	10:24	Madrid	Take-off	Instrumental navigation	—
Vulture	09/07/2016	—	Madrid	Take-off	Instrumental navigation	914
Vulture	07/07/2016	13:32	Madrid	En route	Instrumental navigation	1,829
Vulture	20/05/2016	19:12	Pamplona	En route	Visual navigation	—
Vulture	19/05/2016	—	Madrid	Take-off	Instrumental navigation	1,615
Vulture	13/04/2016	5:10	Barcelona	Take-off	Instrumental navigation	—
Vulture	30/03/2016	12:40	Madrid	Landing	Instrumental navigation	—
Vulture	24/03/2016	15:38	Gerona	—	Instrumental navigation	—
Vulture	16/01/2016	12:17	Castellon	En route	Instrumental navigation	—
Vulture	09/11/2015	—	Madrid	Take-off	Instrumental navigation	182
Vulture	07/10/2015	—	Madrid	Take-off	Instrumental navigation	137

3 | RESULTS

From 2000 to 2018, bird strikes have caused 12 aircraft crashes in Spain and they all involved general aviation aircraft. Six of these crashes resulted in human fatalities (15 total deaths). All the crashes were caused by the studied species: griffon vulture ($N = 8$), cinereous vulture ($N = 2$) and white stork ($N = 2$). Most of these collisions occurred en route, with the mean distance to the nearest airport being 39.04 km (range 0.3–125.6 km). They all occurred at between 152 and 1,372 m AGL (mean 858 m; see Table 2).

There was no detailed information available on the bird species involved in the bird strikes before 2015 (due to legal restrictions), except for severe cases such as crashes. Between 2015 and 2018, the species involved in bird strikes were always reported, except when the involved species could not be identified. During this period, the study species caused 44 bird strikes (including crashed aircraft and those incurring lesser damage), which represent 0.75% of all bird strikes occurring in Spain during that period (Table 3). Twenty-six bird strikes caused by the studied species were collisions with commercial aviation aircraft and occurred mainly during take-off and landing operations on and near the airport (Table 2). Most of the bird strikes caused by these species occurred between March and September (88.6%) and between 10:00 and 16:00 UTC (54.5%; Figure S2; Table 2).

The studied species perform long-distance movements that cover large areas. According to the 95% kernel UD, griffon vultures, cinereous vultures and white storks cover 29.27% (173,036 km^2), 28.41% (165,370 km^2) and 17.69% (102,969 km^2) of the Iberian Peninsula respectively (Figure 1; Figure S3). During long-distance movements, griffon vultures and white storks appear to use defined movement pathways that cross the Iberian Peninsula from northeast to southwest and pass near some major Spanish airports (Figure 1).

For the three studied species, the maximum probability of being in flight occurred at midday (Figure 2; Figure S4). Except for cinereous vultures, the probability of flight was highest during the warmest months of the year (Figure 2; Figure S4). Griffon vultures and cinereous vultures reached the highest altitude (1,931 and 1,646 m AGL respectively) in summer and in the early afternoon hours. White storks reached a maximum of 2,287 m AGL, but showed a bimodal pattern with two peaks during migration in spring and autumn (Figure 2; Figure S4). In general, the studied species' range of flight overlapped that of general aviation aircraft, for which the legal ceiling of flight across most territory was 900 m AGL (Spanish Royal Decree 57/2002).

TABLE 3 Number of total bird strikes (including commercial and general aviation) caused by different bird groups in Spain between 2015 and 2018. Known % column represents the percentage of bird strikes for which it was possible to identify the species involved. Study species are represented in bold. The vulture category includes both: griffon and cinereous vulture

Group	*N*	Total %	Known %	Crashes
Unknown	4,741	80.05	—	0
Passerines	624	10.54	52.84	0
Pigeons and doves	121	2.04	10.25	0
Falcons	120	2.03	10.16	0
Gulls	118	1.99	9.99	0
Shore birds	44	0.74	3.73	0
Owls and nighthawks	33	0.56	2.79	0
Vultures	**33**	**0.56**	**2.79**	**10**
Hawks	23	0.39	1.95	0
Waterfowls	18	0.30	1.52	0
Corvids	13	0.2	1.10	0
Game birds	13	0.2	1.10	0
Storks	**11**	**0.19**	**0.93**	**2**
Bee-eaters, kingfishers and hoopoes	4	0.07	0.34	0
Wader birds	4	0.07	0.34	0
Cormorants	2	0.03	0.17	0

4 | DISCUSSION

Our results showed that in Spain, crashes and fatal bird strikes occurred when general aviation aircraft collided with vultures and storks. Although, the studied species caused relatively few bird strikes (Table 3), they were involved in all the bird strikes involving human fatalities. Evidently, measures are necessary that allow pilots of general aviation aircraft to evaluate and minimize the risk of en route encounters with these species.

Currently, the only method of informing collision mitigation measures in some countries (including Spain) is the use of risk maps based on biological knowledge of problematic species (AESA, 2017; AHAS, 2019). Our data can be used to improve these maps by defining the altitude ranges at which the risk of colliding with the individuals of our studied species is highest. In addition, the Spanish Agency for Aerial Security recommends pilots of general aviation aircraft to fly between 762 and 900 m AGL, which is the legal flight ceiling for general aviation, except for ultralight gliders and helicopters (AESA, 2017). However, collisions occurred up to 1,372 m AGL (probably by flights that illegally exceeded the flight ceiling). Although the maximum flight altitudes of the studied species can reach 2,287 m AGL, our data indicate that 99% of the flying locations of griffon vultures, cinereous vultures and storks were below 1,062, 853 and 1,253 m AGL respectively (Figure 3). Therefore, although we are aware of the difficulties involved in changing legislation, state air agencies should consider increasing the legal flight ceiling for general aviation aircraft from 900 to 1,300 m AGL to markedly reduce the risk of encountering the studied species. Furthermore, our models indicate a time period of maximum collision risk lying between March and September, and from 10:00 to 16:00 UTC. As a result, air authorities should recommend pilots of general aviation aircraft to fly at the lowest possible speed during this period to reduce the kinetic energy of a potential bird strike. This recommendation is supported by

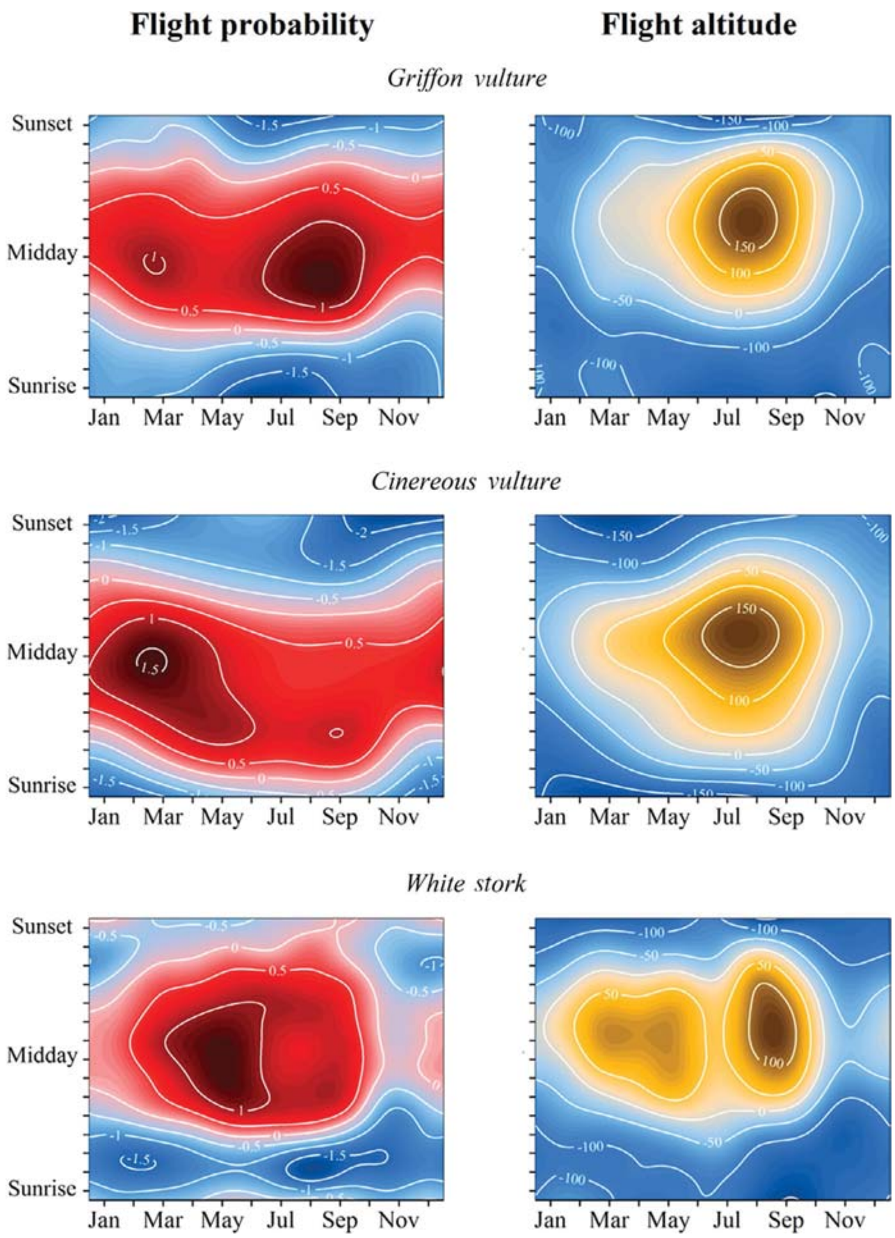

FIGURE 2 Results of the HGAM (Hierarchical Generalized Additive Models) performed to determine the probability of flight (left panels) and the flight altitude AGL (right panels) across the year and throughout the day for the three study species, from top to bottom: griffon vultures, cinereous vultures and white storks. The other models are represented in Figure S4. Isolines are represented in logarithmic scale. Darker colours indicate higher probabilities and altitudes

evidence from experimental studies conducted with other species that suggests that some birds are more likely to be struck at faster vehicle speeds (DeVault et al., 2014, 2015).

Our sample size may seem unrepresentative if we consider the size of the study species' populations (see Materials and Methods). However, information from >200 GPS-tagged birds identified a common unequivocal pattern for flight altitudes across species, which is probably linked with the availability of thermal uplifts (Scacco et al., 2019). The studied species were more likely to fly and reach higher altitudes at midday and in early afternoon hours in the warmest months (Figure 2), which all coincide with the highest bird strike rate period for the studied species (including both commercial and general aviation aircrafts), although more aircraft flying during that period could have also influenced this pattern. Unfortunately, this hypothesis cannot be tested because information about general aviation aircraft traffic intensity is lacking. Moreover, our results show clear species-specific patterns for probability of flight, which may depend on foraging strategies and circannual rhythms, such as migrations for white storks. Our studied species also performed long-distance movements using defined corridors, which suggests that bird strikes can be caused by birds from very distant breeding locations. As these 'bird flyways' are likely predicted by landscape and climatic patterns (Scacco et al., 2019), they cannot be realistically managed. Instead, these 'bird flyways' and their seasonal use can be added to the Spanish risk map (AESA, 2017) to help pilots to avoid high-risk areas and times.

Bird strikes also kill the birds involved. However, populations of the studied species remain stable despite being involved in collision incidents, suggesting that bird strikes might not pose a direct threat to these species. However, the public attention that bird strikes draw may degrade the generally positive perception of these species by wider society (Kronenberg et al., 2017; Morales-Reyes et al., 2018),

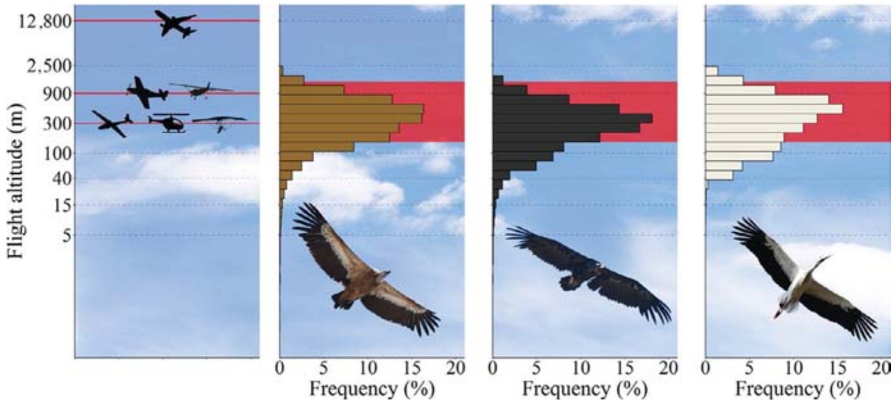

FIGURE 3 Aircraft and bird flight altitudes. The left panel shows maximum legal flight altitudes above-ground level, the red lines indicate the altitude for (from top to bottom): commercial aviation and different types of general aviation aircraft. The three remaining panels represent the frequency distributions of flight altitudes for the three bird species studied (note log-scaled *Y*-axes). The red areas show the range of altitudes for which general aviation aircraft suffered a bird strike with studied species (for values see Table 2)

and culminate in calls for stricter control measures, such as culling (Dolbeer & Franklin, 2013). If we bear in mind that the studied species are strictly protected in Europe in general and in Spain in particular, lethal control would contradicts conservation legislation (Directive 2009/147/EC). The recovery of these species' populations could also be perceived by society as a danger to air safety if incidents increase in frequency or severity (Margalida, 2016).

In Spain, commercial aviation passengers increased from 55 million in 2008 to 80 million in 2018, and the number of private general aviation aircraft registered in the country has increased 42.4-fold since the 1950s (AESA, 2020; World Bank, 2019). This increased flight activity undoubtedly plays an equally important role as the recovery of bird populations in the growing bird strikes conflict (Lambertucci et al., 2015).

As air transport is fundamental for modern society, bird strikes will continue to be a threat to air safety and biodiversity conservation. Minimizing this conflict requires an improved understanding of birds' space use and flight behaviour in relation to environmental factors (Flack et al., 2018). Currently, given the development of GPS technology for wildlife tracking and platforms such as Movebank (https://www.movebank.org/), and other similar technology, it is relatively easy to access large datasets that contain movement information for many of the species frequently involved in bird strikes. Although available information varies depending on species and region of interest, these data repositories will facilitate the study of the flight patterns of species with different flight characteristics to those herein studied. This approach should be considered for the species that cause many bird strikes, such as pigeons, falcons or gulls (see Table 3). Adding the GPS tracking information of these species to current risk maps would help air authorities and pilots to develop more efficient mitigation strategies.

5 | CONCLUSIONS

Fatal bird strikes are an unlikely, but catastrophic event. Reducing the probability of their occurrence requires a better understanding of both involved factors: human air transport and bird habitat use. First, more exhaustive monitoring of general aviation aircraft traffic is necessary to correctly evaluate the risk faced by pilots. Second, our work shows that the GPS tracking of problematic species can improve risk maps, which will allow pilots to evaluate the risk they face in real time, not only on the horizontal plane by tracing the routes that birds most widely use, but also on the vertical plane by quantifying the altitudes most frequently employed by these species. We encourage air authorities and ecologists to collaborate in utilizing available data on birds and plane movements in each region to increase safety and minimize the impacts of human air travel.

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AUTHORS' CONTRIBUTIONS

E.A., M.G.-A., J.A.D. and J.A.S.-Z. conceived the ideas and designed methodology; M.G.-A. analysed the data; E.A. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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