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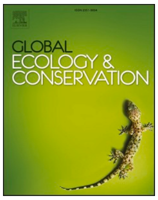

# Wind farms and Griffon Vultures: Evidence that under certain conditions history is not-always turbulent

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ABSTRACT

Since the early stages of wind energy development, there has been concern about the potential impact of wind farms on wildlife, particularly birds and bats. However, the lack of long-term studies has hindered the assessment of the real effect of wind farms on mortality and disturbances. We show a case study in which we researched during the nestling rearing period the long-term effects of a wind farm located in southern Spain on the abundance, displacement, and mortality of the Griffon Vulture, a raptor considered very sensitive to collisions. After 13 years of operation, observation and abundance rates increased significantly during the study period. Griffon Vultures avoided flights between wind turbines by flying at the ends of the rows or through the existing corridor between alignments of wind turbines. Our results are in line with the theory that birds may become habituated to the presence of wind farms suggesting that, under certain conditions, it could be possible to reconcile the presence of wind farms with raptor conservation. Environmental agencies should not only require robust pre-construction surveys, but also that wind energy developers monitor bird abundance and behaviours throughout the lifetime of a wind farm. Since not all wind farms are associated with high mortality rates, such an initiative could be key to gaining more knowledge on the association between wind-farm location, design and risk to birds.

## 1. Introduction

Wind farms are considered an environmentally friendly energy source, and in recent decades they have undergone striking developments in the field of renewable energies. Since the beginning of the 1980 s, the total installed capacity has undergone exponential growth, reaching an overall capacity of 839,730 MW at the end of 2021 (WWEA, 2022). In Europe, Spain has the second-highest amount of installed wind farm power, after Germany, and the fifth-highest amount worldwide. As of December 2020, the total installed capacity of wind energy in Spain was 27,446 MW distributed over 1265 wind farms (AEE, 2022; WWEA, 2022).

Since the early stages of the development of wind energy, there have been concerns about the potential impact of wind farms on

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wildlife, mainly flying animals, particularly birds and bats. Mortality caused by collisions is one of the main adverse impacts of wind farms and has been extensively studied for the last 20 years (e.g. Johnson et al., 2002, May et al., 2019). Although there are some facilities in which no dead flying animals have been found (Strickland et al., 2011), in most wind farms collision rates are relatively low (De Lucas et al., 2005; Erickson et al., 2002; Farfán et al., 2009; Hernández-Pliego et al., 2015; Percival, 2000), with some exceptions where the mortality is high (Orloff and Flannery, 1992; Barrios and Rodríguez, 2004; Ferrer et al., 2012; Zimmerling and Francis, 2016). Especially soaring birds, a group that includes broad-winged large birds such as raptors, generate a particular interest as their flight behaviour conflicts with the same wind resource as wind turbines (Sandhu et al., 2022). In the case of raptors, mortality is frequent (Orloff and Flannery, 1992; Lekuona and Ursúa, 2007; Smallwood and Thelander, 2008; Noguera et al., 2010), probably facilitated by the relative ease with which carcasses are found given their large size. Griffon Vulture (*Gyps fulvus*) is one of the most affected species by collision mortality in areas where it occurs. These include northern Spain where 62% of collided birds are attributed to this species (Lekuona, 2001), and southern Spain where an average mortality rate range between 0.14 and 0.19 birds/turbine/year was recorded (De Lucas et al., 2008; De Lucas et al., 2012; Ferrer et al., 2012, 2022). Disturbances in the spatial use of territory and, consequently, the potential loss of functional habitat, are among other negative impacts of wind farms on birds (Drewitt and Langston, 2006). Previous studies have found reductions in the number of birds and decreases in their use of areas occupied by wind farms, particularly in the close proximity to wind turbines. Thus, Cabrera-Cruz and Villegas-Patraca (2016) have shown that migrating raptors modify their flight paths to avoid wind farms, Farfán et al. (2017a) that six and half years after the construction of a wind farm the abundance of non-raptor birds decreased by 40.6%, and Marques et al. (2020) that the habitat use by soaring birds decreased with the proximity to wind turbines.

Despite published empirical evidence on the effect of wind farms on birds and bats, one of the main difficulties in assessing the extent of incidences of mortality and disturbance is a shortage of long-term studies. Hötker, Thomsen and Jeromin (2006) conducted a review on the impact of wind farms on birds and bats, showing that the 127 studies analysed had an average duration of 2.8 years and that more than a third (51 studies) were only conducted over one year. Some studies have demonstrated that the effect of wind farms on the abundance and displacement of birds varies depending on the time at which the wind farm came into operation (Smallwood et al., 2004; Stewart and Pullin, 2005; Farfán et al., 2017a; Dohm et al., 2019). This finding suggests that short-term studies do not provide robust indicators of their real impact (Madders and Whitfield, 2006), and that long-term monitoring should be performed to better evaluate impacts and provide recommendations not only on management policies once the wind farm is installed, but also to recommend in pre-construction the location of wind farms and wind turbines as a measure to avoid bird fatalities.

Our research objective was to examine the long-term effects of an upland wind farm located in southern Spain on the abundance, displacement, and mortality of the Griffon Vulture, a soaring raptor recognised as vulnerable to collision, by addressing the following specific questions: (1) How does the installation of a wind farm affect the long-term use of the occupied and nearby areas? (2) Are bird flights performed equally in all parts of the wind farm or are there areas of preferential use? In this case study we discuss the management and conservation implications for a species that is highly affected by this type of infrastructure, and for the potential implications in the siting and design of future wind farms.

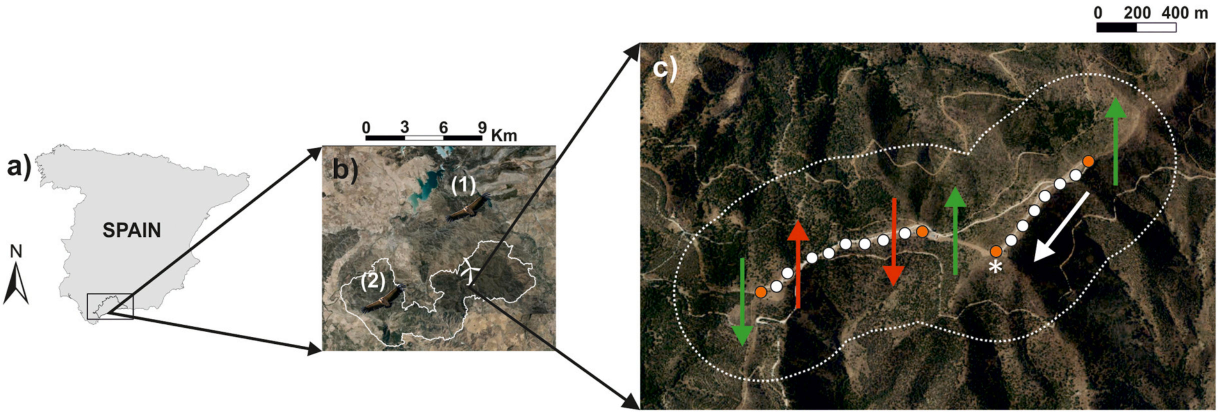

**Fig. 1.** a) Location of the study area. b) Griffon Vulture breeding colonies near the "Sierra de Aguas" wind farm. White line: the Sierras de Alcaparaín y Aguas SAC protected area. (1): original breeding colony (El Chorro); (2): new breeding colony (Alcaparaín); c) Location of the wind turbines (orange circles: external wind turbines; white circles: internal wind turbines), observers (asterisk) in the Sierra de Aguas" wind farm, influence area of 500 m (dotted line) and examples of parallel (white arrow) and transversal (green and red arrows) flights, and external (green rows) and internal (red arrows) flights.
(a) Modified from Farfán et al. (2017). (b) Cartographic source: Esri, Digital Globs, GeoE/e, Earthstar Geographs, CN ES/Aircus Ds, USDA, ISGS, AeroGRID, IGN, and the GIS user community.

## 2. Material and methods

### 2.1. Study area

This case study was conducted at the "Sierra de Aguas" wind farm, which is located on a SW-NE-oriented mountain ridge in southern Spain (Málaga province) (36° 51′ 18″N; 4° 46′ 43″W). It is included in the Sierras de Alcaparaín y Aguas Special Area of Conservation (SAC) protected area (Fig. 1). It has a Mediterranean climate with annual temperatures between 9.7 ºC and 24.7 ºC and a mean annual rainfall ranging from 400 mm to 659 mm. The area is mainly covered by scrub with some bare rock areas and small patches of holm oaks (*Quercus rotundifolia*), maritime pines (*Pinus pinaster*), and Aleppo pines (*Pinus halepensis*). The study area and its surroundings have a large availability of rocky cliffs, making it an area frequented by large cliff-nesting raptors such as the Golden Eagle (*Aquila chrysaetos*), the Bonelli's Eagle (*Aquila fasciata*) and the Griffon Vulture (Junta de Andalucía, 2019). The presence in 2001 of a Griffon Vulture breeding colony (aprox. 26 breeding pairs, in addition to non-breeding individuals; authors unpublished data) in the immediate surroundings (<15 km, "El Chorro" marked as (1) in Fig. 1b), means that the study area was largely integrated into the foraging area of the colony's vultures (range 473–4070 km$^2$) (García-Ripollés et al., 2011; Monsarrat et al., 2013). For a more detailed description of the study area see (Farfán et al., 2009).

The wind farm started operating in March 2005 with 16 850-KW wind turbines. In 2009, two more wind turbines with the same characteristics were added to the western row located at a lower altitude (Fig. 1c). Each turbine is fitted with three 25-m blades mounted on a 44-m cylindrical tower. One third of the blades are painted red, starting from the tip of the blade towards the base. The turbines are approx. 90 m apart and are arranged in two rows separated by a 400-m corridor, with a total length from one end to the other of 1800 m (Fig. 1c).

### 2.2. Data collection

Griffon Vultures significantly increase their foraging activity and home ranges during the breeding season (Xirouchakis and Andreou, 2009; García-Ripollés et al., 2011; Monsarrat et al., 2013), especially during the period from April to June (i.e. nestling rearing period), when adults spend most of their time foraging for chick food, which increases the probability of detection and the observation of interactions with wind turbines. Accordingly, the study was conducted from March 2005 to June 2018 (including five Griffon Vulture nestling rearing periods) during three different periods of the operational phase of the wind farm: Period 1 (April-June 2005 and April-June 2006, immediately after the start of operation); Period 2 (April-June 2010 and April-June 2011, just over six years after installation); and Period 3 (April-June 2018, just over 13 years after installation).

Prior to the construction, the use of the wind farm environment by Griffon Vultures and other raptors was confirmed by an earlier study developed for November 2000-October 2001 (Gil and Molino, 2004). In the period May-June 2001 10.7% of the raptors observed were Griffon Vultures and a flight rate of 0.9 raptors/hour was recorded.

#### 2.2.1. Griffon Vulture abundance and flight behaviour

The presence and the flight behaviour of Griffon Vultures were recorded by two observers equipped with 10 × 42 binoculars and located together in the highest area of the wind farm (949 m above sea level; see Fig. 1). One observer controlled the presence and the flight behaviour of Griffon Vultures on the western row and the other on the eastern row. We pre-established an influence area of 500 m around the wind farm and we only consider the Griffon Vultures observed within this area, a distance where we can be certain that the vultures are not avoiding wind turbines (Marques et al., 2020; Pearce-Higgins et al., 2009). Samplings were performed under favourable weather conditions, i.e., without rain and with clear visibility, on a weekly basis from 9.00 to 11.00 h (UTC) for a total of 120 h (Period 1: 48 h; Period 2: 48 h; Period 3: 24 h), which means that for each nestling rearing period we collected data in 12 sampling days.

Following Farfán et al. (2009), we calculated two variables to determine the abundance of Griffon Vultures per month:

1.- Number of observations/h: the number of groups of Griffon Vultures observed in the wind farm per hour. Each observation may consist of one or more individuals.

2.- Total number of individuals/h: the total number of Griffon Vultures observed in the wind farm per hour.

In addition, we analysed flight behaviour according to the following variables:

- Height. We distinguished three categories: 1 – below the blades (0–19 m); 2 – level with the blades (19–69 m); 3 – above the blades (> 69 m).
- Flight direction. We addressed two different directions relative to the wind turbine rows: t – transversal and p – parallel.
- Location of the flights. As flights perpendicular to the line of wind turbines pose a higher risk of collision we paid special attention to them taking into consideration two different locations for this type of flight (see Fig. 1): flights located at the ends of the wind farm and the central corridor between the two lines of wind turbines (external wind turbines); and flights in between two wind turbines (internal wind turbines).

We used the Kruskal-Wallis test (KW hereafter) to determine differences between periods and annual observation and abundance rates (Sokal and Rohlf, 1981), and the multiple comparisons of mean ranks for all groups to determine significant differences between pairs for each variable considered (Siegel and Castellan Jr, 1988).

We used the $X^2$ (chi-square) test to determine significant differences between height and flight directions in relation to those expected at random (Sokal and Rohlf, 1981). We hypothesized that flight paths around external wind turbines (located at the end of the two rows) were positively selected, while internal wind turbines (located between wind turbines within each line of wind turbines) were negatively selected, rather than randomly. We established Bonferroni 95% confidence intervals for the available proportion of the external and internal wind turbines (Neu et al., 1974; Byers and Steinhorst, 1984) to determine if they were used according to their availability (four external wind turbines and 14 internal wind turbines). We considered that the flight paths around the external and internal wind turbines were realised selectively if the proportion of use of a given class of wind turbines (external vs internal) was either above or below the confidence intervals (i.e. used in a lower or higher proportion than expected, respectively). All reported means are given with their standard error.

The significance level for all statistical tests was set at $\alpha = 0.05$. All statistical analyses were performed using the statistical software SPSS 23 (SPSS Inc., Chicago, IL, USA).

#### *2.2.2. Griffon Vulture mortality*

We searched for Griffon Vulture carcasses once a week for a total of 73 h during the period from April to June throughout the study period (Period 1: 38 h; Period 2: 25 h; Period 3: 10 h), using a similar protocol to that used by other authors (Carrete et al., 2009; De Lucas et al., 2004; Farfán et al., 2009). Thus, we walked a 70-m radius around each wind turbine actively searching for carcasses. When a carcass was found we recorded the age, injuries, and distance and orientation to the closest wind turbine. We estimated a mortality rate per turbine and period and used the methodology proposed by Farfán et al. (2017b) to correct for potential errors caused by carcass removal by scavengers, where the estimated mortality during a specific period of time resulted from the estimated daily mortality rate multiplied by the number of days between successive monitoring days.

## 3. Results

### *3.1. Flight rates and behaviour*

During the study period, we recorded a total of 42 observations and 83 Griffon Vultures (Table 1). There was a significant increase in the observation and abundance rates (Fig. 2) (KW observation rates: $X^2 = 21.890$, df = 2, $p < 0.01$; KW abundance rates: $X^2 = 19.686$, df = 2, $p < 0.01$). Specifically, observation rates were significantly higher in Period 3 than in Periods 1 and 2 (Period 1 – Period 3: $Z = 3.478$, $p < 0.01$; Period 2 – Period 3: $Z = 2.606$, $p < 0.05$), and abundance rates were significantly higher in Period 3 than in Period 1 (Period 1 – Period 3: $Z = 3.314$, $p < 0.01$).

The monthly observations rate varied from 0.0 observations/h during the periods 1 and 2 (nestling rearing periods from 2005 to 2011), to 7.8 observations/h in the period 3 (April 2018) (Table 1), with a mean monthly value and standard error of 0.7 ± 0.5. During the study period, there was a significant increase in observation rates (Fig. 2) (KW, $X^2 = 22.645$, df = 4, $p < 0.01$), which were significantly higher in 2018 than in 2005 and 2006 (Year 2005 – Year 2018: $Z = 3.063$, $p < 0.05$; Year 2006 – Year 2018: $Z = 2.985$, $p < 0.05$).

The monthly Griffon Vulture abundance rate ranged from 0.0 individuals/h during the periods 1 and 2 to 16.2 individuals/h in the period 3 (April 2018) with a mean monthly and standard error of 1.5 ± 1.1 (Table 1). Over the study period, the Griffon Vulture abundance rates showed a pattern of variation similar to that of the observation rates (Fig. 2) (KW, $X^2 = 20.705$, df = 4, $p < 0.01$): abundance rates were statistically higher in 2018 than in 2005 and 2006 (Year 2005 – Year 2018: $Z = 2.919$, $p < 0.05$; Year 2006 – Year 2018: $Z = 2.845$, $p < 0.05$).

Table 2 shows the distribution of the observations and individuals according to height categories. In both cases, the most frequent flights, regardless of whether they are parallel or transversal, occurred above the blades, although the differences only reached statistical significance for the number of individuals (Observations: $X^2 = 5.286$, df = 2, ns ($p > 0.05$); Individuals: $X^2 = 27.060$, df = 2, $p < 0.01$). Similar results were found regarding transversal and parallel flights. Thus, the most frequent transversal flights occurred above the blades, but the differences only reached statistical significance for individuals (Observations: $X^2 = 2.000$, df = 2, ns ($p > 0.05$); Individuals: $X^2 = 11.227$, df = 2, $p < 0.01$). For parallel flights the most frequent movements occurred above the blades,

**Table 1**
Monthly number of observations and Griffon Vulture individuals, and raw monthly variations in observations and Griffon Vulture abundance rates.

| Period | Year | Month | Nº Observations | % | Nº Individuals | % | Observations/h | Individuals/h |
|---|---|---|---|---|---|---|---|---|
| 1 | 2005 | April | 0 | 0.0 | 0 | 0.0 | 0 | 0 |
| | | May | 0 | | 0 | | 0 | 0 |
| | | June | 0 | | 0 | | 0 | 0 |
| | 2006 | April | 0 | | 0 | | 0 | 0 |
| | | May | 0 | | 0 | | 0 | 0 |
| | | June | 0 | | 0 | | 0 | 0 |
| 2 | 2010 | April | 0 | 14.3 | 0 | 28.9 | 0 | 0 |
| | | May | 1 | | 5 | | 0.1 | 0.6 |
| | | June | 2 | | 9 | | 0.3 | 1.2 |
| | 2011 | April | 0 | | 0 | | 0 | 0 |
| | | May | 0 | | 0 | | 0 | 0 |
| | | June | 3 | | 10 | | 0.3 | 1.1 |
| 3 | 2018 | April | 15 | 85.7 | 31 | 71.1 | 7.8 | 16.2 |
| | | May | 7 | | 9 | | 1.1 | 1.4 |
| | | June | 14 | | 19 | | 1.4 | 1.9 |

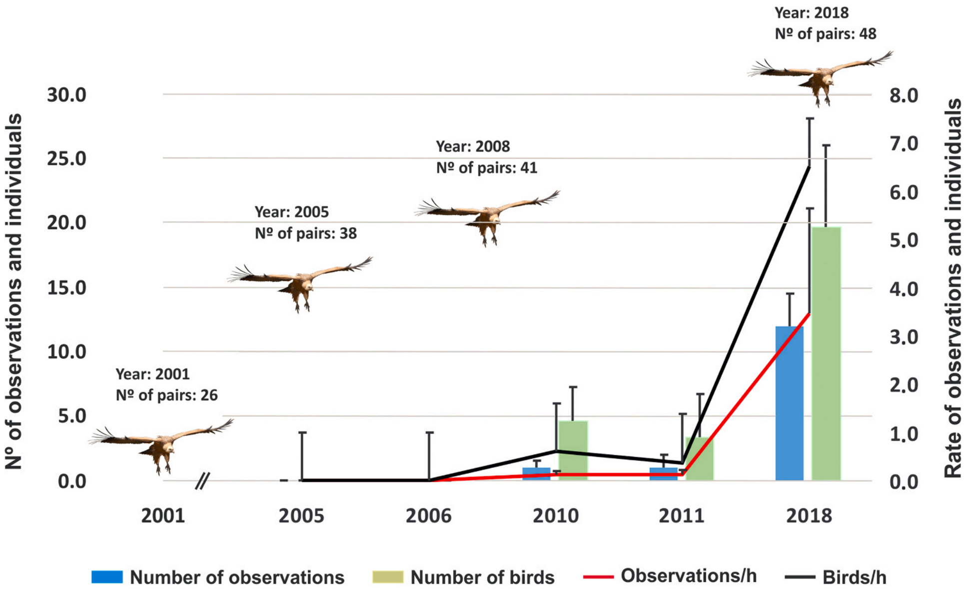

**Fig. 2.** Variation in the number of pairs in the breeding colony of "El Chorro", the closest to the study area, from 2001 and over the study period (obtained from del Moral, 2009, del Moral and Molina 2019 and authors unpublished data for 2001 and 2005), average variation in the number of Griffon Vulture observations and individuals, and corresponding average rates. Bars represent Standard Errors.

**Table 2**
Distributions of the observations and individuals according to height and flight directions and locations. 1 – below the blades; 2 – level with the blades; 3 – above the blades. P – parallel; T – transversal. Int – internal wind turbines; Ext – external wind turbines.

| Height | Flight direction | | Observations | | | | Individuals | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2010 | 2011 | 2018 | | 2010 | 2011 | 2018 | |
| | | | N | N | N | % | N | N | N | % |
| **1** | **P** | | 0 | 0 | 6 | 14.3 | 0 | 0 | 9 | 10.8 |
| | **T** | **Int.** | 0 | 0 | 2 | 4.8 | 0 | 0 | 2 | 2.4 |
| | | **Ext.** | 0 | 0 | 3 | 7.1 | 0 | 0 | 6 | 7.2 |
| **2** | **P** | | 0 | 0 | 4 | 9.5 | 0 | 0 | 5 | 6.0 |
| | **T** | **Int.** | 0 | 0 | 4 | 9.5 | 0 | 0 | 8 | 9.6 |
| | | **Ext.** | 1 | 0 | 1 | 4.8 | 2 | 0 | 1 | 3.6 |
| **3** | **P** | | 0 | 1 | 10 | 26.2 | 0 | 3 | 22 | 30.1 |
| | **T** | **Int.** | 1 | 2 | 2 | 11.9 | 5 | 7 | 2 | 16.9 |
| | | **Ext.** | 1 | 0 | 4 | 11.9 | 7 | 0 | 4 | 13.3 |

but the differences only reached statistical significance for individuals (Observations: $X^2 = 3.714$, df = 2, ns ($p > 0.05$); Individuals: $X^2 = 17.231$, df = 2, $p < 0.01$).

We recorded the same number of transversal and parallel flights: 21 in each case without statistically significant differences ($X^2 =$

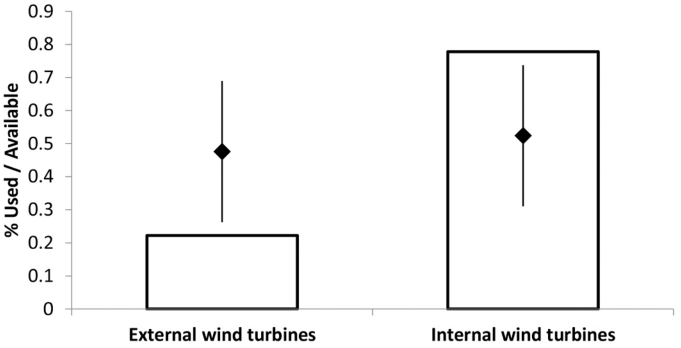

**Fig. 3.** Transversal flight patterns of Griffon Vultures in the study area. Bars represent the available proportion of external/internal wind turbines in the wind farm and black diamonds represent the proportion used (95% confident intervals represented by vertical lines).

0.000, df = 2, ns ($p > 0.05$)).

When crossing the wind farm, i.e. transversal flights to wind turbine rows, the Griffon Vultures avoided flights between internal wind turbines ($X^2 = 21.743$, df = 3, $p < 0.01$) and selected flights at the ends of the rows or through the corridor, i.e., through external wind turbines (Bonferroni selection index: $Z = -1.959$, $p < 0.05$) (Fig. 3).

### 3.2. *Griffon Vulture mortality*

During the period from April to June the entire study period, no dead Griffon Vultures were found in the wind farm.

## 4. Discussion

Raptors, and large soaring species in particular, are particularly vulnerable to collisions. The Griffon Vulture has one of the highest mortality rates cited in literature. De Lucas et al. (2012) found that 135 Griffon Vultures had collided with turbines over a period of two years at 13 wind farms in Tarifa (southern Spain), while Ferrer et al. (2012) reported a collision rate of 0.41 individuals/turbine/year, also in Tarifa. Lekuona and Ursúa (2007) found the carcasses of 227 Griffon Vultures in 13 wind farms over a period of three years in Navarra (northern Spain). Similar results have been found in nearby areas and other regions (Barrios and Rodríguez, 2004; Drewitt and Langston, 2006; De Lucas et al., 2008; Carrete et al., 2012; Martínez-Abraín et al., 2012). These results highlight the particular vulnerability of this species to collisions in wind farms. However, our results of Griffon Vulture mortality during the nestling rearing period in the "Sierra de Aguas" wind farm over 13 years of operation are not in agreement with those obtained by other authors. The question is what is the reason for this apparent contradiction? One factor could be that the last third of the blades are painted red, which increases the visibility of the blades and allows birds to avoid them. This was highlighted by May et al. (2020) who demonstrated a reduction in the annual raptor mortality rate of more than 70% in wind turbines with painted blades compared to wind turbines with unpainted blades.

The abundance of Griffon Vultures in the study area shows two clearly differentiated stages along the study period: 1) Displacement: during the first two years of operation, there was a decrease in the abundance of Griffon Vultures immediately adjacent to the wind turbines and their boundaries; 2) Growth: from the fifth year of operation Griffon Vultures started using again the wind farm area and there was an exponential increase in observations and abundance, until the end of the study period, reaching a maximum of 7.8 observations/h and 16.2 individuals/h, respectively. We know that the use rate of raptors prior to the construction of the wind farm (May-June 2001) was 0.9 raptors/h and that 10.7% of the raptors observed in the period May-June 2001 were Griffon Vultures (Gil and Molino, 2004), so that the values of use of the area before the installation was higher than zero (the use during the two first years of operation). The use of the area would be expected as it is within the feeding home range area (García-Ripollés et al., 2011; Monsarrat et al., 2013) of the individuals from a large breeding colony (Fig. 1). Furthermore, previous studies have shown that soon or relatively soon after the construction of wind farms raptors tend to avoid the areas near to wind turbines (Barrios and Rodríguez, 2004; Walker et al., 2005; Cabrera-Cruz and Villegas-Patraca, 2016). These results are fully in line with our results in relation to the first stage that we have called "displacement stage". However, these studies were of short duration and thus their results are not entirely comparable with our long-term results. Our findings challenge the traditional thinking that longer operational times result in greater declines in bird abundance, as proposed by (Stewart and Pullin, 2005). In contrast, our results are consistent with the theory that birds may become habituated to the presence of wind farms (Langston and Pullan, 2003). In addition, Dohm et al. (2019) demonstrated that although the impact of the construction and operation of wind farms may displace raptors, the impact might diminish over time, at least for certain species. This coexistence, however, could increase the risk of collision, especially in unfavourable weather conditions such as winter, when the combination of strong winds and low visibility is more frequent. In contrast, Marques et al. (2020) recently demonstrated that another soaring raptor, the black kite (*Milvus migrans*), experienced a displacement effect due to the presence of wind farms and appeared to avoid the areas closest to wind turbines (i.e., out to 700 m). In addition, some studies have shown long-term declines in some raptors species, 10–13 years after the installation of wind-farms (Santos et al., 2020a).

The possibility of reconciling wind farm energy with the conservation of one of the raptor species most affected by this type of infrastructure is supported by two findings: the number of breeding pairs of Griffon Vultures in the original breeding colony "El Chorro" has increased by 26.3% over the last 13 years in the study area (del Moral, 2019, 2009); and the appearance in 2018 of a new breeding colony "Alcaparaín" with six breeding pairs in the near vicinity of the wind farm (< 15 km) (see Fig. 1), rising to eight pairs in 2020 (unpublished personal data). Thus, what factors make wind farms a danger to birds? There is a consensus on this issue, suggesting that these factors tend to be related to species-specific morphology and flight behaviour, weather conditions, topography of the area where wind farms are located, and the location of turbines (De Lucas et al., 2008; Marques et al., 2014). Although our wind farm is located in the middle of a mountain ridge, all wind turbines are arranged in two rows separated by a 400-m corridor. Griffon Vultures clearly show turbines avoidance behaviour, by circumventing the wind turbines at the ends of the line, through the corridor or flying higher to the height of turbines. We believe that it is the small size of the wind farm and wind turbines that helps to greatly minimise the barrier effect, as birds can relatively easily avoid the line of wind turbines. This behaviour may lead to a reduction in habitat availability (Drewitt and Langston, 2006) in and around wind farms (Larsen and Guillemette, 2007; Marques et al., 2020), and raises concerns about the potential impact of extensive large-scale wind farm development.

The reduced dimensions of the wind farm and the presence of the corridor, which could be acting as a safe zone, together with the red color of the blades could be the combination of the key factors underlying the recovery of the Griffon Vulture's habitat use 13 years after the construction, and also the absence of mortality found in the wind farm.

The paucity of long-term studies limits current knowledge on this topic. We agree with the recommendation of Dohm et al. (2019)

that environmental agencies should require developers to monitor raptor abundance not only prior to the construction of a wind farm, but also throughout its operational life. In addition, control areas should also be monitored to ensure safe conclusions. This could be key to gaining more knowledge on the association between wind-farm design and risk to birds, and would help to better identify the factors determining their level of danger. The use of high-resolution GPS data loggers (e.g. see Santos et al., 2020b) to track birds before wind farms are installed would enable the reliable identification of those areas that are preferentially used by birds under different environmental conditions, and would help to identify the specific locations that increase the risk of collision or displacement and to build species specific sensitivity maps suggesting wind farm exclusion (Vasilakis et al., 2016). These kinds of studies would provide environmental impact assessment studies with information at the landscape scale, as well as valuable data on the behavioural plasticity and adaptability of these species to wind farms. These aspects are of great relevance given the constant demand for this type of renewable energy.

## 5. Conclusions

Three weaknesses of our results are that: 1) they refer to only one wind farm and the lack of a control area that would allow us to calibrate the data collected at the wind farm, 2) we only have data available for a specific period of the year (i.e. nestling rearing period) and 3) the carcass searches in 70 m distance around turbines are not always able to discover the extent of wind turbine collision mortality. Furthermore, it is important to stress that our single species-site findings should not be applied to the wind industry in general (Santos et al., 2020b). However, the presence of a Griffon Vulture breeding colony in the immediate surroundings prior to the construction of the wind farm and the growth of breeding population during the study period after the start-up of the wind farm, can be a good approximation as a reference situation. Having said that, and with the required prudence, we concluded that: 1) short-term studies do not provide robust indicators of the real impact of wind farms on birds and that long-term monitoring should be performed to better evaluate impacts and inform future projects. We show that the effect of "Sierra de Aguas" wind farm on the abundance and displacement of Griffon Vultures varies depending on the time at which it came into operation with short-term displacement and long-term increase in abundance. Our study highlights the need to encourage long-term studies to assess turbine-wildlife interactions in order to test the theory that indicates how birds may become habituated to the presence of wind farms; 2) not all wind farms are dangerous for Griffon Vultures and, therefore, we also point to the need of a better understanding of the effects of the final design of the wind farm on raptor mortality and displacement having in mind the limited time period for which we have sufficient data to support our conclusions.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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