Global Ecology and Conservation 38 (2022) e02203

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Significant decline of Griffon Vulture collision mortality in wind farms during 13-year of a selective turbine stopping protocol

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ARTICLE INFO

Keywords:
Wind farms
Birds
Soaring birds
Griffon Vulture
Bats
Passerines
Mortality mitigation

ABSTRACT

Avian mortality is one of the most negative impacts of wind energy. Consequently, techniques that effectively reduce avian collision rates are necessary. One of such method is the stop-turbine system, otherwise known as a Turbine Shutdown System (TSS). Here, we analyzed changes in mortality during 15 years, starting two years before the application of a selective stopping protocol (2006–2007) and after 13 years of application (2008–2020). This protocol was applied in Cadiz area (southern Spain) to 20 wind farms, totaling 269 wind turbines. The priority in the shutdown protocol was to avoid large soaring birds, mainly raptors, collisions. In total, 2903 birds and 354 bats were found to have collided with wind turbines in this 15-year period. This represents a rate of 0.830 birds/turbine/year and 0.101 bats/turbine/year. After implementation of the selective stopping protocol, we found a significant reduction of 61.7 % in mortality of soaring birds (mainly raptors and storks). Considering only mortality records of Griffon Vultures, a reduction of 92.8 % was achieved. Counts of Griffon Vultures increased more than 7-fold during the study period, and number of turbine stops due to vultures at risk in wind farms, also increased by around 2.5 times. Our finding of Griffon Vulture mortality being reduced by over 92 % through turbine shutdowns was associated with only an estimated loss of less than 0.51 % in energy production. This substantial disparity in conservation benefits versus industrial costs suggests that this mitigation method could have net-beneficial application elsewhere.

1. Introduction

In order to slow down climate change, scientists recommend reducing the use of pollutant energy sources and developing renewable energies to both cope with excessive CO2 emission and decrease the use of fossil fuels. Among renewable energy sources, wind power is one of the most wide-spread worldwide (Panwar et al., 2011; Nazir et al., 2020). It is considered to have a lower environmental impact by reducing environmental pollution and water consumption (Saidur et al., 2011). However, as the production of wind energy increases worldwide, adverse effects of turbines and development activities have been documented for many avian groups, especially raptors (i.e. orders *Falconiformes, Accipitriformes* and *Strigiformes*; Mitkus et al., 2018). Wind farms have shown potential adverse effects on the surrounding wildlife through two main disturbances: collision and avoidance (May, 2015; Fielding et al., 2021). Studies conducted at some wind farm developments in Europe indicate that bird populations are not greatly impacted by

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https://doi.org/10.1016/j.gecco.2022.e02203
Received 2 March 2022; Received in revised form 15 June 2022; Accepted 18 June 2022

collisions with turbines (De Lucas et al., 2004, 2005), and low collision rates have been registered, such as 0.065 birds/turbine/year, 0.04 and 0.06 birds/turbine/year (De Lucas et al., 2008) and 0.001 birds/turbine/year have been found (Hunt, 1999). These findings indicate that mortality rates per turbine are quite variable because the probability of collisions depends on a range of factors such as the species, species-specific flight behavior, weather and topography around wind turbines (De Lucas et al., 2008, 2012a, 2012b; Ferrer et al., 2012; May, 2015). One problem in wind energy development is that in the past environmental impact assessment studies assessing the risks to birds were inappropriately conducted at the wind farm scale instead of wind turbine scale (Ferrer et al., 2012; Fielding et al., 2021), necessitating urgent development of efficient mitigation actions to reduce mortality at poorly placed turbines.

Among studies that have shown some of the highest collision rates published for birds (1.33/turbine/year) with the Griffon Vulture *Gyps fulvus* being the most frequently killed raptor species (0.41 deaths/turbine/year; de Lucas et al., 2012a; Ferrer et al., 2012). There is a consensus that raptors may be more prone to colliding with blades than other birds (Beston et al., 2016) because of their morphology, foraging behavior, or flight behavior (Janss, 2000; Kikuchi, 2008). Limitations in the degree to which raptors perceive turbines as dangerous (Martin, 2011; May, 2015; Hunt and Watson, 2016; Fielding et al., 2022) are thought to contribute to collisions of a number of species worldwide.

Win farms could have an important impact in raptor populations, because raptors have longer life spans and lower reproductive rates, resulting in population growth rates that are highly sensitive to adult and subadult mortality (Madders and Whitfield, 2006). The high mortality rates of Griffon Vultures reported by De Lucas et al. (2008) motivated the adoption of mitigation measures. In 2008, a new protocol of the stop-turbine system, otherwise known as a Turbine Shutdown System (TSS, Birdlife International, 2015), developed by Migres Foundation (De Lucas et al., 2012a), was implemented, trying to mitigate those high rates of Griffon Vulture collisions. After two years of application, preliminary results showed a significant reduction in Griffon Vulture mortality by 50 %, with a reduction in energy production by the wind farms by only 0.07 % per year. Here we provide the first published demonstration that long-term adoption of a mitigation measure at a wind farm – a selective stopping protocol – can successfully reduce raptor mortality with a minimal reduction in power output.

In the present study, we analyzed the effectiveness of this selective stopping protocol, which was established in Cadiz area (southern Spain) in 2008, applied to 20 wind farms, totaling 269 wind turbines. We analyzed if there were any temporal changes in bird mortality before and after the implementation of this selective turbine stopping protocol to support continued use of selective stopping as a mitigation system. At the same time, we were interested in potential changes in efficacy of the protocol over the 13-year of application period and if there was differences among group of species in the reduction achieved. A decrease over the years of application of the stopping protocol in mortality rates of the main victim, (e.g. the Griffon Vulture), was detected. Consequently, we have tried to elucidate if it was due a decrease in vulture's abundance or in the use of wind farm areas by vultures.

2. Material and methods

2.1. Study area and species

The Strait of Gibraltar separates southernmost Spain from northern most Morocco (35°45′–36°10N and 5°10′–6°00W). It is the shortest sea crossing between Europe and Africa and it acts as a major concentration point for Palearctic soaring migrants (Bernis,

Table 1
Characteristics of wind farms in this study.

Wind farm Number	Number of turbines	Power output (mW)	Height (m) (Without blades)	Blade length (m)
WF 1	11	2	78	42.3
WF 2	11	2	80	44
WF 3	17	0.8	60	27.25
WF 4	30	0.8	60	27.25
WF 5	10	2	67	40
WF 6	20	0.8	60	28.75
WF 7	11	1.8	80	44
WF 8	28	1.67	70	35.5
WF 90	15	0.8	60	28.75
WF 10	6	2	78	40
WF 11	8	2	67	40
WF 12	6	2	67	40
WF 13	4	1.5	78	36
WF 14	6	1.67	70	35.5
WF 15	27	1.8	80	44
WF 16	6	2	67	40
WF 17	16	0.8	60	28.75
WF 18	9	2	80	44
WF 19	10	2	84	33.3
WF 20	18	2	84	33.3
All Grps	269			

1980; Zalles and Bildstein, 2000). The Griffon Vulture population in Cadiz province is the third largest population of Spain consisting of about 2000 breeding pairs. Annually, during October and November, vultures from other areas, mainly northern Spain, accumulate in our study area before crossing to Africa during their dispersive movements. During this period, a maximum of 1800 birds can be present daily, waiting for good weather conditions to cross the sea. Each autumn between four and five thousand juvenile Griffon Vultures disperse from their breeding colonies and cross the Strait of Gibraltar to northwest Africa (Migres Foundation, unpublished data). Other species such as Common Kestrel *Falco tinnunculus*, Peregrine Falcon *Falco peregrinus*, Egyptian Vulture *Neophron percnopterus,* Short-Toed Eagle *Circaetus gallicus* and Eagle Owl *Bubo bubo* are common in the area. Except the Egyptian vulture, none of these species are endangered in Spain. Besides being an important breeding area, during the migration period, around 70,000 Honey Buzzards *Pernis apivorus*, 120,000 Black Kites *Milvus migrans*, 110,000 White Storks *Ciconia ciconia*, and 20,000 Booted Eagles *Aquila pennata* and Short-Toed Eagles, pass through this area. The vegetation in the study area is characterized by brushwood and wild olive *Olea europaea* var. *sylvestris* and cork oak *Quercus suber* woodland with patches of scrub and rocky areas on the mountain ridges, and pasture land used for cattle grazing predominating in the lower areas.

For this study, we consider four different groups of species potentially affected by collision with the blades: Soaring birds (medium and large species of raptors, storks and herons, excluding Griffon Vultures), Griffon Vultures, passerines, and bats. All the species considered in each one of these groups are presented in Tables 1–4. The selective stopping protocol was designed to cover only soaring birds and specially Griffon Vultures. Bats and passerines were considered only for comparison.

2.2. Wind farms and stopping protocol

We studied 20 wind farms containing a total of 269 wind turbines with different power ratings (Table 1). Turbines were arranged in rows running north–south so they optimized the use of prevailing easterly and westerly winds. These wind farms were constructed and began operation between 2005 and 2006. According to environmental impact (EID) regulations, the facilities were required to develop surveillance programs (Ferrer et al., 2012; Janss et al., 2010). The main goal of these programs is to document all mortalities caused by collisions of birds with turbine blades. These programs have been conducted annually every day of the year (365 days) from dawn to dusk (between 8 and 14 daylight hours in winter and summer, respectively) by 12–17 trained observers who were coordinated and interconnected by cellular telephones. Mortality searches were made at every turbine on a daily basis, with a fixed search effort of 100 m radius to find dead birds or bats. The observers were evenly distributed throughout the area covered by the wind farms and this high search effort obviated the need to apply corrections for search efficiency and scavenger removal. Anyway, our main goal was to detect relative trends in mortality at turbines over the years, and not to obtain an estimate of the number of victims. Data gathered consisted of the species and number of individuals that collided with turbines distances from the turbine tower of the recorded casualties. These data enable us to determine how mortalities were distributed in space and time among the different wind farms and their turbines.

Table 2
Species of soaring birds and mortality recorded in this study.

Soaring birds		
Species	Number of individuals killed per year	Number of deaths/turbine/year
Gyps fulvus	36.23	0.1346
Falco tinnunculus	13.92	0.0517
Milvus migrans	10.46	0.0388
Ciconia ciconia	8.15	0.0303
Circaetus gallicus	5.77	0.0214
Hieraaetus pennatus	3.46	0.0128
Accipiter nisus	2.00	0.0074
Circus pygargus	1.54	0.0057
Buteo buteo	1.46	0.0054
Egretta garzetta	1.46	0.0054
Pernis apivorus	1.38	0.0051
Falco naumanni	1.38	0.0051
Tyto alba	1.00	0.0037
Larus michahellis	1.00	0.0037
Athene noctua	1.00	0.0037
Larus fuscus	0.92	0.0034
Circus aeruginosus	0.85	0.0031
Bubo bubo	0.77	0.0028
Neophron percnopterus	0.77	0.0028
Falco peregrinus	0.69	0.0025
Pandion haliaetus	0.23	0.0008
Elanus caeruleus	0.23	0.0008
Ciconia nigra	0.23	0.0008
Milvus milvus	0.15	0.0005
Geronticus eremita	0.15	0.0005
Hieraaetus fasciatus	0.08	0.0002
Other species	24.00	0.0892

Table 3
Species of passerines and mortality recorded in this study.

Passerines		
Species	Number of individuals killed per year	Number of deaths/turbine/year
Miliaria calandra	40.15	0.1492
Carduelis carduelis	8.62	0.0320
Passer domesticus	8.31	0.0308
Melanocorypha calandra	6.92	0.0257
Galerida cristata	5.31	0.0197
Apus apus	4.08	0.0151
Delichon urbicum	3.69	0.0137
Apus melba	2.31	0.0085
Sturnus unicolor	2.15	0.0080
Apus pallidus	1.62	0.0060
Carduelis cannabina	1.54	0.0057
Passer hispaniolensis	1.00	0.0037
Cisticola juncidis	0.77	0.0028
Hirundo rustica	0.69	0.0025
Sturnus vulgaris	0.69	0.0025
Calandrella brachydactyla	0.69	0.0025
Sylvia atricapilla	0.62	0.0022
Lanius senator	0.54	0.0020
Carduelis chloris	0.46	0.0017
Saxicola rubicola	0.46	0.0017
Tachymarptis melba	0.46	0.0017
Motacilla alba	0.31	0.0011
Sylvia melanocephala	0.31	0.0011
Alauda arvensis	0.31	0.0011
Phoenicurus ochruros	0.31	0.0011
Merops apiaster	0.31	0.0011
Apus apus	0.31	0.0011
Acanthis cannabina	0.23	0.0008
Acrocephalus scirpaceus	0.23	0.0008
Phylloscopus collybita	0.23	0.0008
Ptyonoprogne rupestris	0.23	0.0008
Sylvia borin	0.15	0.0005
Passer domesticus	0.15	0.0005
Phylloscopus bonelli	0.15	0.0005
Upupa epops	0.15	0.0005
Cecropis daurica	0.15	0.0005
Other species	1.00	0.0037

Table 4
Species of bats and mortality recorded in this study.

Bats		
Species	Number of individuals killed per year	Number of deaths/turbine/year
Pipistrellus sp.	10.77	0.0400
Pipistrellus pipistrellus	4.77	0.0177
Microchiroptera	3.77	0.0140
Eptesicus isabellinus	2.31	0.0085
Eptesicus serotinus	0.69	0.0025
Pipistrellus kuhlii	0.69	0.0025
Pipistrellus pygmaeus	0.62	0.0022
Nyctalus lasiopterus	0.38	0.0014
Nyctalus leisleri	0.38	0.0014
Myotis blythii	0.38	0.0014
Myotis myotis	0.15	0.0005
Tadarida teniotis	0.15	0.0005
Nyctalus noctula	0.15	0.0005
Hypsugo savii	0.15	0.0005
Nyctalus sp.	0.08	0.0002
Miniopterus schreibersii	0.08	0.0002
Plecotus austriacus	0.08	0.0002

After 2007, selective stopping of turbines by observers when dangerous situations are detected were mandatory. A typical dangerous situation occurs when, for example, a Griffon Vulture flies in a trajectory which will potentially result in a collision with turbine blades, or when a group of vultures flies within or near a wind farm. In these cases, the observers telephone the wind farm control office to switch off the turbines involved in the risk, stopping the turbine within a maximum of 3 min. To re-start the turbine, a new phone call must be done. All the 20 studied wind farms (Table 1) have been required to conduct this stopping procedure, for all medium- to large-sized birds (including Griffon Vultures, soaring birds and specially raptors) that were observed in a risk situation. As a result, we were able to obtain data from the 269 wind turbines in these 20 wind farms from 2006 to 2007 without any shutdown protocol in operation and from 2008 to 2020 (13 years) with the protocol in operation. The data were recorded according to the protocol designed by Migres Foundation and collected by the Andalusia Environmental Ministry. We use data of duration and number of stops during 2008–2020 as a proxy of intensity of use of the wind farm areas by Griffon Vultures.

2.3. *Census of Griffon Vultures*

Annual counts of dispersing Griffon Vultures (among other species) over the Strait of Gibraltar have been recorded using standardized protocols since 1999, conducted during the postnuptial migration between mid-julys until the end of November (De la Cruz et al., 2011). The period selected for censuses was the period with the highest Griffon Vulture mortality in these wind farms before the establishment of the selective stopping protocol (De Lucas et al., 2012a). Numbers of individuals were recorded on a daily basis at two different observatories (Algarrobo 36°0525N, 5°2902W and Cazalla 36°158N, 5°3436W). Counts at both sites were conducted simultaneously. At each observatory, counts were carried out by a minimum of four observers with at least one of the observers being a trained ornithologist (De la Cruz et al., 2011). All observers were equipped with binoculars. Counts were not conducted on days with persistent rain or when crosswind speeds exceeded Beaufort scale 6. However, under adverse weather conditions in the Strait, such as high speed winds, rain, or low visibility between Europe and Africa, the crossing of soaring birds is usually delayed, and birds are forced to wait until weather conditions improve (Shamoun-Baranes et al., 2006; Vansteelant et al., 2014; Miller et al., 2016). In addition, we used data of local breeding colonies (Cadiz province) to assess any potential effect of wind farm mortality in number of breeding pairs.

2.4. *Statistical methods*

We used linear regression and generalized linear models (GLM) with a normal distribution and log link functions to perform parametric analyses (Sokal and Rohlf, 1981). To determine which factors can better explain the evolution of mortality, we used an information-theoretic approach to develop a priori model sets. A GLM estimating vulture mortalities, including year as random factor, and number of stops per year and census of vultures in the area per year as explanatory variables was conducted. We ranked models

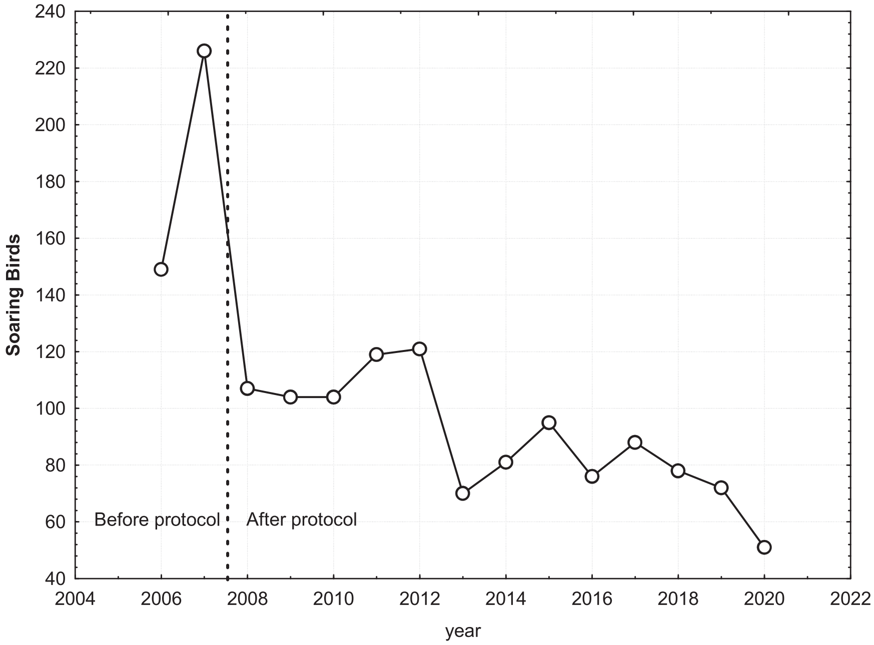

Fig. 1. A significant negative relationship between year and mortality of soaring birds (r = − 0.7567; p = 0.0011; r2 = 0.5726) was found, with a reduction of 65.2 % from 2006 to 2020. Dotted line divides the period in two, before (2006–2007) and after (2008–2020) the implementation of the selective stopping protocol. Considering only the second period, again a significant negative relationship between year and mortality of soaring birds (r = − 0.6439; p = 0.0175; r2 = 0.4146) was found, with a reduction of 51.1 %.

using Akaike's information criterion. In using AIC the lowest model value as being considered the most competitive. The degree to which 95 % confidence intervals for slope coefficients (β) overlapped zero was also used to evaluate the strength of evidence for competing models within the model set (Arnold, 2010; Dugger et al., 2016). We used Statistica 12.0 software package to estimate model coefficients and model selection statistics. We used an alpha value of 0.05 to assess significance of results when necessary.

3. Results

3.1. *Change of mortality records 2006–2020*

From 2006 to 2020, a total of 401 bats and 3021 birds were found to have collided with wind turbines, which are 26.73 bats and 232.38 birds per year (Tables 2–4). This represents a rate of 0.863 birds/turbine/year and 0.099 bats/turbine/year. Excluding vultures, a total of 1080 others soaring birds were found from 2006 to 2020, which give us a mortality rate for this group of 0.381 soaring birds/turbine/year.

Significant differences in number of victims before and after the application of the selective stopping protocol were found in soaring birds (before: mean = 187.50 + 54.4; after: 89.69 + 20.77; F = 26,477; p = 0.0001) and Griffon Vultures (before: mean = 116.50 + 26.16; after: 36.23 + 14.06; F = 47.45; $p < 0.0001$). Contrarily, no differences in bats or passerines accidents were found between both periods (passerines, before: mean = 66.00 +26.87; after: 103.69 + 37.15; F = 1.85; p = 0.1966; bats, before: mean = 23.50 + 4.94; after: mean = 27.23 + 21.23; F = 0.05; p = 0.8146).

Considering all the period 2006–2020, a significant decrease in mortality of soaring birds over time was found (r = – 0.7567; p = 0.0011; r^2 =0.5726; Fig. 1). According to this regression, a reduction of 65.2 % was achieved from 2006 to 2020 (95 % confidence coefficient: 54.5–81.4 %). Considering only Griffon Vultures, in the period 2006–2020, a significant negative relationship between year and mortality (r = – 0.8152; p = 0.0002; r^2 = 0.6646) was found. According to this regression, a reduction of 92.8 % was achieved (95 % confidence coefficient: 75.4–100.0 %). No significant variations over the years in mortality of passerines (r = 0.2162; p = 0.4579; r^2 = 0.0467) or bats (r = – 0.2269; p = 0.4354; r^2 = 0.0515) were found.

3.2. *Trends of mortality during the application of the protocol*

Selecting only the 2008–2020 period of application of the selective stopping protocol, a significant negative relationship between year and mortality for soaring birds was found, showing decreasing mortality over time (soaring birds: r = – 0.6439; p = 0.0175; r^2 = 0.4146; Fig. 1). According to this regression, a reduction of 51.1 % was achieved from 2008 to 2020 (95 % confidence coefficient: 44.8–59.6 %). Considering only Griffon Vultures, 471 were found during this period at the 20 wind farms, ranging from 61 in 2008 to 18 in 2020. The average vulture mortality rate over this period was 0.1346 vulture deaths/turbine/year, ranging from 0.2267 in 2008

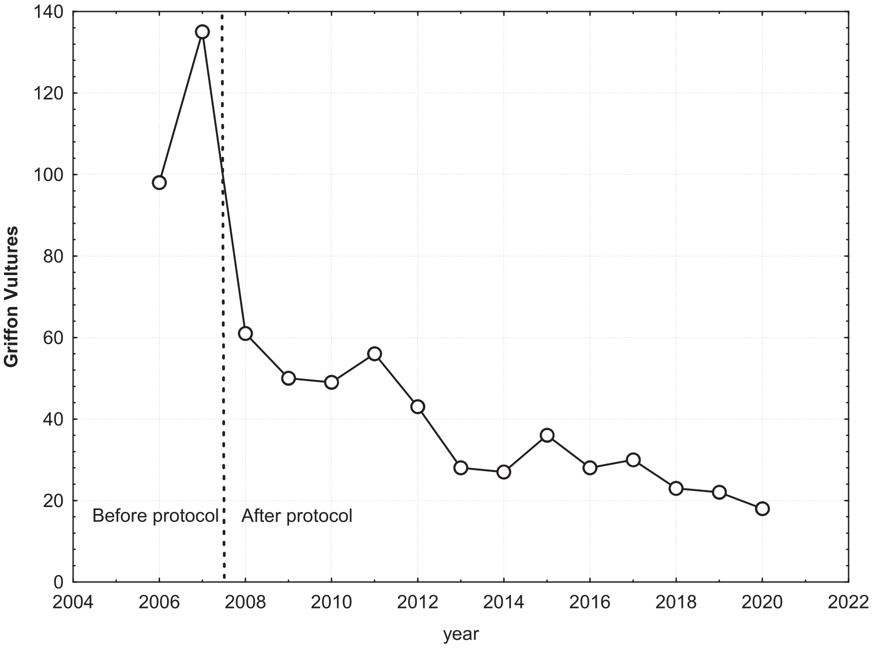

Fig. 2. A significant negative relationship between year and mortality of Griffon Vultures (r = – 0.8152; p = 0.0002; r^2 = 0.6646) was found, with a reduction of 92.8 % from 2006 to 2020. Dotted line divides the period in two, before (2006–2007) and after (2008–2020) the implementation of the selective stopping protocol. Considering only the second period, again a significant negative relationship between year and mortality of soaring birds (r = – 0.9013; $p < 0.0001$; r^2 = 0.8124) was found, with a reduction of 71.4 %.

to 0.0669 in 2020. There was a negative significant regression during this period (Griffon Vultures: $r = -0.9013$; $r^2 = 0.8124$; Fig. 2), showing a significant decrease over time of Griffon Vultures mortality records. According to this regression, a reduction of 71.4 % was achieved from 2008 to 2020 (95 % confidence coefficient: 63.4–80.5 %).

No significant trend over time, however, was found in passerines ($r = -0.0046$; $p = 0.9888$; $r^2 = 0.0000$; Fig. 3). From 2008 to 2020, we recorded a total of 1352 dead passerine birds at the 20 wind farms, which give us a mortality rate of 0.386 passerines per turbine and year. Likewise, bats showed no trend in mortality over the years ($r = -0.3423$; $p = 0.2523$; $r^2 = 0.1172$; Fig. 4). We recorded a total of 354 dead bats at the 20 wind farms, which is a mortality rate of 0.101 bats per turbine and year.

3.3. *Abundance and use of wind farm areas by Griffon Vultures*

Counts of Griffon Vultures at the Algarrobo and Cazalla observatories in October and November from 2008 to 2020 showed a significant increase over the years ($r = 0.7561$; $p = 0.0044$; $r^2 = 0.5717$; Fig. 5). In 2008, 606 vultures were counted, and this increased more than 7-fold to 4418 in 2020. Our observed increase in Griffon Vultures was in accordance with a general increase of the populations of this species throughout Spain (Del Moral and Molina, 2018).

Regarding local colonies, again an important increase has been recorded, from 1929 pairs breeding in Cadiz province in 2008 to 2630 in 2018, showing an increase over 36 % (Del Moral and Molina, 2018).

3.4. *Selective stopping of turbines*

The number of turbine stops due to vultures at risk in wind farms, under selective stopping protocol, also increased from 3517 in 2008 to 8927 in 2020. That is around 2.5 times more frequent at the end of the study period ($r = 0.6255$; $p = 0.0531$; $r^2 = 0.3913$; Fig. 6), revealing a general increase in intensity of use of wind farms areas by Griffon Vultures.

The mean number of minutes of every selective stop was 108 min. Consequently, and taking into account that during the last 3 years the average number of stops was 6700, total time per year of stopped turbines in the area was around 723,600 min, which is equivalent to a reduction of 0.51 % of the total energy generated per year in those wind farms.

A GLM estimating vulture mortalities, including year as random factor, and variables, number of stops per year and census of vultures in the area per year as explanatory variables was conducted. Among the models ranked using AIC, a year-only model obtain the lowest AIC values, and all models including year outperformed models without year (Table 5), supporting the idea that the significant reduction in Griffon Vulture mortality was not related to reduce number of birds or reduce intensity of use of wind farm areas.

4. Discussion

As we established (De Lucas et al., 2012a; Ferrer et al., 2012), vulture mortality rates per turbine in this area were relatively high. In fact, mortality rates found in our study were among the highest ever published for wind farms. For this reason, selective stopping protocol was mandatory in 2008, obtaining a highly significant reduction of mortality of Griffon Vultures (50.8 %) just the firsts two years of the application of the protocol (De Lucas et al., 2012a). In 2008, at the beginning of the mandatory application of the selective stopping protocol, mortality rates of Griffon Vultures were 0.2267 per turbine and year, that is and average of 61 death vultures per year in the 20 wind farms. To date, after 13 years of application of this protocol, the rate in 2020 was three times and a half lower (0.0669 vultures/turbine/year), which means a reduction over 71 % over the time of application of the protocol, and a total of reduction in collisions of 93 % from 2006 to 2020. Considering only soaring birds, reduction achieved during application of the protocol was 51.1 % and 65.2 % for all the period. As far as we know, there are no other mitigation measures published with as high a reduction in mortality by collision of soaring birds with wind turbines. Even if originally, the stopping protocol was mainly focused on reducing vulture mortality, an overall reduction of 65.2 % in mortality across all soaring birds beyond Griffon Vultures was achieved.

In contrast, we observed no reduction in mortality for passerines and bats over the years. The obvious limitations of the technique (daylight observation with binoculars of birds at risk) preclude its application to bats or small birds. Nevertheless, the fact that there were no changes in number of this kind of victims along the years in both groups support the idea of no substantial changes in populations or use of wind farm areas in those groups.

Counts of Griffon Vultures since 2008 demonstrate a steady increase in local population, especially evident in the last 5 years (Fig. 5). This could be associated with the general increase in vulture populations throughout Spain (Del Moral and Molina, 2018), including local colonies in Cadiz province. Whatever the reasons for the population increase, this suggests that reduced Griffon Vulture mortality at wind turbines was not due to a smaller population of vultures passing through the study area. In the same way, the number of turbine stops increased over the years (Fig. 6), probably responding to an increasing local population. This suggests that the reduced griffon mortality at wind turbines was not simply a result of decreased intensity of use of wind farms.

Results of the GLM demonstrated that only year, but not count or stops, was selected as the best fitted model explaining variations in Griffon Vulture mortality. Around 81 % of the variance in vulture mortality was explained by year since the stopping protocol was established, showing a very significant decrease over the years.

Potential explanations for the highly significant decrease observed in vulture mortality over the years could include variation in density of the species, avoidance of wind farm areas or increase in effective application of the stopping protocol. As we have shown, no decrease in local vulture population was recorded. To the contrary, the number of vultures increased 7-fold from 2008 to 2020. Regarding avoidance, we do not have robust data (such as telemetry coordinates of movement in and around wind farms), but if we admit that number of stops could be considered as a proxy of use of wind farm areas, again number of stops increases over the study

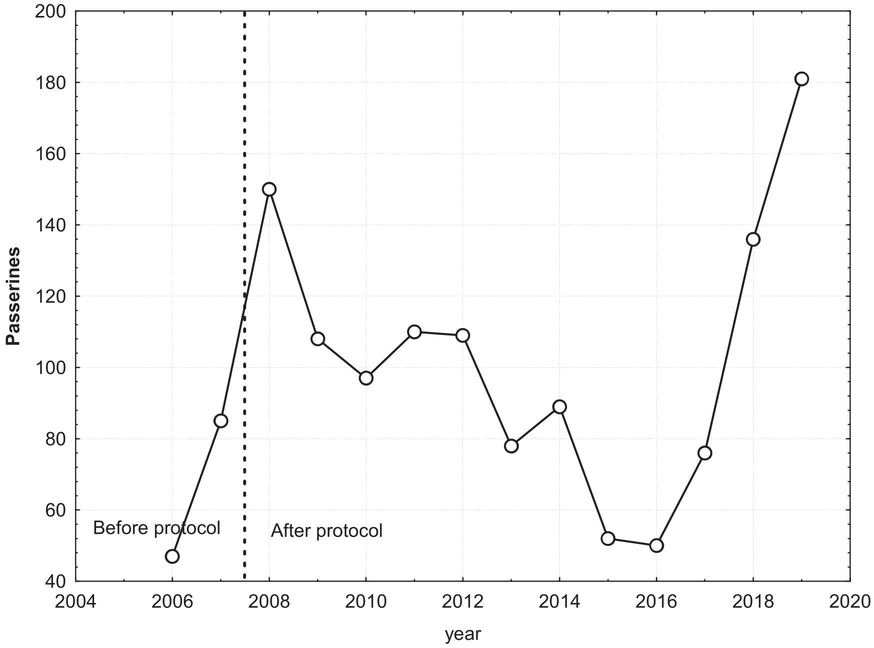

Fig. 3. No significant trend in mortality over time was found in passerines (r = 0.2162; p = 0.4579; r^2 = 0.0467).

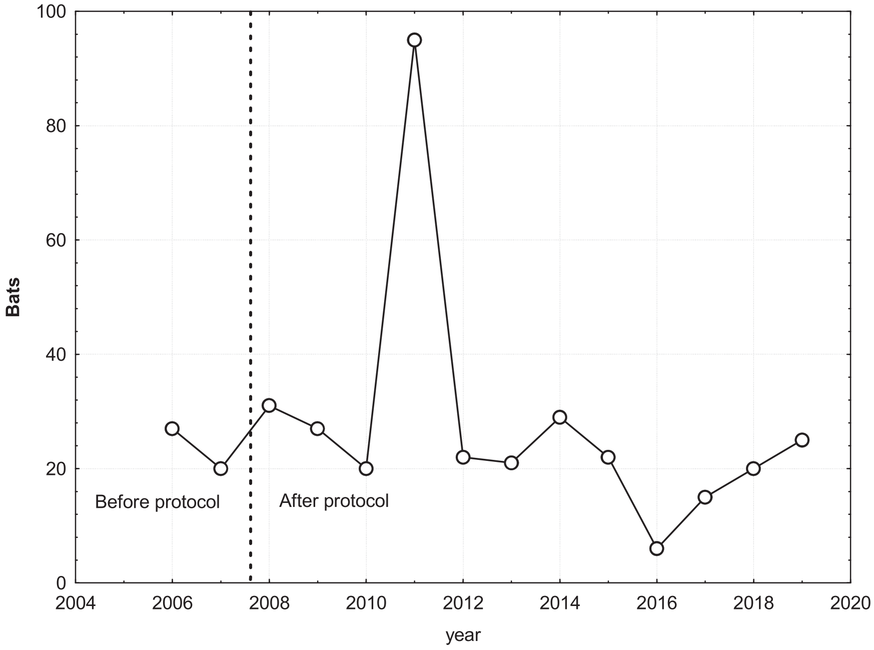

Fig. 4. Bats showed no trend in mortality over the years (r = – 0.2269; p = 0.4354; r^2 = 0.0515).

period, being more than 2.5 times more frequents in 2020 that in 2008, giving no support to a decrease in the intensity of use of the wind farm areas by vultures as a potential explanation.

An increase in the ability of the observers and a better trained personal would be the reason behind this important decrease in mortality rates of vultures and soaring birds. Since 2008, on a yearly base, observers must take courses of identification, determination of risk situations, management of wounded birds, etc. and they must pass an examination to assert their skills. Most of the current personal have been working on this project for more than four years and consequently they are now experienced personal. Consequently, we suggest that trained observers can be effectively used to mitigate mortality rates in operating wind farms and that the efficacy of this system depend heavily on trained personal, as demonstrated by the improvement over the years recorded in our study.

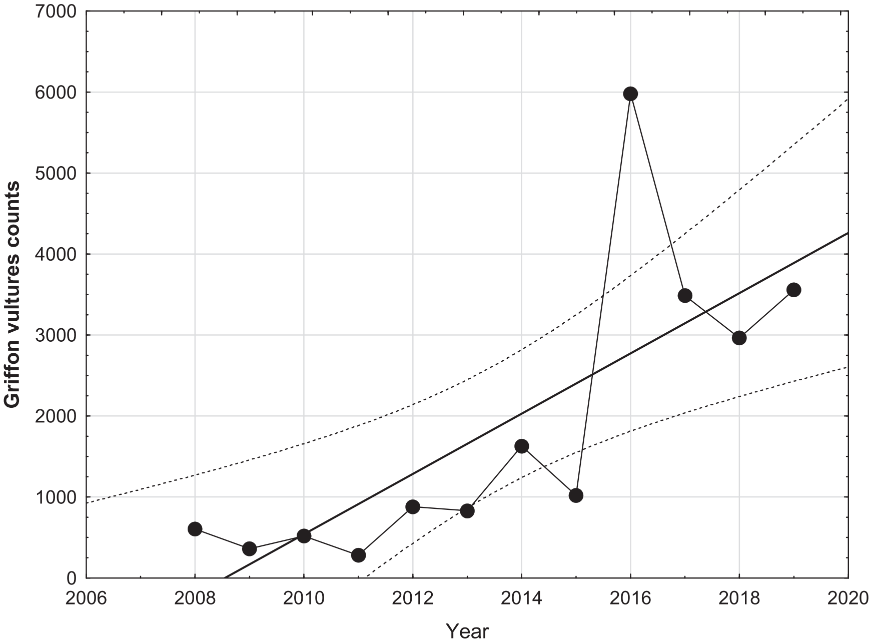

Fig. 5. Counts of Griffon Vultures at the Algarrobo and Cazalla observatories in October and November from 2008 to 2020 showed a significant increase over the years (r = 0.7561; p = 0.0044; r2 = 0.5717).

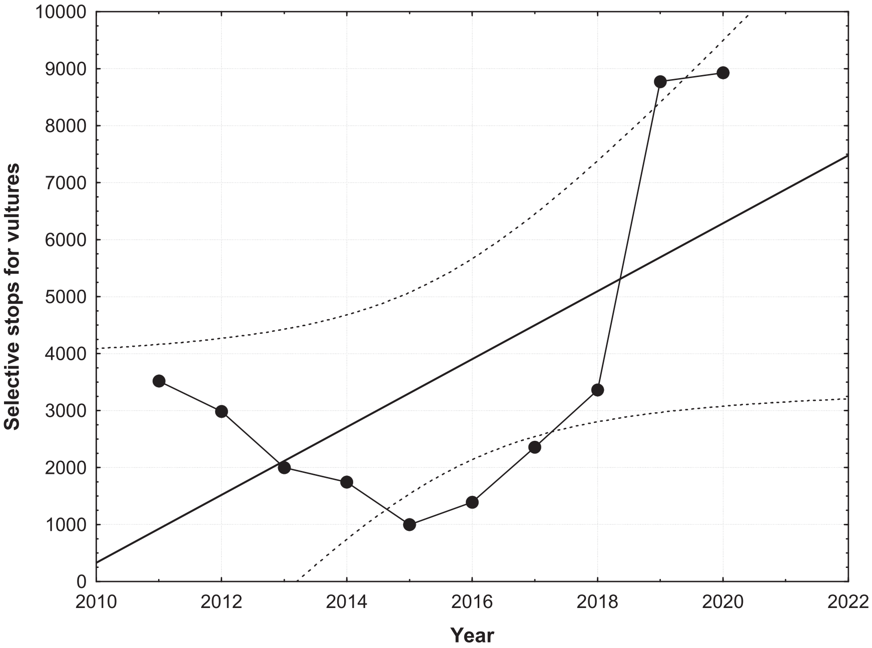

Fig. 6. The number of turbine stops due to vultures at risk in wind farms, under selective stopping protocol, also increased around 2.5 times more frequent at the end of the study period (r = 0.6255; p = 0.0531; r2 = 0.3913), revealing an increase in intensity of use of wind farms areas by Griffon Vultures.

As vultures are large, diurnal, soaring raptors, most of the accidents occur from 2 h after sunrise until 2 h before sunset. Therefore, short stops of wind turbines are necessary only during daylight hours. Since turbines can operate normally at night, the decrease in energy production is minimized. As our data show, mortality of Griffon Vultures can be decreased by over 92 % with only an estimated reduction in energy production of less than 0.51 %. As far as we know, this is the first time that a long-term successful mitigation method to decrease soaring bird mortality at wind farms has been published.

Table 5
GLM results showing the most competitive model at the top; the one including only "year". Estimates and 95 % confidence intervals for slope coefficients (β) are show, with "year" being the only variable with the interval no-overlapping zero.

Var. 1	Var. 2	Var. 3	Degr. of Freedom	AIC	L.Ratio Chi^2
Year			**1**	**64.342**	**13.77**
Year	Stops		2	66.276	14.45
Year	Census		2	66.342	13.78
Year	Stops	Census	3	68.274	14.51
Census			1	73.390	7.07
Stops	Census		2	73.903	7.08
Stops			1	80.388	1.53
Effect	**Estimate**	**Standard Error**	**Wald Stat.**	**Lower CL 95,0 %**	**Upper CL 95,0 %**
Year	**-0.1230**	**0.03512**	**12.2769**	**-0.1919**	**-0.0542**
Stops	0.0000	0.00003	0.81021	-0.0000	0.0001
Census	0.0000	0.00005	0.06762	-0.0001	0.0001
Scale	5.1740	1.15694		3.3380	8.0197

Regarding mortality, bats are killed directly when struck by turbine blades, or indirectly by decompression near blades, although the latter is still controversial (Rollins et al., 2012). Bats would be attracted to wind turbine towers as tall elements dominating the landscape that in turn attract insects, particularly the lights installed according air safety instructions. Whatever the case, it seems that other mitigation systems, like an increase in the minimum wind speed at which turbine start to operate, typically over 5.5 m/s, are able to significantly decrease the number of victims (Peste et al., 2015). For passerines, however, no published results have found an effective mitigation system. Probably because a lower population impact for these species seems to be assumed, few efforts have been made to reduce turbine impacts to this group.

Mortality in wind farms is one of the main adverse effects on birds and bats through collision with turbines. The turbine stopping protocol we implemented proved to be an effective program focused on reducing the mortality of Griffon Vultures, with a minimal effect on total energy production of the wind farms. Furthermore, other species of soaring birds, including many raptor species, benefitted as well. Not only did we dramatically reduce mortalities with the stopping protocols, but we further reduced mortalities every year thanks to trained personal. Probably, more experienced and better trained personnel were able to achieve lower mortalities rates over the years because they able to better identify birds farther away and they able to more quickly determine which birds would be at risk.

Automated systems using cameras are likely to be the near future in collision mitigation. Whatever the system, the approach of shutting down certain turbines in certain situations has proven highly effective in reducing mortality with low loss of power output.

CRediT authorship contribution statement

Miguel Ferrer: Conceptualization, Methodology, Supervision, Writing – original draft. **Angèle Alloing:** Writing – review & editing. **Ryan Baumbush**: Writing – review & editing. **Virginia Morandini:** Writing – review & editing.

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.

Acknowledgements

We would like to thank Asociación Eólica de Tarifa for their collaboration and all the workers of the Surveillance Program. The Andalusia Environmental Ministry provided all data on bird mortality to perform the study. Phil Whitfield and anonymous referee greatly improved early versions of this paper.

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