Wind turbines cause functional habitat loss for migratory soaring birds

Ana Teresa Marques[1,2,3]*, Carlos David Santos[4,5]*, Frank Hanssen[6], Antonio-Román Muñoz[7], Alejandro Onrubia[8], Martin Wikelski[4,9], Francisco Moreira[2,3], Jorge Manuel Palmeirim[1], João Paulo Silva[1,2,3]

[1] Centro de Ecologia, Evolução e Alterações Ambientais, Faculdade de Ciências, Universidade de Lisboa, Edifício C2, Campo Grande, 1749-016 Lisboa, Portugal

[2] Centro de Ecologia Aplicada "Professor Baeta Neves" (CEABN), InBio, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

[3] REN Biodiversity Chair, CIBIO/InBIO Associate Laboratory, Universidade do Porto, Campus Agrário de Vairão, 4485-661 Vairão, Portugal

[4] Department of Migration and Immuno-ecology, Max Planck Institute for Ornithology, Am Obstberg 1, 78315 Radolfzell, Germany

[5] Núcleo de Teoria e Pesquisa do Comportamento, Universidade Federal do Pará, Rua Augusto Correa 01, Guamá, 66075-110 Belém, Brazil

[6] Norwegian Institute for Nature Research, Box 5685 Sluppen, N-7485 Trondheim, Norway

[7] Biogeography, Diversity and Conservation Research Team, Departamento de Biología Animal, Facultad de Ciencias, Universidad de Málaga, Spain

[8] Fundación Migres (CIMA), Ctra. N-340, Km.85, Tarifa, 11380 Cádiz, Spain

[9] Department of Biology, University of Konstanz, Universitätsstr. 10, 78464 Konstanz, Germany

* These authors contributed equally to this work.

Corresponding author: Ana Teresa Marques (ateresamarques@gmail.com, +351 962483032). Centro de Ecologia, Evolução e Alterações Ambientais, Faculdade de Ciências, Universidade de Lisboa, Edifício C2, Campo Grande, 1749-016 Lisboa, Portugal

Abstract

1. Wind energy production has expanded to meet climate change mitigation goals, but negative impacts of wind turbines have been reported on wildlife. Soaring birds are among the most affected groups with alarming fatality rates by collision with wind turbines and an escalating occupation of their migratory corridors. These birds have been described as changing their flight trajectories to avoid collision with wind turbines, but this behaviour may lead to functional habitat loss, as suitable soaring areas in the proximity of wind turbines will likely be underused. This impact has, however, never been adequately quantified.

2. We used state-of-art tracking devices to monitor the movements of 130 black kites (*Milvus migrans*) in an area populated by wind turbines, at the migratory bottleneck of the Strait of Gibraltar. Landscape use by birds was mapped from GPS data using dynamic Brownian bridge movement models and generalized additive mixed modelling was used to estimate the effect of wind turbine proximity on bird use while accounting for orographic and thermal uplift availability.

3. We found that areas up to 880m away from the turbines were less used than expected given their uplift potential. Within that distance threshold, bird use decreased with the proximity to wind turbines. We estimated that the footprint of wind turbines affects 15-19% of the areas suitable for soaring in our study area during east winds, and similar habitat losses are expected in other migratory bottlenecks.

4. *Synthesis and applications*. We present evidence that the impacts of wind energy industry on soaring birds are greater than previously acknowledged. In addition to the commonly reported fatalities, the avoidance of turbines by birds causes habitat losses in their soaring corridors. It is critical that the authorities recognize this further impact of wind energy production and establish new regulations that protect soaring habitat adequately.

We also showed that soaring habitat for birds can be modelled at a fine scale using publicly available data. Similar approaches should be used before the implementation of new wind energy developments to avoid overlap between critical soaring areas and the location of new wind turbines.

Keywords:

Aerial habitat; avoidance behaviour; migration; orographic uplift; raptor; thermal uplift; wind farms

Introduction

Wind energy generation has increased immensely over the last decades and this growth is expected to continue in the forthcoming years, with a predicted annual increase of 5% of the installed capacity until 2020 (IPCC, 2011; GWEC, 2015). Despite the immediate benefits for climate change mitigation, negative interactions between wind energy production and wildlife, mainly birds and bats, have been widely reported (see Saidur et al., 2011 for a review). Soaring birds, including most raptors, storks and other large birds, are among the groups of highest concern, as their movement corridors have been populated by wind farms (Katzner et al., 2012; Cabrera-Cruz & Villegas-Patraca, 2016; Martín et al., 2018) leading to high fatality rates through collisions with turbines (e.g. Barrios & Rodriguez, 2004; Smallwood & Thelander, 2008; Ferrer et al., 2012).

Soaring flight allows large birds to travel long distances with a reduced energetic cost (Pennycuick, 1975; Duriez et al., 2014). However, soaring depends on updrafts, which are relatively scarce and scattered across the landscape (Horvitz et al., 2014; Katzner et al., 2015). Two types of updrafts are commonly used by terrestrial soaring birds: (1) orographic uplift that results from the deflection of horizontal winds by sloping terrain and (2) thermal uplift that is formed during the day due to the heating of the land surface by solar radiation (Kerlinger, 1989). Soaring birds use orographic uplift either to gain altitude and glide downwards in a desired direction, or to travel along uplift-rich areas, typically mountain ranges (Bohrer et al., 2012; Katzner et al., 2015). Orographic uplift is particularly useful when generated from mountain ranges oriented in the migration direction (Kerlinger, 1989; Dennhardt et al., 2015). In the case of thermal uplift, soaring birds typically climb in thermals with a circular trajectory from which they glide linearly towards the next thermal in the desired direction (Kerlinger, 1989; Katzner et al., 2015; Santos et al., 2017). Due to such specific requirements, soaring birds tend to move along areas with high uplift potential, often named corridors (sensu Dennhardt et al., 2015). Besides the physical requirements for soaring, the importance of different corridors may vary dramatically depending on their geographic position relative to migration routes of soaring birds. For example, areas in the vicinity of narrow sea crossings may experience higher traffic during migrations, as soaring birds avoid crossing large bodies of water (Newton, 2008).

Soaring birds and wind energy developments may compete for the same areas both at the local and regional scales. At local scales, wind turbines are frequently installed along the top of mountain ranges, in order to maximize exposure to horizontal winds, and these areas also tend to have high orographic uplift potential for soaring birds (Katzner et al., 2012). At a broader scale, migratory bottlenecks of soaring birds often correspond to narrow sea crossings or mountain passages where the topography favours high wind speeds, thus being well suited for wind-power production (Hilgerloh et al., 2011; Villegas-Patraca et al., 2014; Martín et al., 2018). Therefore, understanding how wind turbines impact movement corridors of migratory soaring birds is of utmost importance to allow the necessary development wind power production without compromising wildlife conservation goals.

In general, birds tend to avoid wind turbines through evasive movements and changes in space use (reviewed in May, 2015). Soaring birds were shown to change their flight trajectories to avoid turbines (de Lucas et al., 2004; Villegas-Patraca et al., 2014) and to decrease in numbers in the close proximity of the turbines (Barrios & Rodriguez, 2004; Pearce-Higgins et al., 2009). Similarly, comparisons between the pre- and post-construction phases showed that soaring birds reduce their use of the areas where the turbines are installed and their trajectories become more scattered in the nearby areas (Garvin et al., 2011; Johnston et al., 2014; Cabrera-Cruz & Villegas-Patraca, 2016; Farfan et al., 2017). While these avoidance behaviours suggest that soaring birds are to some extent able to cope with the presence of wind turbines (Marques et al., 2014), they may also cause functional habitat loss (i.e. loss of aerospace in movement corridors; Diehl, 2013), which is a potentially important, but a largely neglected, impact of wind-power generation (Davy et al., 2017).

In this study we investigated the footprint of wind turbines on movement corridors of migratory soaring birds using high-frequency GPS tracking (1-minute temporal resolution or higher). Tracking technology is a powerful tool to study multiscale interactions between birds and wind turbines, but only recently was introduced in this field (e.g. Cleasby et al., 2015; Thaxter et al., 2015; Cranmer et al., 2017; Thaxter et al., 2018). We tracked 130 black kites (*Milvus migrans*) during the post-breeding migration in an area highly populated by wind turbines in the region of Tarifa, Spain. Black kites and other soaring birds concentrate in this region to cross the Strait of Gibraltar during their migration to Africa (MIGRES, 2009). Birds were captured and tracked during periods of strong crosswinds at the Strait of Gibraltar, which forced them to roam around Tarifa while waiting for conditions favouring the sea crossing. Bird movements were used to map space use intensity using Brownian bridge movement models. The influence of the wind turbines on the birds' use of the landscape was then modelled taking into account the main predictors of soaring flight, orographic and thermal uplift (Kerlinger, 1989; Bohrer et al., 2012). We predicted that (1) birds will use areas with greater uplift (orographic and thermal) more, and (2) the area in the proximity of the wind turbines will be less frequented regardless of its uplift potential.

Materials and methods

Study area

This study was conducted in the region of Tarifa (36.0132ºN, 5.6027ºW), on the Spanish side of the Strait of Gibraltar. The Strait is a narrow sea crossing between Europe and Africa and is the main migration bottleneck for soaring birds travelling through the Western European–West African Flyway (Newton, 2008). The region of Cádiz (that includes Tarifa) is of high importance for the wind energy industry, with ca. 70 wind farms and over 1300MW of installed wind-power capacity (IECA, 2015). Our focal area had 160 operating wind turbines on seven wind farms, representing 132MW of power generation (Fig. 1, Table S1). These turbines were mainly arranged in rows from North to South (Fig. 1).

Bird captures and tracking

Our model species, the black kite, is an obligate soaring migrant, and one of the most common soaring species crossing the Strait of Gibraltar during the post-breeding migration (between 100 and 150,000 individuals are counted on a regular basis; Martín et al., 2016). These features make this species susceptible to interactions with wind turbines and fatalities due to collision with wind turbines have been recorded in earlier studies in this region (Ferrer et al., 2012).

We captured and fitted 130 birds with GPS data loggers during the post-breeding migration (July to September) in 2012 and 2013. Birds were captured during periods of strong Levanter winds (10-20 m/s blowing from the east), which are frequent in the summer (Dorman et al., 1995) and are known to prevent the passage of soaring birds to Africa, causing them to congregate around Tarifa for periods up to one week (Miller et al., 2016). Birds were captured in a walk-in trap (7 x 7 x 3.5 m) baited with carrion, located 3.5 km North of Tarifa (36.0426ºN, 5.6150ºW). We captured more birds than those eventually tracked, which enabled us to select similar numbers of adults and juveniles in each capture event. Overall, we tracked 72 adults and 58 juveniles. Sex ratio was also relatively balanced (69 females, 59 males and 2 unidentified, results from molecular sexing).

Birds were equipped with GPS-GSM data loggers (42g, TM-202/R9C5 module, Movetech Telemetry, UK, https://www.uea.ac.uk/movetech) attached as backpacks using Teflon ribbon. A weak-link was built into each harness to allow the loggers to automatically detach. The weak-link was made from rubber band in the birds tagged in 2012 and from biodegradable plastic thread in those tagged in 2013. Previous tests showed that the rubber band breaks within two to four weeks when exposed solar radiation and the biodegradable plastic thread within a year. Birds were released a few hours after capture, immediately after the tagging was completed. Loggers were set to obtain a GPS position at least once a minute. GPS mean error calculated from ca. 1500 fixes collected by two stationary dataloggers was 1.4 m in horizontal and 1.5 m in vertical, with maximum errors of 15 m and 31 m respectively. Data were sent to an online server via the GSM network.

Estimation of orographic and thermal uplift

The orographic and thermal uplift velocities were estimated using a modified version of the methodology employed by Bohrer et al. (2012) and Brandes and Ombalski (2004) for high resolution spatial data, described in Santos et al. (2017). The estimation of orographic uplift uses parameters from local topography (terrain aspect and slope) and wind (direction and speed). Local topography was obtained from a Digital Elevation Model of 30 m spatial resolution available at http://gdex.cr.usgs.gov/gdex/ (NASA JPL, 2009). Wind direction and speed was obtained at a weather station in Tarifa (36.0138°N, 5.5988°W). Measurements of wind for the whole migration season of black kites (mid-July to mid-September; MIGRES, 2009) during in 2012 and 2013 lead to the conclusion that there are two predominant wind conditions: (1) strong Levanter winds (wind direction from 80 to 120°; speed from 4 to 15 m/s) lasting for periods up to a week; and (2) western breeze (wind direction from 270 to 310°; speed from 1 to 6 m/s), typically intercalating Levanters (Fig. S1). These wind conditions match with that generically described for the Summer at the Strait of Gibraltar (Dorman et al., 1995). In this context, we decided to build three different orographic uplift models, the first representing uplift for average conditions of wind during the collection of our tracking dataset (direction = 97.8°, speed = 8.8m/s), and the other two models for average conditions of levanter wind (direction = 100°, speed = 7.7m/s) and western breeze (direction = 290° and speed = 4.1m/s) during the migration season of black kites. Uplift estimated from the first model was used as predictor in bird space-use models (described in the section below), while the remaining two uplift models were used to estimate generic soaring habitat suitability during levanter wind and western breeze (see figure 5).

The estimation of thermal uplift velocity according to Santos et al. (2017) is based on land surface temperature derived from LANDSAT imagery. In general, satellite images obtained in the same season show high correlation if no major changes of land use are observed (Zhu, 2017). Consequently, high correlation is also expected for thermal uplift models built from those images.

Santos et al. (2017) confirmed that uplift models build for the study area in different days during the summers of 2012 and 2013 are highly correlated (r > 0.77). Therefore, we decided to build a single thermal uplift model that used land surface temperature estimated from a LANDSAT 8 OLI/TIRS image acquired on July 17th 2013, available at http://earthexplorer.usgs.gov/ (NASA Landsat Program, 2015). The model was representative of uplift at 231m height, which is the mean flight height of birds in our tracking dataset, and its spatial resolution was 100 m, corresponding to that of the LANDSAT 8 OLI/TIRS thermal band (Santos et al., 2017).

Bird movement modelling

Our modelling approach followed the concept of Resource Utilization Function (RUF) proposed by Marzluff et al. (2004) and following the recommendations of Hooten et al. (2017). RUF uses a two-step analysis, the first that estimates the density or intensity of space use (i.e. Utilization Distribution; UD) over the geographic domain of interest and the second links the space use to a set of spatially explicit covariates in a regression model (Hooten et al., 2017).

Our modelling dataset included GPS positions of flying birds (i.e. GPS speed >1 m/s) collected during daylight and in days of Levanter wind (direction: mean = 97.8°, SD = 0.22, range = 83.2-116.3°; speed: mean = 8.8m/s, SD = 2.2, range = 4.2-12.7 m/s). Very few tracking data was collected with different wind conditions than Levanter because birds cross the Strait of Gibraltar as soon as the Levanter ceases (Miller et al., 2016). These data were thus excluded from the analysis. We also concentrated the analysis in the area where the concentration of bird movement was highest (see Fig. 1). We did not exclude GPS records based on flight altitude because to our knowledge there are no studies indicating the vertical limits to where birds react to wind turbines.

We used dynamic Brownian bridge movement models (dBBMM; Kranstauber et al., 2012) to estimate the UD of each bird in each day on a 100x100m grid. The Brownian bridge movement models produces UD values for each bird based on the properties of a conditional random walk between successive pairs of locations, accounting for the distance and elapsed time between successive locations, which is a major improvement compared to conventional UD estimation (Horne et al., 2007). Additionally, dBBMM allows for changes in behaviour, using likelihood statistics to determine change points along the animal's movement path (Kranstauber et al., 2012). By incorporating information on the sequence of locations of tracking data, this approach allows for identification of areas with high activity but also to estimate the movement corridors between locations, allowing for a more realistic estimate of the space use by moving animals (Kranstauber et al., 2012). The dBBMM were implemented in R (R Core Team, 2016) with the function brownian.bridge.dyn of the package move (Kranstauber et al., 2017), using a window size of 25 locations and a margin of 5 locations, following the recommendations of Kranstauber et al. (2012). The UD calculated of each bird in each day were summed in order to produce a general UD for our study area. This was the UD used in later analysis.

In order to evaluate the effect of wind turbines on birds, we fitted a generalized additive mixed model (GAMM) using the function gamm of the R package mgcv (Wood, 2018). We selected GAMM as modelling technique because we expected non-linear relationships between our predictors and the response variable, and also because it can be used to model spatially correlated data (aqui mete uma daquelas refs que vimos sobre a prestação dos gamms na correção da correção especial). Our model included the distance to wind turbines and the orographic and thermal uplift velocities as predictors of bird UD. Orographic and thermal uplift are the most important drivers of soaring flight (Kerlinger, 1989), thus we expected bird UD to be fundamentally determined by those factors but potentially affected by the proximity of wind turbines. We must emphasise that orographic and thermal uplift estimates result from static uplift models, representing the generic conditions for the period of tracking data collection (see section above). We added a Gaussian spatial correlation structure to the model to account for spatial autocorrelation (Dormann et al., 2007; Beale et al., 2010; Wood, 2017). This was done with the function corGaus of the R package mgcv (Wood, 2018) following Zuur et al. (2009). Bird UD was log-transformed to normalize its distribution. No random factors were included in the model. The degree of smoothing of predictors (k) was first left free to be optimized by cross-validation (the default method of the gamm function). However, we found that uplift variables were given too much complexity in regions little supported by data points (grafico). In contrast, the fitting of both uplift variables in the regions well supported by data points was approximately linear (grafico). Therefore, we set these two predictors as linear in our final model. The modelling dataset was restricted to grid cells at distances up to 2 km from wind turbines, as the influence of wind turbines on bird UD is expected to dissipate with distance.

A second model was built for grid cells positioned far away from the influence of the wind turbines (1 to 2 km away from turbines) using only the orographic and the thermal uplift velocities as predictors. We used this model to estimate soaring suitability in the absence of wind turbines (used for the results presented in figures 4 and 5). This model was a Generalized Least Squares (GLS) since the two predictors used (orographic and thermal uplift velocities) were considered to have a linear influence on the UD. The model was fitted with the function gls of the R package mgcv (Wood, 2018). As in the GAMM model, in this model we used function corGaus to account for spatial autocorrelation of the data, and the bird UD was log-transformed to normalize its distribution.

Both models were validated through 10-fold cross-validation. The original dataset was randomly split into a training subset with 90% of the data that was used to fit the model, and a testing subset with 10% of the data against which the model is tested. This procedure was repeated 10 times in a way that the training and testing subsets of each run were complementary and cover all the original dataset (Geisser, 1993). The precision and predictive performance of models were evaluated from their Normalized Root Mean Square Error (nRMSE), defined as the root mean square error divided by the range of the model response variable.

Results

We tracked 130 individual black kites for an average of 2 days each, generating ca. 220,000 GPS locations (Fig. 1). Movements were concentrated within a radius of ca. 40 km from Tarifa, with individual birds moving about 120 km on average before they crossed the strait of Gibraltar. From the original dataset, 77,000 GPS locations were used for modelling purposes (Fig. 1; see methods of further details on data selection).

The Utilization Distribution (UD) estimated from dBBMMs showed an uneven spatial pattern, with reasonably defined areas of concentration of movement (Fig. 1). Higher intensity of movement was observed along two central areas aligned approximately North-South and along the coastline (Fig. 1).

The estimates of uplift showed highly heterogeneous distributions (Fig. 2). The highest orographic uplift velocities were estimated along the east-facing mountain slopes in the most western and eastern regions of the study area (Fig. 2a). In contrast, the highest estimates of thermal uplift were concentrated in a valley located in the centre of the study area (Fig. 2b). Compared to thermal uplift, orographic uplift was spatially more concentrated with more extreme velocities, but the former showed higher values in average (orographic uplift velocity: mean of grid cell values = 0.35m/s, SD = 0.72, range = 0-6.18m/s; thermal uplift velocity: mean of grid cell values = 1.69m/s, SD = 0.26, range = 0.10-2.19m/s).

We showed bird UD was significantly affected by the distance of wind turbines and the two types of uplift through a General Additive Mixed Model (GAMM, Table 1, Fig. 3). A negative effect of wind turbine proximity on bird UD was observed up to a distance of 880 m, which dissipates beyond that. However, it should be noted that there was a slight drop of bird UD after the 880 m. Both orographic and thermal uplift velocities had a positive effect on bird UD (Table 1, Fig. 3).

When the previous model was fitted with data obtained beyond the influence of the wind turbines (i.e. 1 to 2 km from wind turbines) the effects of orographic and thermal uplift velocities on bird UD remained generically the same (Fig. S2, Table 1). Predictions of this model applied to areas up to 880 m from the wind turbines were significantly higher than the dBBMM estimates for the same areas (Fig. 4). This indicates that birds used areas close to turbines less than expected from their soaring suitability. After extrapolating this model to the entire study area we found that between 15 and

19% of the area suitable for soaring was within the area of influence of wind turbines (i.e. up to 880 m from wind turbines; Fig. 5).

Discussion

We found that wind turbines affect a large area of suitable soaring-habitat around them. GPS-tracked black kites showed a reduced use of the areas up to 880 m away from the wind turbines, and this effect was stronger at shorter distances (Fig. 3). We also demonstrated that areas within 880 m of the wind turbines had suitable uplift conditions for soaring flight but they were little used by the black kites (Fig. 4). Interestingly, there was a slight peak on bird use at areas near the 880 m that might have been a consequence of birds changing direction to avoid entering the areas adjacent to the turbines (Villegas-Patraca et al., 2014; Cabrera-Cruz & Villegas-Patraca, 2016).

We must emphasise, however, that our models include a large amount of unexplained variance (see table x), although comparable to that found in previous studies linking bird soaring behaviour to uplift proxies (Sapir et al., 2011; Bohrer et al., 2012; Dodge et al., 2014; Hernandez-Pliego et al., 2015; Santos et al., 2017). This may result from natural variance in the relationship between the predictors of our models and the bird UD, or/and we might be missing some relevant predictors of bird UD in our models. In addition, uplift predictors were estimated for a single generic circumstance in time, which may have promoted some mismatch between uplift and bird UD. Tracking data used in the models were collected in highly uniform conditions of wind direction, therefore we do not expect the areas of orographic uplift to change geographically in time. But the variation observed in wind speed may have affected overall uplift intensity of those areas. This could potentially have influenced the birds' trade-off in using orographic uplift or thermal uplift in nearby areas. Regarding the thermal uplift, a considerable temporal variation is expected within a day and between days mostly due to the amount of solar radiation heating the earth surface (Stull, 1988). Like in the case of orographic uplift, we do not expect such variation to promote geographical changes in uplift but some changes are expected in its intensity that could influence the birds' trade-off in the use of the alternative sources of uplift.

The displacement effects of wind-power plants have been demonstrated in earlier studies for soaring birds (Barrios & Rodriguez, 2004; de Lucas et al., 2004; Pearce-Higgins et al., 2009; Garvin et al., 2011; Johnston et al., 2014; Villegas-Patraca et al., 2014; Cabrera-Cruz & Villegas-Patraca, 2016). However, only a single study quantified the extent of the area affected by this phenomenon (Pearce-Higgins et al., 2009). That study reports lower densities of two species of raptors during their breeding season in areas up to 800 m from turbines, which coarsely matches the estimates of our model. Furthermore, there are no attempts to estimate the proportion of soaring corridors that could be lost or negatively affected by the establishment of wind farms. Here, we estimated that 5-16% of the areas suitable for soaring in our study area are impacted by wind-energy production during Levanter (Easterly) winds, and that percentage decreases to 1-13% during western breeze (Fig. 5). These two sorts of wind comprise most wind conditions found in Tarifa during the migration season of black kites (fig s..). The magnitude of this impact is likely similar in other critical areas for migratory soaring birds where new large wind-power projects are being constructed, such as the Gulf of Suez in Egypt (Hilgerloh et al., 2011) or the Isthmus of Tehuantepec in Mexico (Villegas-Patraca et al., 2014). It should be emphasized that soaring birds are restricted to fly in soaring corridors (e.g. Leshem & Yom-Tov, 1998; Shamoun-Baranes et al., 2003; Santos et al., 2017), thus, small losses of suitable area may have large constraints for their vital activities. Losses in movement corridors may be particularly important during migrations, as soaring birds already experience considerable mortality while overcoming natural barriers, such as deserts and sea stretches (Bildstein et al., 2009; Strandberg et al., 2010; Klaassen et al., 2014). Suboptimal soaring conditions may force birds to delay or suspend migration or to use flapping flight, which is energetically unsustainable for most species (Newton, 2008).

The reason why migratory soaring birds avoid wind turbines is still unclear. The fact that birds are displaced far beyond the areas occupied by the physical infrastructure of wind-power plants could be a consequence of neophobia, as turbines do not belong to their natural environment (Walters et al., 2014), but it could also be a consequence of earlier negative experiences, such as birds being caught in the airflow around turbines, or even witnessing fatalities of conspecifics. In addition, the functioning of wind turbines disturbs local airflow regimes (e.g. Magnusson & Smedman, 1999; Sorensen et al., 2015), which may compromise uplift generation. However, this is expected to affect only the areas behind the turbine rotors (e.g. Magnusson & Smedman, 1999; Sorensen et al., 2015).

Our findings indicate that the negative effects of wind-power developments on soaring birds may be far more extensive than the commonly reported mortality caused by collision (Marques et al., 2014). Avoidance behaviour may suggest that soaring birds, as well as other birds, are partly able to cope with the existence of wind turbines (Marques et al., 2014). However, our results make clear that this is a simplistic interpretation and may lead to the underestimation of the real impacts of wind-power generation. We recommend that the authorities responsible for wildlife protection and wind industry regulations recognize the loss of aerial habitat caused by wind turbines and the potential associated negative impacts on soaring birds. It becomes clear from our results that individual turbines greatly differ on their impact depending on their geographical position (Fig.5), thus it is possible to significantly reduce overall impact of wind-power production with adequate planning. The method we used to map updrafts uses only data that is publicly available (Santos et al., 2017) and can be used in environmental impact assessment studies to guide the selection of low-impact locations for new wind turbines. We are convinced that wind-energy production is necessary to face global warming, but the accelerating increase of wind-power developments needs to be accompanied by science-based solutions to minimize its impacts on wildlife.

Authors' contributions

A.T.M., C.D.S., J.P.S., J.P., F.M. and M.W designed the study; C.D.S., A.-R.M, A.O. and J.P.S. collected the data; A.T.M., C.D.S. and F.H. analysed the data; A.T.M. and C.D.S. wrote the manuscript. All authors discussed the results and commented on the manuscript.

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Data accessibility

The data that support the findings of this study were included in the Supplementary Information for reviewing purposes only (file: Supporting dataset_BD kites.txt). These data are deposited in Movebank Data Repository (https://www.datarepository.movebank.org/) and will be published in case this manuscript is accepted for publication.

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Tables and figures

Figure 1. Use of the aerospace in the study area (Tarifa, Spain) by the black kites during the post-breeding migration of 2012 and 2013, and the locations of the wind turbines. Left panel: GPS locations of 130 tracked birds. Locations are only shown for birds flying (speed >1 m/s) during daylight in periods of Levanter wind (blowing from the east). Right panel: Cumulative Utilization Distribution modelled from dBBMMs. Map grid with 100m spatial resolution.

Figure 2. Estimated orographic (left) and thermal (right) uplift velocities in the study area. Orographic uplift represents deflected Levanter winds during the period of bird tracking (wind direction: mean = 97.8º, SD = 0.22, range = 83.2-116.3º; wind speed: mean = 8.8m/s, SD = 2.2, range = 4.2-12.7 m/s). Thermal uplift velocity was modelled for 231m height (mean flight height of birds) using land surface temperature estimated from a Landsat 8 OLI/TIRS image acquired in July 17^{th} 2013 (NASA Landsat Program, 2015) (available at the USGS archive, http://earthexplorer.usgs.gov/). Light hill shading was added to illustrate interaction between topography and uplift. Black dots represent wind turbines.

Figure 3. GAMM partial effects of distance to turbines, orographic uplift and thermal uplift on black kite UD. Shaded areas represent 95% confidence intervals. Modelling dataset includes grid cells up to 2 km from wind turbines.

Figure 4. Comparison between soaring suitability and the use by black kites of the areas close to wind turbines (up to 880 m of distance) and far from wind turbines (located at 1 to 2 km distance from the closest turbine). Bird use corresponds to the UD obtained directly from the dBBMM, and the soaring suitability is the UD predicted from a GLS fitted with orographic and thermal uplift velocities as predictors and the dBBMM UD as response variable (see methods for further details). The GLS model was fitted with data of grid cells placed far away from the influence of wind turbines (between 1 and 2 km distance of the closest turbine). These data was randomly divided in two datasets, the first was used to fit the GLS model (with 90% of the data) and the second was used to represent bird use far from turbines in the plot (with 10% of the data). Error bars in the plot represent 95% confidence intervals.

Figure 5. Soaring habitat affected by wind turbines during Levanter wind (blowing from the east) and western breeze. Wind turbine influence is represented as circles of 880 m radius around each turbine. Soaring suitability was estimated from a GLS model fitted with data of grid cells placed far away from the influence of wind turbines (between 1 and 2 km distance of the nearest turbine). In this model the orographic and thermal uplift velocities were the only predictors and the dBBMM UD was the response variable (see methods for further details). The UD predictions produced from the GLS model were simplified in soaring suitability categories: very high suitability – are the 10% highest UD values; high suitability – are the following highest 15% UD values; moderate suitability – are the following highest 25% UD values; and low suitability – are the lowest 50% UD values. The inset plot shows the percentage of area under the influence of wind turbines considering different scenarios of soaring suitability. Confidence intervals in the plot result from confidence intervals of fitted values of GLS model predictions.

Table 1. Summary statistics for the two models explaining black kite UD. The first model tested the effect of wind turbines on bird UD while accounting for the effects of uplift. The model was a GAMM fitted with grid-cell data at distances up to 2 km from wind turbines, and included the distance to the wind turbines, the orographic and the thermal uplift velocities as predictors. The second model was designed to evaluate soaring suitability grid cells independently of the effect of wind turbines. The model was a GLS fitted with data obtained far from the influence of wind turbines (between 1 and 2 km distance) and used only orographic and thermal uplift velocities as predictors. Both models were corrected for spatial autocorrelation (see methods for details). Fitting and cross validation Normalized Root Mean Square Error ($nRMSE_{fit}$ and $nRMSE_{cv}$) are shown for the evaluation of precision and predictive performance of the models respectively. For $nRMSE_{cv}$ we show the range of the nRMSE calculated for the 10 models produced in the cross validation procedure (see methods for further details). edf – Estimated degrees of freedom; SE – Standard error.

	Estimate	**SE**	**Z**	**edf**	**F**	**P-value**	**$nRMSE_{fit}$ (%)**	**$nRMSE_{cv}$(%)**
Model: Effect of wind turbines								
Intercept								
s(distance to turbines)						<0.001		
orographic uplift						<0.001		
thermal uplift						<0.001		
Model: Soaring suitability								
Intercept								
orographic uplift						<0.001		
thermal uplift						<0.001		