Flight altitudes of a soaring bird suggest landfill sites as power line collision hotspots

Abstract

Anthropogenic structures are increasingly encroaching wildlife habitats, creating conflicts between humans and animals. Scaling up renewable energy requires new infrastructures such as power lines, that cause high mortality among birds since they act as obstacles to flight and are used for perching and nesting, which can result in collisions or electrocutions. These interactions often endanger wildlife populations and may also result in high financial costs for companies. Flight behaviour plays a crucial role in collision risk, and the study of flight altitudes enables us to understand what drives birds to fly at collision risk altitudes. This allows the identification of high-risk areas, conditions and bird behaviours, and the implementation of mitigation measures by power line companies. In this study, we use boosted random tree modelling to identify drivers of white stork (*Ciconia ciconia*) flight altitudes and to investigate the factors that lead them to fly at collision risk altitudes. We found that the main drivers of flight altitude for this soaring bird species were time of day, distance to the nearest landfill site and cloud cover density. Bird age, habitat type and season were comparatively less important. Collision risk increases during crepuscular hours near landfill sites, also in days with high cloud cover density and during the breeding season. In recent years, hundreds to thousands of storks congregate daily at landfill sites to take advantage of the predictability and superabundance of anthropogenic food waste. Some of these sites have high density of power lines, becoming collision risk hotspots for storks and other landfill users. Despite being susceptible to collision, our results suggest that white storks can avoid power lines to a certain extent, by changing their flight altitude at ca. 80m from these structures. This study shows that the implementation of mitigation measures for existing power lines should be prioritised in areas in the vicinity of landfill sites within white stork distribution ranges, and the projection of new lines should avoid those areas. These measures would benefit species vulnerable to mortality due to power line collision, and it would also reduce associated power outages and economic costs.

Keywords: collision risk, collision hotspot, power lines, landfills, flight altitudes, mitigation measures

1. Introduction

Anthropogenic disturbance of air space is increasing, creating conflicts between human infrastructures and volant animals (Chilson et al., 2017), as is the case of birds. Along with wind turbines, buildings, communication towers and aeroplanes, overhead power lines pose a threat to avian wildlife, not only through collision and electrocution risk but also due to indirect impacts such as habitat changes, barrier effects, and the disruption of typical movement patterns (Benítez-López et al., 2010; Chilson et al., 2017). There is compelling evidence that these effects influence population dynamics (Chevallier et al., 2015; Richardson et al., 2017), and can ultimately jeopardize the long-term population viability of many species and populations (Benítez-López et al., 2010).

Worldwide, tens of millions of birds die annually due to power lines (Loss et al., 2015), making avian collisions with these structures a global conservation concern (Jenkins et al., 2010). Nevertheless, bird collision and electrocution also represent an economic concern to electricity companies by causing electrical malfunctioning, short-circuits, outages and fires. For example, in Spain alone, it is estimated that the economic impact of fauna mediated wildfires caused by power lines is of 170 to 280 thousand euros per year (Guil et al., 2018). In Italy, a 16h-blackout in 2003 originated losses of more than 1.15 billion euros (Schmidthaler and Reichl, 2016), and in the United States, power outages are estimated to cost 21 to 150 billion euros, annually (Peretto, 2010). Adding to the continuous increase in energy demand, the shift towards renewable energy to combat climate change results in a further need for energy infrastructures (Nies, 2019). Consequently, the electricity grid is growing at an annual rate of 5% (Jenkins et al., 2010), which will certainly exacerbate human-wildlife conflicts, and increase the need to find solutions that effectively reduce collision risks and associated economic costs.

A key challenge to reduce avian mortality rates driven by power line collision is to identify the factors that influence birds' flight altitudes and to assess under which circumstances birds fly at collision risk altitudes (Bernardino et al., 2018). This knowledge could be the basis for the identification and development of appropriate management strategies that could be implemented by power line companies, in order to decrease the likelihood of birds flying at collision risk heights in the vicinity of these infrastructures. This would benefit both species conservation and corporations, by reducing costs related to avifauna (Maricato et al., 2016) and promoting an environmentally friendly business (Moreira et al., 2017).

Flight altitudes, and consequently bird collision risk is influenced by both extrinsic (site-specific and line-specific) and intrinsic (species-specific) factors (Bernardino et al., 2018; Chilson et al., 2017; D'Amico et al., 2018). Despite some evidence that birds may avoid power lines by adjusting flight altitudes upward when approaching these obstacles (Luzenski et al., 2016), collision is not always prevented. Topographic variations, habitat features, weather and light conditions, as well as anthropogenic disturbance levels are considered site-specific factors; while line configuration, wire diameter and height are line-specific factors of collision risk (Bernardino et al., 2018). Topography defines orographic and thermal uplifts, with mountains and depressions providing different flyways for soaring and consequently, different flight altitudes. Habitat features associated with different land uses such as vegetation density, should also influence flight altitude, as open areas allow birds to fly lower than in forested habitats. Moreover, foraging habitats are likely associated with lower flight altitudes as birds frequently approach and leave these sites during their foraging trips. Strong winds, heavy rainfall, or fog may force birds to fly at lower altitudes due to both little visibility conditions and absence of thermal updrafts, reducing individuals ability to avoid collisions (Murphy et al., 2016b). Periods of low light levels such as twilight and night are especially dangerous when flying at low altitudes due to reduced visibility (Murphy et al., 2016b). Among intrinsic factors (species-specific), morphology, vision and behaviour can all be linked with collision risk (Martin and Shaw, 2010). Wing loading, body weight and visual capacity influence species' in-flight manoeuvrability, making large and heavy species with narrow visual fields more vulnerable to unexpected obstacles (Rayner, 1988). Behavioural susceptibility to collision risk may be related to nocturnal activity, migratory habits and gregariousness, as well as age, sex and health status (Bernardino et al., 2018). During the breeding period, collision with power lines often occurs during daily movements between foraging and nesting sites (Bernardino et al., 2018), when birds fly at lower altitudes and increase landings and take-offs. Younger and more inexperienced birds, with lower manoeuvrability (e.g., Henderson et al. 1996) and less familiar with the landscape are likely to be at higher collision risk. Finally, birds using power lines for hunting, resting, or nesting could also be more exposed to collision risk.

The white stork (*Ciconia ciconia*) is a very adaptable, opportunistic species. In recent decades white storks have established a unique relationship with the energy infrastructure (Moreira et al., 2017); this species increasingly uses electricity pylons as nesting structures (Moreira et al., 2017), however, power lines also cause high mortality rates by electrocution and collision (Garrido and Fernández-Cruz, 2003; Kaługa et al., 2011; Schaub and Pradel, 2004). Mortality can occur in two different ways, electrocution and collision. While electrocution is considered the main source of mortality for white storks (e.g. Schaub and Pradel, 2004; Kaluga et al., 2011), collision events represent an important proportion of power line driven mortality in the species (Garrido and Fernández-Cruz, 2003; Shaw et al., 2021), and as such, it should be properly addressed. In Portugal, white storks’ mortality rate driven by transmission power lines alone is estimated at 11% of the breeding population, but these numbers are likely to increase in the future, following the rapid population growth and the continuing expansion of the electrical grid (Moreira et al., 2017).

White stork numbers are increasing in Iberia, which is widely attributed to their high resiliency and behavioural plasticity to use landfill sites year-round (Gilbert et al., 2016). Estimates indicate that the probability of this species attending landfill sites is of 60% and 44% during the non-breeding and breeding season, respectively (Soriano-Redondo et al., 2021). Superabundance of anthropogenic waste from landfills provide white storks with a spatially and temporally predictable food source that greatly influences species activity and movement patterns, significantly reducing individual’s foraging time and range and ultimately enhancing overall breeding success and population growth rate (Arizaga et al., 2018; Gilbert et al., 2016). Landfills are mostly located close to areas with high human population density, thus likely to be associated with high presence and density of power lines. With thousands of storks travelling to and from landfills to forage, especially on the breeding season to feed their offspring, these sites can constitute hotspots of bird collision and significantly increase white stork mortality.

In this study, we use a large flight altitude dataset of white storks in Portugal to assess the risk of collision for this species. To do so, we (1) identify and evaluate the relative importance of potential drivers of flight altitudes as a proxy to collision risk, and specifically investigate if landfills can work as collision hotspots for this species; (2) assess reaction distances and avoidance behaviour in response to power lines; and (3) propose mitigation strategies to reduce the impact of power line associated mortality. To fulfil our first objective, we model the influence of habitat type, distance to the nearest landfill, season, age, cloud cover and time of day on flight altitude. Secondly, we use a smaller dataset on the flight altitudes of storks near power lines to assess whether storks change their flight altitudes in the proximity of these structures. Finally, we use the results of this study to propose measures to minimise mortality associated with collisions with power lines.

2. Materials and Methods

2.1 Bird capture and tracking

For this study, we collated GPS data from 34 white storks (19 juveniles and 15 adults) tagged in 2017 and 2018. Storks were captured and tagged in four areas in central-southern Portugal, along with three landfill sites (Fig.1). Juveniles were first-year birds tagged before fledging, while adults were breeding birds (>3 years old). None of the birds nested on electricity pylons. We used two models of GPS/GSM backpack loggers – Flyway 50 by Movetech Telemetry and Ornitrack-50 by Ornitela – that were attached to the storks with a Teflon harness (Gilbert et al., 2016; Soriano-Redondo et al., 2020). Loggers were programmed to transmit timestamp, position, and height with a frequency of ~20 min. See further details on individuals' tagging year and location in Table S1 and detailed methods in supplementary material. While adults were resident individuals overwintering in Portugal, all first-year juveniles migrated to African winter grounds ca. 38 days after fledging. Juvenile data was consequently trimmed to only account for the period between fledging and the moment they leave the Portuguese territory, as detailed power line data was not available outside of Portugal. The fledging date was defined as the first day of fledging after flying 50 meters away from the nest.

2.2 Assessing storks' flight altitudes

GPS tags from Ornitela and Movetech measure, respectively, the altitude above mean sea level and altitude relative to the ellipsoid. The vertical accuracy of the GPS tags was ~10m (author's unpublished data). To avoid losing precision associated with geoid undulation images resolution, we did not convert height above the ellipsoid to height above sea level. Instead, flight altitudes above ground were calculated by subtracting the ground elevation value from the height above the ellipsoid and by subtracting orthometric height to altitudes measured above mean sea level. High-resolution ellipsoid and orthometric topography images (30-meter resolution) were obtained from NASA Shuttle Radar Topography Mission (Farr et al., 2007). All fixes with ground speed below 1.39m/s (Limiñana et al., 2012; Shamoun-Baranes et al., 2011) were excluded from the analysis to select only for flight fixes. In-flight behaviour was further supported by selecting measured heights above 5m and by discarding records less than 20 minutes apart (Poessel et al., 2018). A detailed description of this section is provided in the supplementary material.

2.3 Drivers of storks' flight altitude

To determine the main drivers of flight altitude, we selected a range of potential variables (both intrinsic and extrinsic factors) based on recent literature (Bernardino et al., 2018; Chilson et al., 2017) and observed in-field behaviour of storks near anthropogenic structures. These included habitat type, distance to the nearest landfill, season, age, cloud cover and time of day (Table 1).

Habitat type was classified as foraging versus non-foraging habitat since we expected that storks flew at lower altitudes in foraging areas. Wetlands, agricultural areas and landfill sites were considered potential foraging areas (Moreira et al., 2018). Habitat type was thus used as a binomial variable considering the presence of flight fixes in foraging or non-foraging areas.

Distance to the nearest landfill was used as a predictor of flight altitude and defined as the Euclidean distance from each white stork flight fix to the closest landfill centroid. Landfills provide an all-year abundant food supply for storks and constitute important foraging areas during both the breeding and non-breeding seasons (Gilbert et al., 2016). We expected storks to fly at lower altitudes close to landfills as they approach them to feed and subsequently leave. To assess if landfill sites had higher powerline presence compared to other areas, we randomly generated 50 points in the study area. We then compared the power line presence in a 1km buffer around these sites and 11 landfills, using t-tests.

Season was divided into breeding season, between December (when adults start visiting and using nests for extended periods) and July (when most juveniles leave the nests), and non-breeding season from August to November. During the breeding season, adults make more trips between foraging areas and nesting sites to feed their offspring (Henderson et al., 1996), likely flying at lower altitudes than during the non-breeding season.

Age may also influence flight altitudes and consequently, collision risk, as juvenile birds probably have inferior thermal soaring performance and more difficulty in adjusting fine-scale movements (Harel et al., 2016). We hypothesize that juveniles fly lower than adults, with a larger proportion of collision risk altitudes.

Cloud cover was the main weather variable which could directly impact both birds' visibility and thermal uplift velocity (Mallon et al., 2016; Shamoun-Baranes et al., 2017). Thus, we used cloud cover as a proxy of visibility and potential driver of flight altitude, as it could influence white storks to fly at lower altitudes, closer to a collision risk altitude. Cloud cover at low altitude (<2km) was obtained from the Environmental-Data Automated Track Annotation system (Dodge et al., 2013) and described as a proportion of cloud covered cells, calculated based on surface pressure (Dee et al., 2011).

Time of day was used as a proxy of air temperature, light-dark cycle and thermal uplifts and defined at an hourly base. As soaring birds, storks take advantage of atmospheric vertical air currents to fly without spending much energy. These updrafts usually occur in the middle of the day when low masses of air warm up and rise (Leshem and Yom-Tov, 1996). We found the time of day and thermal uplift variables to be correlated (r_s=-0.271, p<0.0001), and consequently the time of day was favoured due to the low temporal granularity of thermal uplift data (every 6 hours). Data was filtered to only account for daylight hours according to local time and season.

2.4 Behaviour in response to power lines

To analyse white storks' flight behaviour in the vicinity of power lines, we chose flight fixes at up to 300m of a power line and a maximum altitude of 156m (four times the maximum height of a power line), as at higher altitudes there is likely no effect of power line structures on storks' flight altitude. We assessed the electrical network on the Portuguese territory, a total of approximately 88,000 km (Fig.1), and considered both transmission (high voltage lines that feed substations: 110 – 400 kV, 30 to 39 meters of height) and distribution lines (medium voltage lines that feed the individual consumers: 6 – 60kV, usually at 14 to 30 meters high) in the analyses. Distance to the nearest power line was defined as the Euclidean distance from each white stork fix to the closest line. Previous studies show that birds react at a ground distance beyond 25m from a power line (Brown and Drewien 1995, Murphy et al. 2016a). However, to the best of our knowledge, there is no information on how far white storks see and respond to the presence of overhead power lines. Thus, to be conservative, we defined 300m as the distance to search for a reaction distance of storks.

2.5 Data analysis

We implemented gradient-boosted regression trees (BRT, Friedman 2001, De'ath 2007) to model (1) the main drivers of storks flight altitude as a proxy of collision risk (with lower altitudes being associated with higher collision risk) and (2) the effects of power line distance on flight altitude to look for avoidance behaviour in the vicinity of overhead power lines. For the first model, we associated the predictors habitat type, distance to the nearest landfill, season, age, cloud cover and time of day with stork flight altitude fixes. For the second model, we used the same variables and included the distance to the nearest power line as a predictor of flight altitude, using only fixes at a maximum of 300m from a power line. BRT is a machine-learning method that offers several advantages over traditional regressions. This method has recently been widely applied in ecological studies due to its high efficiency in handling different types of variables (Fernandes et al., 2016; Leathwick et al., 2006; Moreira et al., 2018).

To reduce stochasticity caused by random sampling and bagging, we generated 100 BRT models and averaged the relative importance of each predictor, presenting standard deviations. Model performance was based on explained deviance and cross-validation correlation. After running initial exploratory models, we found the distance to the landfill variable to have intricate patterns with no ecological meaning, although it contributed to increasing model fit (see Fig S1). Such patterns usually occur when complex interactions are allowed in the model (Elith et al., 2008; Leathwick et al., 2006), and it is a common practice to impose a monotonic trend to variables in such situations (e.g. Leathwick et al. 2006, Zhang et al. 2012, Moreira et al. 2017). Consequently, we refitted the models imposing a monotonic decreasing trend to the distance to the landfill, as the trend of the unconstrained function matched the monotonic version. To show the effects of each variable on flight altitude, we fitted partial dependence plots by controlling for the other explanatory variables. Models were fitted in R (R Core Team, 2019) using "gbm" and "dismo" libraries (Greenwell et al., 2019; Hijmans et al., 2017). For each set of models, we calculated correlations (using Pearson correlation coefficient) and collinearity between predictors (using variance inflation factor statistics) and assessed spatial autocorrelation in storks' flight altitudes. We found no collinearity between predictors (VIF<1.05) and no correlation between explanatory variables (|r|<0.17). We assessed spatial autocorrelation in model residuals through correlograms (100 runs) and took it into account using Residuals Autocovariate (RAC) approach (Crase et al., 2012). Autocovariate was calculated through *autocov_dist* function from "spdep" package (Bivand and Wong, 2018) and was included in the BRT models.

3. Results

Individual white storks were tracked for an average of 180 days (SD=220) between 2017 and 2019, for a total of 6116 tracking days (Adults: mean=360, min=41, max=680; Juveniles: mean=37, min=10, max=65). Our tacking dataset included a total of 10,465 flight fixes (mean fixes/day 3.0±1.3) with mean flight altitudes of 212.39m (SD=251.9, min=5, max=1499). 26% (n=2685) of all flight fixes were in the proximity of power lines (<300m). Landfill sites were found to have a higher presence of power lines than random areas (t=4.4, df=49, p<0.0001).

3.1 Drivers of storks' flight altitude

Positive spatial autocorrelation was present in the model residuals, with maximum values within a 1.5 km radius distance. Therefore, the value was used to compute the residual autocovariate (RAC). After running the model including the autocovariate, the explained variance improved from 27% to 41%. RAC became the most important variable, but the order of importance and the trend of the initial variables did not change significantly compared to the first run (Fig S2). There was no significant spatial autocorrelation in the residuals of the autocovariate-including model.

The BRT model for drivers of storks' altitude explained 25-27% of the total deviance with a correlation coefficient of 0.47-0.48. Four of the six variables accounted for 90% of the explained variability. Time of day was the most important variable, explaining 31.6±0.5% of flight altitude. Storks flew higher at midday compared to the early morning and afternoon (Fig 2). Distance to the nearest landfill was the second most important predictor in the model (relative importance (RI) ± standard deviation, 21.2±0.33%), showing that storks flew at lower altitudes when close to landfill sites, especially in a buffer of 1km around it (Fig 2). Cloud cover and age had similar levels of importance in the model (RI: 20.4±1.10% and 17.6±0.39%, respectively). Flight altitudes decreased with higher cloud cover (Fig. 2). Flight altitude was also influenced by age, with adults flying at lower altitudes than juveniles (on average 40m lower) (Fig. 2). Additionally, season (RI: 6.26±0.17%) and habitat type (RI: 2.89±0.11%) were the least important variables in the model. Storks flew at lower altitudes during the breeding season and when overflying foraging areas (Fig. 2).

3.2 Behaviour in response to power lines

Similarly to the results found in the first model, positive spatial autocorrelation was present in the distance to power line model residuals, at up to 1.8km. Residuals autocovariate was computed at this distance radius. After running the model including the residuals autocovariate, the explained variance improved from 18% to 20%. The autocovariate was the second most important variable, but the order of importance and the trend of the initial variables did not change significantly compared to the first run (Fig S3). There was no significant spatial autocorrelation in the residuals of the autocovariate-including model.

The BRT model to evaluate flight behaviour in response to power lines explained 18-19% of the total deviance, with a correlation of 0.35-0.36. Time of day was the most important variable describing flight altitude, explaining 35.4±0.65% of the total variance, followed by the distance to the nearest power line, distance to the nearest landfill and cloud cover, with similar values (17.8± 0.83%, 15.4± 0.32% and 14.2± 0.48%, respectively). Season (8.6± 0.21%), age (4.5± 0.10%) and habitat type (4.0± 0.07%) were the least important explanatory variables. All the variables had similar shapes to the previous model (Fig 3). Storks were found to promptly change their flight altitude at ca. 80m from power lines, flying higher to cross them (Fig 3).

4. Discussion

Our results show ca. 25% of the white storks' flight locations are close to (<300 m) transmission and distribution power lines. Moreover, 62% of the flight fixes near power lines were at collision risk altitudes (between 5 and 49 meters, i.e., minimum, and maximum height of a power line, corrected for the GPS altitudinal error of ±10 meters). These findings highlight that white storks often fly at altitudes presenting a high risk of collision, which has implications for power line managers, due to increased risk of power outages and consequent economic costs.

We found that (ordered by relative importance) time of day, proximity to landfill sites, cloud cover, age, presence on foraging habitats and seasons influence white storks' flight altitudes. Our model can be used to derive an indicator of collision risk with power lines, enabling the identification of high-risk conditions and areas.

Time of day was the most important variable found to influence flight altitude. White storks are soaring birds and are consequently dependent on strong thermal convection to glide (Chevallier et al., 2010), being most active during the day and resting at night. Thermals are more likely to form when solar radiation at the earth surface is greatest, around mid-day (Leshem and Yom-Tov, 1996). Consequently, at dusk and dawn, when there are fewer thermal updrafts, and the visibility is lower, white storks fly closer to collision risk altitudes and are more prone to collide with power lines. Furthermore, often at dusk and dawn, storks commute between foraging sites and the roosting or nesting sites, which can increase collision risk in those areas. In fact, from 2016 to 2020, 56% of the white storks tracked by the authors that died due to power line collision (n=9; unpublished data) perished during twilight and night hours. Environmental conditions also influenced bird activities. As expected, cloud cover was associated with decreased flight altitudes. Cloud cover can influence flight altitudes not only through limiting visibility during twilight hours and in foggy days, but also through lower uplift velocities. This behaviour is described for other soaring birds such as turkey vultures (*Cathartes aura*) and black vultures (*Coragyps atratus*), that tend to engage less in thermal soaring when cloud cover is high (Mallon et al., 2016), and consequently, fly at lower altitudes.

Distance to the nearest landfill was the second most important variable in the model. Landfills are key foraging areas for white storks, and lower flight altitudes recorded within these areas are likely a consequence of an increase in the number of take-offs and landings. Landfill sites are often associated with a high presence of power lines in the vicinity, as most are located close to peri-urban and urban areas, thus increasing the risk of collision with these infrastructures. In Iberia, thousands of storks heavily rely on anthropogenic food subsidies across the annual cycle and the predictability and superabundance of this resource at landfills is considered responsible for the increase of the number of resident birds, that no longer migrate to their African wintering grounds (Catry et al., 2017; Gilbert et al., 2016, Soriano-Redondo et al., 2021), as well as for the overall rapid increase of population growth. In this sense, landfills may act as ecological traps for storks by attracting birds to areas with a higher risk of mortality (Plaza and Lambertucci, 2017). Beyond collision, there is evidence of high electrocution risk (Garrido and Fernández-Cruz, 2003) and anecdotal evidence of massive electrocution events in power lines around landfill sites. In 2003, two large power line mortality events occurred in landfill sites in Spain, causing the death of 125 and 60 white storks in one day (ABC, 2003a, 2003b). Furthermore, from 2016 to 2020, ca. 42% of white storks tracked by the authors that died on power lines (both from collision and electrocution) were close to landfills (<1km). The same pattern found for landfills is also likely to occur in other important feeding habitats, such as rice fields and wetlands as storks flew at lower altitudes when close to foraging habitats, compared to non-foraging habitats. During the breeding season, adults make additional foraging trips from these sites to the nest to feed their offspring, also supporting the observed lower flight altitudes during this season..

Previous studies showed that juvenile birds are more prone to collision than adults (Jenkins et al., 2010; Sundar and Choudhury, 2005), and have higher mortality rates caused by power lines (Garrido and Fernández-Cruz, 2003; Schaub and Pradel, 2004). Therefore, we expected that juvenile storks flew more at collision risk altitudes than adults, but found the opposite. A possible explanation for this unexpected finding is that although flying, on average, at higher altitudes (soaring), when approaching power lines, inexperienced birds are less able to avoid collision due to their lower manoeuvring skills and less efficient flight behaviour (Harel et al., 2016; Rotics et al., 2016), as flying at lower altitudes requires more flapping and manoeuvrability.

White storks have one of the highest mortality rates caused by power lines in Europe (Garrido and Fernández-Cruz, 2003; Kaługa et al., 2011; Moreira et al., 2017; Schaub and Pradel, 2004). In this work, we addressed the potential drivers of collision risk. Several characteristics make white storks highly vulnerable to collisions, as they are large birds with limited manoeuvrability, limited binocular fields and large blind areas (D'Amico et al., 2018; Martin and Shaw, 2010). Nonetheless, our results suggest that storks can avoid power lines to a certain extent and can reduce collision risk. When encountering power lines, storks appear to see the wires and avoid them by adjusting flight altitudes upward ca. 80m before reaching them. Even so, at that distance, because storks fly at an average speed of 10m/s when close to the reaction distance (80-150m), they only have 8s to change flight altitude and avoid collision, a short period considering their size.. Due to their low in-flight manoeuvrability, white storks' capacity to adjust paths to avoid power lines is very limited and primarily constrained by thermal uplift conditions, cloud cover and in specific circumstances of low sunlight, visibility, and high densities of lines. Previous studies showed observed in-field birds reaction to power lines beyond 25m (Brown and Drewien, 1995; Gális and Ševčík, 2019; Murphy et al., 2016a). To our knowledge, this is the first time we estimate a specific value of reaction distance of white storks to power lines. Endorsing this result, we observed that, when in the presence of transmission power lines (30 to 39m of height), storks flew higher than when close to lower distribution power lines (14 to 30m of height) (see Fig S4).

4.1 Implications on mitigation measures and future perspectives

Conflicts between roaming wildlife and humans are likely to increase with the current rapid economic and human population growth (Jenkins et al., 2010; Tucker et al., 2018). The number of anthropogenic structures, such as buildings, wind turbines, and power lines, across the globe is increasing, with major consequences for population viability of birds (Chevallier et al., 2015; Jenkins et al., 2011). Although a shift towards renewable energy is essential, it also requires the construction of further power line infrastructures, possibly exacerbating the negative impacts for wildlife. In the light of the Paris Agreement Compatible Scenarios for Energy Infrastructure goals and the Renewables Grid Initiative, which aims to find common grounds between companies, scientists and environmental organizations (Nies, 2019), the results obtained in this study have direct implications in terms of solutions for infrastructure management and the implementation of mitigation measures.

Landfill sites were found to be high-risk areas for collision. Consequently, mitigation measures applied to power lines at less than 1km of landfill sites should be considered as a priority to reduce collision of white storks, and simultaneously, the power outages and the associated economic costs. Storks form flocks of thousands of individuals in landfills, often flying at low altitudes from there to the nests in the breeding season, or between roosts and landfills during the non-breeding season at dawn or dusk, making these areas highly-prone to stork collisions (Garrido and Fernández-Cruz 2003). The best practice to prevent bird collisions with power lines in close proximity to landfill sites would be to bury existing power lines and use underground cabling for new structures (Marques et al., 2020), as power line marking is not efficient enough in preventing collisions (Bernardino et al., 2019). This encompasses much higher costs (Bernardino et al., 2018; Hall, 2013) than traditional overhead power lines, thus we recommend its implementation only within 1km of landfill sites. Alternatively, existing power lines could be potentially re-routed away from these areas, whenever possible, at a lower cost.

Moreover, measures that promote the visibility of power lines at a distance, in hours of low visibility, should be implemented in most important breeding and foraging areas, and particularly, in the surroundings of landfill sites. Several types of bird flight diverters (e.g. spirals, plates, swivels) have been used to increase the visibility of power lines (Barrientos et al., 2011; Jenkins et al., 2010; Pavón-Jordán et al., 2020), decreasing bird collision at an average of 50% (Bernardino et al., 2019), although with varying effectiveness across species. Glow-in-the-dark devices, with higher detectability at twilight, should be prioritized and their effectiveness tested. Finally, although we did not address electrocution risk in this work, securing poles against electrocution around landfill sites is also essential, as electrocution is a critical cause of death for white storks (Kaluga et al., 2011).

In this study, we did not assess the influence of power line structure-specific characteristics. Nevertheless, the effect of power line wire configuration in collisions is dependent on flight altitudes, and configurations with multiple levels of wires will increase the collision risk area, posing a higher threat to birds. The development of movement sensors to detect collisions of tracked birds proposed by Bernardino et al., 2018 would significantly help to identify power line sectors in which birds are more prone to collision and consequently to prioritize other areas in which mitigation measures should be implemented.

4.2 Study considerations and limitations

In this study, thermal and orographic updrafts explain the time of day as a primary driver of flight altitudes for soaring birds. More complex models used to predict flight altitude would require high-resolution spatial and temporal data on topographic features, weather conditions and visibility, which are rarely available at a small-time scale for long study periods. Although the GPS devices used in this study had minor location error (<5m) in a horizontal plane (authors' unpublished data), altitude measurement errors had to be taken into consideration (Péron et al., 2020; Poessel et al., 2018). Almost 34% of our original flight records were below ground values, a value considered as typical for flight height data

(Péron et al. 2017). We addressed this issue by removing fixes below a threshold (Poessel et al., 2018; Shamoun-Baranes et al., 2011) of 5m above ground level. Furthermore, the flight altitude estimation error should not influence the results of this study, as we do not evaluate specific flight altitudes, but the difference among them.

4.3 Conclusions

We show that, for the white stork, the worst condition scenario for power line collision would be flying near landfills, at dusk and dawn, with high cloud cover, during the breeding season. Landfills were found to be collision hotspots for this species. Although white stork populations are well established and expanding in Europe (Newton, 2007), the increased use of power lines as nesting sites (Moreira et al., 2018) and landfills to forage (both considered collision and electrocution hotspots) makes urgent the implementation of mitigation measures to reduce mortality caused by power lines, as landfills could potentially be acting as ecological traps for this species. These measures would benefit other bird species with poor conservation status and high power line-associated mortality rates, as well as other species that frequently use landfills, such as the threatened Egyptian vulture (*Neophron percnopterus*) (Tauler-Ametller et al., 2017), kites and gulls. Collaboration between industry partners, scientists and environmental organisations is vital to ensure that the ongoing powerline grid expansion is not detrimental to wildlife. In a win-win scenario, biodiversity conservation would coincide with the minimization of economic costs for infrastructure companies and the promotion of a biodiversity-friendly attitude (Bernardino et al., 2018; D’Amico et al., 2018).

Acknowledgements

This work was financed by the FEDER Funds through the Operational Competitiveness Factors Program — COMPETE and by National Funds through FCT – Foundation for Science and Technology within the scope of the project ‘POCI-01-0145-FEDER-028176’, by InBIO (UID/BIA/50027/2013 and POCI-01-0145-FEDER-006821), with support from the REN Biodiversity Chair, and by the National Environmental Research Council (NERC), via the EnvEast DTP, and NERC and Engineering and Physical Sciences Research Council (EPSRC), via the NEXUSS CDT Training in the Smart and Autonomous Observation of the Environment. Funding for the development of the GPS tracking devices was provided by NERC (NE/K006312), Norwich Research Park Translational Fund, University of East Anglia Innovation Funds and Earth and Life Systems Alliance funds. J.M was supported by a doctoral grant (SFRH/BD/114683/2016) and I.C., J.P.S. and F.M. by contracts DL57/2016/CP1440/CT0023, DL57/2016/CP1440/CT0021 and IF/01053/2015, respectively, from FCT.

References

ABC, 2003a. Mueren 125 cigüeñas electrocutadas en un tendido junto al vertedero de Toledo. https://www.abc.es/espana/castilla-la-mancha/toledo/abci-mueren-ciguenas-electrocutadas-tendido-junto-vertedero-toledo-200307230300-196565_noticia.html (accessed 14 August 2020)

ABC, 2003b. Aparecen otras sesenta cigüeñas muertas en el tendido de Iberdrola junto al vertedero. https://www.abc.es/espana/castilla-la-mancha/toledo/abci-aparecen-otras-sesenta-ciguenas-muertas-tendido-iberdrola-junto-vertedero-200308050300-199327_noticia.html (accessed 14 August 2020)

Arizaga, J., Resano-Mayor, J., Villanúa, D., Alonso, D., Barbarin, J.M., Herrero, A., Lekuona, J.M., Rodríguez, R., 2018. Importance of artificial stopover sites through avian migration flyways: a landfill-based assessment with the White Stork *Ciconia ciconia*. Ibis. 160, 542–553. https://doi.org/10.1111/ibi.12566

Barrientos, R., Alonso, J.C., Ponce, C., Palacín, C., 2011. Meta-analysis of the effectiveness of marked wire in reducing avian collisions with power lines: wire marking to reduce bird collisions. Conserv. Biol. 25, 893–903. https://doi.org/10.1111/j.1523-1739.2011.01699.x

Barron, D.G., Brawn, J.D., Weatherhead, P.J., 2010. Meta-analysis of transmitter effects on avian behaviour and ecology: Meta-analysis of avian transmitter effects. Methods Ecol. Evol. 1, 180–187. https://doi.org/10.1111/j.2041-210X.2010.00013.x

Benítez-López, A., Alkemade, R., Verweij, P.A., 2010. The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis. Biol. Conserv. 143, 1307–1316. https://doi.org/10.1016/j.biocon.2010.02.009

Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J.F., Marques, A.T., Martins, R.C., Shaw, J.M., Silva, J.P., Moreira, F., 2018. Bird collisions with power lines: State of the art and priority areas for research. Biol. Conserv. 222, 1–13. https://doi.org/10.1016/j.biocon.2018.02.029

Bernardino, J., Martins, R.C., Bispo, R., Moreira, F., 2019. Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies. J. Environ. Manage. 252, 109651. https://doi.org/10.1016/j.jenvman.2019.109651

Bivand, R.S., Wong, D.W.S., 2018. Comparing implementations of global and local indicators of spatial association. TEST. 27, 716–748. https://doi.org/10.1007/s11749-018-0599-x

Brown, W.M., Drewien, R.C., 1995. Evaluation of Two Power Line Markers to Reduce Crane and Waterfowl Collision Mortality. Wildl. Soc. Bull. 23, 217–227.

Catry, I., Encarnação, V., Pacheco, C., Catry, T., Tenreiro, P., Leão, F., Bally, F., Roda, S., Capela, C., Alonso, H., et al., 2017. Recent changes on migratory behaviour of the White stork (*Ciconia ciconia*) in Portugal: Towards the end of migration? Airo. 24, 28–35.

Chevallier, C., Hernández-Matías, A., Real, J., Vincent-Martin, N., Ravayrol, A., Besnard, A., 2015. Retrofitting of power lines effectively reduces mortality by electrocution in large birds: an example with the endangered Bonelli’s eagle. J. Appl. Ecol. 52, 1465–1473. https://doi.org/10.1111/1365-2664.12476

Chevallier, D., Handrich, Y., Georges, J.-Y., Baillon, F., Brossault, P., Aurouet, A., Le Maho, Y., Massemin, S., 2010. Influence of weather conditions on the flight of migrating black storks. Proc. R. Soc. B. 277, 2755–2764. https://doi.org/10.1098/rspb.2010.0422

Chilson, P.B., Frick, W.F., Kelly, J.F., Liechti, F., 2017. Aeroecology. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1007/978-3-319-68576-2

Crase, B., Liedloff, A.C., Wintle, B.A., 2012. A new method for dealing with residual spatial autocorrelation in species distribution models. Ecography. 35, 879–888. https://doi.org/10.1111/j.1600-0587.2011.07138.x

D’Amico, M., Catry, I., Martins, R.C., Ascensão, F., Barrientos, R., Moreira, F., 2018. Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines. Ambio. 47, 650–656. https://doi.org/10.1007/s13280-018-1025-z

De’ath, G., 2007. Boosted Trees for Ecological Modeling and Prediction. Ecology. 88, 243–251.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., et al., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137, 553–597. https://doi.org/10.1002/qj.828

Dodge, S., Bohrer, G., Weinzierl, R., Davidson, S.C., Kays, R., Douglas, D., Cruz, S., Han, J., Brandes, D., Wikelski, M., 2013. The environmental-data automated track annotation (Env-DATA) system: linking animal tracks with environmental data. Mov. Ecol. 1, 3. https://doi.org/10.1186/2051-3933-1-3

Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecology. 77, 802–813. https://doi.org/10.1111/j.1365-2656.2008.01390.x

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., et al., 2007. The Shuttle Radar Topography Mission. Rev. Geophys. 45, RG2004. https://doi.org/10.1029/2005RG000183

Fernandes, P.M., Monteiro-Henriques, T., Guiomar, N., Loureiro, C., Barros, A.M.G., 2016. Bottom-Up Variables Govern Large-Fire Size in Portugal. Ecosystems. 19, 1362–1375. https://doi.org/10.1007/s10021-016-0010-2

Friedman, J.H., 2001. Greedy Function Approximation: A Gradient Boosting Machine. Ann. Stat. 29, 1189–1232.

Gális, M., Ševčík, M., 2019. Monitoring of effectiveness of bird flight diverters in preventing bird mortality from powerline collisions in Slovakia. Raptor J. 13, 45–59. https://doi.org/10.2478/srj-2019-0005

Garrido, J.R., Fernández-Cruz, M., 2003. Effects of power lines on a White Stork Ciconia ciconia population in central Spain. Ardeola. 50, 191–200.

Gilbert, N.I., Correia, R.A., Silva, J.P., Pacheco, C., Catry, I., Atkinson, P.W., Gill, J.A., Franco, A.M.A., 2016. Are white storks addicted to junk food? Impacts of landfill use on the movement and behaviour of resident white storks *(Ciconia ciconia)* from a partially migratory population. Mov. Ecol. 4, 7. https://doi.org/10.1186/s40462-016-0070-0

Greenwell, B., Boehmke, B., Cunningham, J., GBM Developers, 2019. gbm: Generalized Boosted Regression Models.

Guil, F., Soria, M.Á., Margalida, A., Pérez-García, J.M., 2018. Wildfires as collateral effects of wildlife electrocution: An economic approach to the situation in Spain in recent years. Sci. Total Environ. 625, 460–469. https://doi.org/10.1016/j.scitotenv.2017.12.242

Hall, K.L., 2013. An Updated Study on the Undergrounding Of Overhead Power Lines, Out of Sight, Out of Mind 2012. Hall Energy Consulting, Inc., Washington, D.C.

Harel, R., Horvitz, N., Nathan, R., 2016. Adult vultures outperform juveniles in challenging thermal soaring conditions. Sci. Rep. 6, 27865.

Henderson, I.G., Langston, R.H.W., Clark, N.A., 1996. The response of common *terns Sterna hirundo* to power lines: An assessment of risk in relation to breeding commitment, age and wind speed. Biol. Conserv. 77, 185–192. https://doi.org/10.1016/0006-3207(95)00144-1

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2017. dismo: Species Distribution Modeling.

Jenkins, A.R., Shaw, J.M., Smallie, J.J., Gibbons, B., Visagie, R., Ryan, P.G., 2011. Estimating the impacts of power line collisions on Ludwig's Bustards *Neotis ludwigii*. Bird. Conserv. Int. 21, 303–310. https://doi.org/10.1017/S0959270911000128

Jenkins, A.R., Smallie, J.J., Diamond, M., 2010. Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. Bird. Conserv. Int. 20, 263–278. https://doi.org/10.1017/S0959270910000122

Kaługa, I., Sparks, T.H., Tryjanowski, P., 2011. Reducing death by electrocution of the white stork *Ciconia ciconia*: The end of death by electrocution. Conserv. Lett. 4, 483–487. https://doi.org/10.1111/j.1755-263X.2011.00203.x

Leathwick, J., Elith, J., Francis, M., Hastie, T., Taylor, P., 2006. Variation in demersal fish species richness in the oceans surrounding New Zealand: an analysis using boosted regression trees. Mar. Ecol Prog. Ser. 321, 267–281. https://doi.org/10.3354/meps321267

Leshem, Y., Yom-Tov, Y., 1996. The use of thermals by soaring migrants. Ibis. 138, 667–674. https://doi.org/10.1111/j.1474-919X.1996.tb04768.x

Limiñana, R., Romero, M., Mellone, U., Urios, V., 2012. Mapping the migratory routes and wintering areas of Lesser Kestrels *Falco naumanni*: new insights from satellite telemetry: Lesser Kestrel migration and wintering areas. Ibis. 154, 389–399. https://doi.org/10.1111/j.1474-919X.2011.01210.x

Loss, S.R., Will, T., Marra, P.P., 2015. Direct Mortality of Birds from Anthropogenic Causes. Annu. Rev. Ecol. Evol. Syst. 46, 99–120. https://doi.org/10.1146/annurev-ecolsys-112414-054133

Luzenski, J., Rocca, C.E., Harness, R.E., Cummings, J.L., Austin, D.D., Landon, M.A., Dwyer, J.F., 2016. Collision avoidance by migrating raptors encountering a new electric power transmission line. Condor. 118, 402–410. https://doi.org/10.1650/CONDOR-15-55.1

Mallon, J.M., Bildstein, K.L., Katzner, T.E., 2016. In-flight turbulence benefits soaring birds. Auk 133, 79–85. https://doi.org/10.1642/AUK-15-114.1

Maricato, L., Faria, R., Madeira, V., Carreira, P., de Almeida, A.T., 2016. White stork risk mitigation in high voltage electric distribution networks. Ecol. Eng. 91, 212–220. https://doi.org/10.1016/j.ecoleng.2016.02.009

Marques, A.T., Martins, R.C., Silva, J.P., Palmeirim, J.M., Moreira, F., 2020. Power line routing and configuration as major drivers of collision risk in two bustard species. Oryx. 1–10. https://doi.org/10.1017/S0030605319000292

Martin, G.R., Shaw, J.M., 2010. Bird collisions with power lines: Failing to see the way ahead? Biol. Conserv. 143, 2695–2702. https://doi.org/10.1016/j.biocon.2010.07.014

Moreira, F., Encarnação, V., Rosa, G., Gilbert, N., Infante, S., Costa, J., D’Amico, M., Martins, R.C., Catry, I., 2017. Wired: impacts of increasing power line use by a growing bird population. Environ. Res. Lett. 12, 024019. https://doi.org/10.1088/1748-9326/aa5c74

Moreira, F., Martins, R.C., Catry, I., D’Amico, M., 2018. Drivers of power line use by white storks: A case study of birds nesting on anthropogenic structures. J. Appl. Ecol. 55, 2263–2273. https://doi.org/10.1111/1365-2664.13149

Murphy, R.K., Dwyer, J.F., Mojica, E.K., McPherron, M.M., Harness, R.E., 2016a. Reactions of Sandhill Cranes Approaching a Marked Transmission Power Line. J. Fish Wildl. Manag. 7, 480–489. https://doi.org/10.3996/052016-JFWM-037

Murphy, R.K., Mojica, E.K., Dwyer, J.F., McPherron, M.M., Wright, G.D., Harness, R.E., Pandey, A.K., Serbousek, K.L., 2016b. Crippling and Nocturnal Biases in a Study of Sandhill Crane (*Grus canadensis*) Collisions with a Transmission Line. Waterbirds. 39, 312–317. https://doi.org/10.1675/063.039.0312

Newton, I., 2007. Recent changes in bird migrations, in: Newton, I., Brockie, K. (Eds.), The Migration Ecology of Birds. Elsevier, London, pp. 617–637.

Nies, S., 2019. The European Energy Transition: Actors, Factors, Sectors, European Energy Studies. Claeys & Casteels, Deventer, Netherlands.

Pavón-Jordán, D., Stokke, B.G., Åström, J., Bevanger, K., Hamre, Ø., Torsæter, E., May, R., 2020. Do birds respond to spiral markers on overhead wires of a high-voltage power line? Insights from a dedicated avian radar. Glob. Ecol. Conserv. e01363. https://doi.org/10.1016/j.gecco.2020.e01363

Peretto, L., 2010. The role of measurements in the smart grid era. IEEE Instrum. Meas. Mag. 13, 22–25. https://doi.org/10.1109/MIM.2010.5475163

Péron, G., Calabrese, J.M., Duriez, O., Fleming, C.H., García-Jiménez, R., Johnston, A., Lambertucci, S.A., Safi, K., Shepard, E.L.C., 2020. The challenges of estimating the distribution of flight heights from telemetry or altimetry data. Anim. Biotelemetry. 8, 5. https://doi.org/10.1186/s40317-020-00194-z

Péron, G., Fleming, C.H., Duriez, O., Fluhr, J., Itty, C., Lambertucci, S., Safi, K., Shepard, E.L.C., Calabrese, J.M., 2017. The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. J. Appl. Ecol. 54, 1895–1906. https://doi.org/10.1111/1365-2664.12909

Plaza, P.I., Lambertucci, S.A., 2017. How are garbage dumps impacting vertebrate demography, health, and conservation? Glob. Ecol. Conserv. 12, 9–20. https://doi.org/10.1016/j.gecco.2017.08.002

Poessel, S.A., Duerr, A.E., Hall, J.C., Braham, M.A., Katzner, T.E., 2018. Improving estimation of flight altitude in wildlife telemetry studies. J. Appl. Ecol. 55, 2064–2070. https://doi.org/10.1111/1365-2664.13135

R Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rayner, J.M.V., 1988. Form and Function in Avian Flight, in: Johnston, R.F. (Ed.), Current Ornithology. Springer US, Boston, MA, pp. 1–66.

Richardson, M.L., Wilson, B.A., Aiuto, D.A.S., Crosby, J.E., Alonso, A., Dallmeier, F., Golinski, G.K., 2017. A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation. Biodivers. Conserv. 26, 1801–1815. https://doi.org/10.1007/s10531-017-1341-9

Rotics, S., Kaatz, M., Resheff, Y.S., Turjeman, S.F., Zurell, D., Sapir, N., Eggers, U., Flack, A., Fiedler, W., Jeltsch, F., et al., 2016. The challenges of the first migration: movement and behaviour of juvenile vs. adult white storks with insights regarding juvenile mortality. J. Anim. Ecol. 85, 938–947. https://doi.org/10.1111/1365-2656.12525

Schaub, M., Pradel, R., 2004. Assessing the Relative Importance of Different Sources of Mortality from Recoveries of Marked Animals. Ecology. 85, 930–938. https://doi.org/10.1890/03-0012

Schmidthaler, M., Reichl, J., 2016. Assessing the socio-economic effects of power outages ad hoc. Comput. Sci. Res. Dev. 31, 157–161. https://doi.org/10.1007/s00450-014-0281-9

Shamoun-Baranes, J., Bouten, W., Camphuysen, C.J., Baaij, E., 2011. Riding the tide: intriguing observations of gulls resting at sea during breeding: Gulls riding the tide at sea. Ibis. 153, 411–415. https://doi.org/10.1111/j.1474-919X.2010.01096.x

Shamoun-Baranes, J., Liechti, F., Vansteelant, W.M.G., 2017. Atmospheric conditions create freeways, detours and tailbacks for migrating birds. J. Comp. Physiol. A. 203, 509–529. https://doi.org/10.1007/s00359-017-1181-9

Shaw, J. M., Reid, T. A., Gibbons, B. K., Pretorius, M., Jenkins, A. R., Visagie, R., Michael, M. D., Ryan, P. G., 2021. A large-scale experiment demonstrates line marking reduces power line collision mortality for large terrestrial birds, but not bustards, in the Karoo, South Africa. Condor, 123, 1–10. https://doi.org/10.1093/ornithapp/duaa067

Soriano-Redondo, A., Acácio, M., Franco, A.M.A., Herlander Martins, B., Moreira, F., Rogerson, K., Catry, I., 2020. Testing alternative methods for estimation of bird migration phenology from GPS tracking data. Ibis. 162, 581–588. https://doi.org/10.1111/ibi.12809

Soriano-Redondo, A., Franco, A.M.A., Acácio, M., Martins, B.H., Moreira, F., Catry, I., 2021. Flying the extra mile pays-off: foraging on anthropogenic waste as a time and energy-saving strategy in a generalist bird. Sci Total Environ 146843. https://doi.org/10.1016/j.scitotenv.2021.146843

Sundar, K.S.G., Choudhury, B.C., 2005. Mortality of sarus cranes (*Grus antigone*) due to electricity wires in Uttar Pradesh, India. Envir. Conserv. 32, 260–269. https://doi.org/10.1017/S0376892905002341

Tauler-Ametller, H., Hernández-Matías, A., Pretus, J.LL., Real, J., 2017. Landfills determine the distribution of an expanding breeding population of the endangered Egyptian Vulture *Neophron percnopterus*. Ibis. 159, 757–768. https://doi.org/10.1111/ibi.12495

Tucker, M.A., Böhning-Gaese, K., Fagan, W.F., Fryxell, J.M., Van Moorter, B., Alberts, S.C., Ali, A.H., Allen, A.M., Attias, N., Avgar, T., et al., 2018. Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. Science. 359, 466–469. https://doi.org/10.1126/science.aam9712

Zhang, Y., Chen, H.Y.H., Reich, P.B., 2012. Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. J. Ecol. 100, 742–749. https://doi.org/10.1111/j.1365-2745.2011.01944.x

Table for the manuscript:

Variable	Description	Descriptive Statistics (mean±SD, min, max)	
		Flight altitude drivers	Avoidance behaviour
Habitat	Foraging (wetlands, agricultural areas, landfill sites); Non-foraging (Forest, water bodies, shrublands)	F: 8163 obs. NF: 2302 obs.	F:2159 obs. NF: 526 obs.
Distance to landfill	Distance (km) to the closest landfill	12.2±11 (0.01, 51.77)	6.9±8.0 (0.01, 47.6)
Season	Breeding (December - July); Non-breeding (August - November)	B: 8720 obs. NB: 1745 obs.	B: 2212 obs. NB: 473 obs.
Age	Adult (> 3 years); Juvenile (1st year)	A: 7756 obs. J: 2709 obs.	A: 2262 obs, J: 423 obs.
Cloud cover	The proportion of the model grid cell covered by cloud occurring in low levels of the troposphere (0-1)	0.08±0.17 (0, 0.99)	0.1±0.18 (0, 0.99)
Time of day	Hour of day (hourly)	13±3 (4, 20)	12.5±3.5 (4, 20)
Distance to power line	Distance (m) to the closest power line	-	146.1±83.1 (0.18, 299.98)

Table 1. Description and descriptive statistics (mean, standard deviation, minimum and maximum values) of the explanatory variables for the flight altitude drivers and avoidance behaviour near power lines models.