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RESEARCH ARTICLE

The Global Energy Transition: Ecological Impact, Mitigation and Restoration

Flight behaviour of Red Kites within their breeding area in relation to local weather variables: Conclusions with regard to wind turbine collision mitigation

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Abstract

1. Birds and bats are prone to collisions with wind turbines. To reduce the number of bat collisions, weather variables are commonly used to shut down wind turbines when a certain constellation of weather variables occurs. Such a general approach might also be interesting to mitigate raptor collisions. Studies on the relationship between flight behaviour and weather variables are needed.
2. To investigate the flight behaviour of raptors within their breeding area in relation to local weather variables, we used high resolution data of flight tracks of Red Kites collected on a wind energy test site (Germany). Birds were tracked with a laser range finder (LRF) or with Global Positioning System (GPS) transmitters. Weather variables were continuously registered on site. We used generalised linear mixed models to analyse the influence of weather variables and of the measurement method on different flight parameters. Furthermore, we investigated the probability of flying within a virtual rotor height range defined by three hub heights (84, 94 and 140 m; diameter: 112 m).
3. The median flight altitude measured by LRF (52.5 m, 95% CI: 44.9–61.0, $N=2511$) was on average 25 m higher than the corrected one resulting from GPS (27.8 m, 95% CI: 24.7–31.2, $N=6792$). Flight speed also differed between methods (GPS: 29.2 km/h, 95% CI: 28.2–30.3 km/h; LRF: 25.1 km/h, 95% CI: 24.0–26.3 km/h). The effects of the weather variables were weak. Birds tended to fly less and lower during wet (humid, rainy or foggy) than dry weather, and lower during strong than weak winds. Probabilities of flying within a height range of virtual rotors increased with decreasing hub height, and hence ground clearance.
4. *Synthesis and applications*: Flight behaviour was highly variable. Flights occurred during all weather conditions at different altitudes throughout the day over the entire season. Further research into the relationship between flight behaviour, weather variables, collisions and other factors is needed as a basis for developing shutdown regimes generally suitable for raptors. The mean flight altitude and

speed differed between the measurement methods. Any values resulting from studies should be interpreted in the context of the method.

KEYWORDS
collision, curtailment, mitigation, satellite telemetry, wind turbine

1 | INTRODUCTION

Currently, the energy sector contributes a high proportion of global greenhouse gas emissions, and the transition to a low-carbon energy sector is identified as a key driver to mitigate climate change (IRENA, 2021). As a result, the development of wind power plants is globally promoted to increase installed capacity each year (GWEC, 2023). However, the negative impacts of wind turbines on biodiversity are known (Bennun et al., 2021). Among others, birds and bats are prone to fatal collisions at rotor blades of wind turbines (Marques et al., 2014).

For bats, collision rates and curtailment time have been shown to be predicted with reasonable precision, since the activity of different bat species is in general closely correlated with seasonal and diurnal activity, wind speed and air temperature (e.g. Behr et al., 2023; Voigt et al., 2022). Linking a curtailment algorithm with weather variables like wind speed or air temperature can be done relatively easily, as these variables are usually measured at wind turbines (Barré et al., 2023; Behr et al., 2023). Of that, the question arises whether such a general approach would also be suitable for birds. The idea of including weather conditions to optimise the curtailment of wind turbines for birds was discussed in Germany (Schreiber, 2017). However, experts were critical, as there is a lack of precise data for many bird species (KNE, 2018).

Depending on season and topography, small birds like passerines are at least as prone to collisions (e.g. Aschwanden et al., 2018) as large birds like raptors. However, raptors especially are a major concern in public and scientific awareness given their longevity, low reproduction speed and hence their sensitivity to additional mortality causing population declines (Marques et al., 2014; Watson et al., 2018). In Europe, the endemic Red Kite especially is a major issue. A comprehensive project was launched to quantify the main causes of Red Kite mortality in the EU (European Commission, 2019). Among other causes, the species is also vulnerable to collisions at wind turbines, especially at the breeding sites (Bellebaum et al., 2013).

In the current study, we investigate the flight behaviour of Red Kites within their breeding area in relation to local weather variables. Data on Red Kite flight behaviour and meteorological data were collected at a test site in southern Germany. We registered high-resolution three-dimensional flight tracks of Red Kites with a Laser Range Finder and with solar panel GPS transmitters fixed on the back of four Red Kites. The main questions were (1) how locally measured weather variables influence the so-called flight parameters individual flight activity, flight altitude and flight speed of Red Kites and (2) how is the probability that birds are flying within a virtual wind turbine rotor height range (Vestas V112-3.0 MW). The virtual height range was defined by three hub heights (84, 94 and 140 m), resulting in different ground clearances (28, 38 and 84 m). Beside the classically used weather variables wind speed, temperature and precipitation, we also included horizontal and vertical visibility because raptors strongly rely on visual orientation during foraging flights (Potier et al., 2018). As bird flight parameters are of growing scientific interest in terms of generally suitable potential mitigation measures or to feed bird collision risk models like the Band model (Band, 2012; Masden & Cook, 2016), our results are descriptively discussed together with methodological aspects of measurements.

2 | MATERIALS AND METHODS

2.1 | Study area, background, species and wind turbines

The study area is located in Germany on the plateau of the Swabian Alb about 50 km to the east-southeast from the city of Stuttgart (N 48.664, E 9.838, 660 m a.s.l., federal state of Baden-Württemberg). In this area, the Wind Energy Research Cluster South (WindForS) has initiated a wind energy test site in a topographically complex terrain. With its infrastructure and measuring equipment, the test field operated by the Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) is also available for nature conservation research (see Appendix S1 in Supporting Information). The present work emerged from the framework of the project 'NatForWINSENT' (Nature Conservation Research at the Wind Test Site). The basic scope of this project is the planning and testing of measures for the mitigation of bird and bat collisions at wind turbines. In this area, the Red Kite, *Milvus milvus*, is a common species that is generally present between mid-February and the beginning of November (Hölzinger & Bauer, 2021). Typically, three to five nesting sites were occupied within a radius of 3 km around the test site. Ethical approval with the permission for trapping and attaching transmitters on Red Kites was granted by the Regierungspräsidium Stuttgart, Referat 35 Veterinärwesen, Lebensmittelüberwachung (permits 35-9185.81/G-18/31 and RPS35-9185-99/373) and Referat 55 Naturschutz Recht (permit 55-8850-.68/GP/ZSW Stuttgart).

During the time of data collection for the current study, there were no wind turbines on the test site (pre-construction). To define the virtual height range affected by wind turbine rotors, we chose the dimensions of a typical onshore wind turbine (Vestas V112-3.0 MW) that are commercially available with three different hub heights (84, 94 and 140 m) and a rotor diameter of 112 m (Vestas, 2012). The upper height passed by the rotor tips depending on hub height is at 140, 150 and 196 m and the lowest height passed by the rotor tips (ground clearance) is at 28, 38 and 84 m.

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2.2 | Data collection

2.2.1 | Laser range finder (LRF)

One method of collecting individual flight tracks of Red Kites of unknown age or sex was the localisation of Red Kites with a Laser Range Finder (LRF, Vector Aero 21), which was connected to a laptop to visualise the flight paths and save the data. Birds were manually tracked, positions were digitally recorded (distance, azimuth, elevation, xyz-coordinates and timestamp) and plausibility of localisations was checked visually. The Red Kites were tracked from the centre of the test field during 65 selected days for a total of 225 h between 25 March 2019 and 28 June 2021 resulting in approximately 1000 tracks consisting of 15,000 flight localisations (Appendix S2). The LRF was calibrated and the accuracy of the measurements (xyz coordinates) was regularly checked by measuring objects of known position and height (Appendix S3).

2.2.2 | Telemetry (GPS)

To obtain continuous high-resolution tracks, the adult Red Kites were equipped with satellite telemetry tags. GPS transmitters (OrniTrack E25B 3G) were fixed with a backpack harness on four breeding birds (2 males and 2 females, Appendix S1). GPS transmitters are equipped with a solar panel for battery recharge and an altimeter. Data were collected between 20 May 2019 and 21 October 2021 (Table 1).

GPS transmitters fixed their positions during daylight every 5 s within the core of the study area (inner geofence, Appendix S1) and every 10 s within an extended core area (outer geofence, Appendix S1) and every 2 min outside of the core areas when the charge state of the batteries was 75%–100%. The frequency of GPS-fixes was reduced when the charge state of batteries was less than 75%.

GPS data can be inaccurate, especially on the *z*-axis (e.g. Poessel et al., 2018). We included only the positions that were fixed based on at least four satellites with a HDOP (horizontal dilution of precision) of ≤2 (e.g. Poessel et al., 2018). The flight altitude recorded by the barometric altimeter on the GPS device was corrected by local air pressure. All analyses, including flight altitudes, are based on corrected values. The accuracy of the corrected flight altitude was checked on the basis of localisations registered at known height (Appendix S3).

There is no perfect method to assign single positions to a certain behaviour ('stationary' or 'flying', Poessel et al., 2018). We decided to classify single positions as stationary when the corrected altitude was lower than 30 m agl with a speed of less than 8 km/h. Data included 217,230 flight positions and 218,730 stationary positions in total within the study area.

2.3 | Meteorological data

Weather variables were measured directly at the test site by sensors on two meteorological masts (height 100 m, about 130 m NW and NE in relation to the centre of the test site, Table 2, Appendix S1) mounted at different heights and with a ceilometer (Lufft CHM 15K). Of the data measured at the masts, we mainly used the data of the NW mast. If data were missing, we filled the data gaps with data measured at the same height of the other mast (NE).

The ceilometer was located about 250 m north-west of the test site. For the analyses, we used the vertical visibility (in meters up to 3000 m), the Sky Condition Index (dry, fog, rain, ice rain/snow) and the cloud cover (0/8 to 8/8). The combination of Sky Condition Index and the cloud cover we call 'weather status' with the categories 'dry and cloudless', 'dry and slightly cloudy', 'dry and cloudy', 'dry and very cloudy', 'fog', 'rain', 'ice rain/snow' (Appendix S4).

2.4 | Flight parameters and statistical analyses

2.4.1 | General statistical information

Statistical analyses were performed with software R 4.0.5 (R Core Team, 2021). We applied GLMM generalised linear mixed models using Bayesian methods as implemented in 'Stan' (Carpenter et al., 2017) which we accessed through the package 'brms' (Bürkner, 2017). In all models, the continuous predictor variables were centred to a mean of zero and scaled to a standard deviation of one (Table 3). The sine and cosine of the wind direction were used as predictors to account for its circular nature. For fitting

TABLE 1 Number of GPS-localisations (stationary and in flight) of the standardised data set (5-min interval) per breeding Red Kite and year depending on the area considered.

Transmitter ID	Sex	Periods of data included	Year	Number of localisations: Total breeding area	Number of localisations: Area test site
180909	Male	6 June–10 Nov.	2019	15,142	7528
		18 Feb.–11 Nov.	2020	30,413	20,226
180810	Male	20 May–14 Nov	2019	21,252	11,331
		18 Feb.–20 Nov.	2020	28,290	9364
		21 Feb.–8 Nov.	2021	21,367	6119
180913	Female	7 July–16 Oct.	2021	5646	1658
191777	Female	2 July–21 Oct.	2021	10,506	9252

TABLE 2 List of weather variables with sensors, measurement height above-ground level and measurement location.

Variable	Sensor	Height agl (m)	Location
Wind speed (m/s)	Thies First Class Anemometer	100	Masts NW and NE
Temperature (°C)	Thies Hygro-Thermo transmitter compact ventilated	96	Masts NW and NE
Wind direction (°)	Thies First Class Wind Direction Transmitter	86	Masts NW and NE
Humidity (%)	Thies Hygro-Thermo transmitter compact ventilated	96	Masts NW and NE
Probability of rain	Thies Precipitation Monitor 5.4103.10.000	10	Mast NE
Horizontal visibility (m)	Visibility Sensor VS2k-UMB	20	Mast NW
Air pressure (hPa)	Setra barometric pressure transducer	96	Masts NW and NE
Vertical visibility (m)	Lufft CHM 15K	0	Ceilometer
Sky Condition Index	Lufft CHM 15K	0	Ceilometer
Cloud cover (0–8)	Lufft CHM 15K	0	Ceilometer

TABLE 3 List of predictor variables in the fixed and random parts, correlation structure and distributional assumptions in the models for each response variable.

	Flight activity		Flight altitude		Flight speed		Probability for flight within rotor range[a]	
	M	C	M	C	M	C	M	C
Fixed effects								
Wind speed	L & Q	–	L & Q	–	L & Q	–	L & Q	–
Wind direction	L	–	L	–	L	–	L	–
Temperature	L & Q	–	L & Q	–	L & Q	–	L & Q	–
Humidity	L & Q	–	L	–	L & Q	–	L	–
Air pressure	L & Q	–	L	–	L & Q	–	L	–
Horizontal visibility	L & Q	–	L	–	L & Q	–	L	–
Precipitation	L & Q	–	L	–	L & Q	–	L	–
Vertical visibility	–	L & Q	–	L & Q	–	L & Q	–	L & Q
Weather state	–	F	–	F	–	F	–	F
Method	–	–	F	F	F	F	F	F
Height range	–	–	–	–	F	F	–	–
Month	F	F	–	–	–	–	–	–
Hour	F	F	–	–	–	–	–	–
Random effects								
Date	–	–	F	F	F	F	–	F
Track ID	–	–	F	F	F	F	–	F
Year_Individuum	F	F	–	–	–	–	–	–
Autocorrelation	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Transformation	–	–	Log	Log	Sqrt	Sqrt	–	–
Family	Binomial	Binomial	Gauss	Gauss	Gauss	Gauss	Bernoulli	Bernoulli

Note: M = Mast, C = Ceilometer, L = linear, Q = quadratic, F = Factor.
[a]Probability for flight within rotor range: A separate model was calculated for each of the three hub heights (84, 94 and 140 m).

the model, we used four Markov chains of length 4000 each. We used the second half of the chains to describe the posterior distributions of the model parameters. We evaluated convergence of the chains using the standard diagnostics as implemented in shinystan (Gabry & Veen, 2022). We assessed the fit of the model using graphical posterior predictive model checking. In addition, we measured temporal autocorrelation in the residuals and included a temporal autocorrelation structure in the models where necessary.

We usually modelled the influence of weather variables on response variables separately for the data set joined with meteorological data originating from meteorological masts and for the data set joined with meteorological data originating from ceilometer (Table 3). This was done due to maximisation of data availability, as meteorological data sets differed in time periods covered and in data gaps caused by technical failures.

Of the parameter estimates, we report the means and the 2.5%–97.5% quantiles of the posterior distributions. The latter two, we indicate as CI for the 'compatibility' or 'uncertainty' interval. The interval gives the range of parameter values for which the compatibility between the model and the data is high. The interval measures the uncertainty of the parameter estimates if the natural process that generated the data is reduced to the mechanics captured by our much simpler generalised linear mixed models.

2.4.2 | Individual flight activity during daylight and weather

Flight activity was determined per individual based on the full GPS-data set which was standardised to 5-min time intervals (first value selected per 5-min). We defined the hourly flight activity during daylight as the proportion of 5-min intervals per hour when a bird was flying.

The hourly flight activity was analysed using binomial logistic mixed regression models. As predictors in the fixed-effects part of the model, we included hourly average weather variables of the different sensors (Table 3). In addition, we included month (factor with 10 levels) and hour (factor with 16 levels). To account for repeated measures of the same individual and within the same year, we included a factor with one level per individual Red Kite and year as a random factor. We did not include separate effects of year and individual because not every bird was tracked in each year (Tables 1 and 3).

2.4.3 | Flight altitude or flight speed and weather

To determine flight altitude above-ground level (agl), LRF- and GPS data were imported into QGIS (3.16.8-Hannover) and joined with the digital elevation model of the local landscape (resolution 5 m). The ground level (above sea level = a.s.l.) was subtracted from the flight altitude (a.s.l.). The flight speed (ground speed) within LRF-data was calculated on the basis of the distance between each position divided by the time needed to cover the distance. Within GPS data, flight speed was directly registered by the device. Both datasets were standardised (LRF: first value per minute, GPS: first value per 5 min), compiled, and a subset of flight localisations lying on the plateau of the Swabian Alb (Appendix S1) within a radius of 2 km around the centre of the test site was selected. The timestamps of the localisations were used to join the compiled data set with the meteorological data sets. For joining, we used the nearest values of the meteorological data (10-min values).

The influence of weather variables on flight altitude and flight speed was analysed with linear mixed effects models based on a normal distribution. In addition to weather variables (Table 3), we included the method of measurement (factor with two levels: GPS, LRF) as fixed effect and the date and track ID as random effects. The flight speed models also contained the fixed effect of height range (factor with 5 levels: 0–50 m, 51–100 m, 101–150 m, 150–200 m and >200 m).

2.4.4 | Probability of flying within a virtual rotor height range and weather

Flight altitude values were used to construct for each hub height a binary variable for each point position of the standardised and compiled data set (cf. 2.4.2). The binary variable contained information on whether a localisation was outside (= lower or higher) of the height range of virtual rotors (0) or within the height range of virtual rotors (1). For each hub height, binary logistic regression models were calculated to estimate the influence of weather variables on the probability of flying within a virtual rotor height range (Table 3).

3 | RESULTS

3.1 | Individual flight activity, altitudinal distribution and flight speed

The individual flight activity of Red Kites determined based on GPS data ($N = 10{,}408$, hourly values) generally depends strongly on the hour of the day and on month (Figure 1). Individual flight activity constantly increases from 40% in the morning to almost 80% during midday and decreases towards the evening below 25% (Figure 1a). From February to July, the proportions of flight activity range from 30% to 70%, with a strong decline to 25% from August to October. Till November, flight activity is increasing again (Figure 1b).

The proportion of localisations (standardised LRF- and GPS-data combined) within the virtual height range of rotors differed depending on the hub height (Table 4). 17.7% ($N = 2551$) of the flight time occurred within 84–196 m agl (hub height 140 m), 40.1% ($N = 5785$) within 38–150 m agl (hub height 94 m), and 50.7% ($N = 7311$) within 28–140 m agl (hub height 84 m; Table 4). The model estimate of the median flight altitude measured by LRF was 52.5 m (95% CI 44.9–61.0, $N = 2511$), which was on average about 25 m higher (Figure 2a, Appendix S5) than the estimated flight altitude resulting from GPS altimeter with 27.8 m (95% CI: 24.7–31.2, $N = 6792$).

The median estimated flight speed stored by GPS transmitters was on average 29.2 km/h (95% CI: 28.2–30.3 km/h). This is higher compared to the estimated flight speed of 25.1 km/h (95% CI: 24.0–26.3 km/h) determined by LRF-data (Appendix S5). Flight

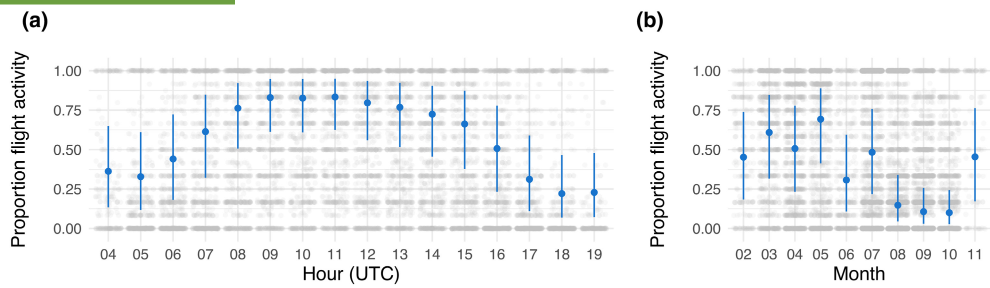

FIGURE 1 Proportion of individual flight activity depending on hour (a) and on month (b). Grey dots: Hourly proportion values of flight activity (*N* = 10,408, GPS-data). Blue dots with vertical bars are predicted values from the model keeping all other predictors at their means with 95% CI.

TABLE 4 Number and proportions of localisations (LRF and GPS-data combined) below, within and above hight range of wind turbine rotors depending on hub height (*N* = 14,414, standardised data sets).

Hub height (m)	Lower limit agl (ground clearance)	Upper limit agl	Localisations below lower limit	Localisations within rotor range	Localisations higher than upper limit
84	28	140	5655 (39.2%)	7311 (50.7%)	1448 (10.1%)
94	38	150	7364 (51.1%)	5785 (40.1%)	1265 (8.8%)
140	84	196	11,167 (77.5%)	2551 (17.7%)	696 (4.8%)

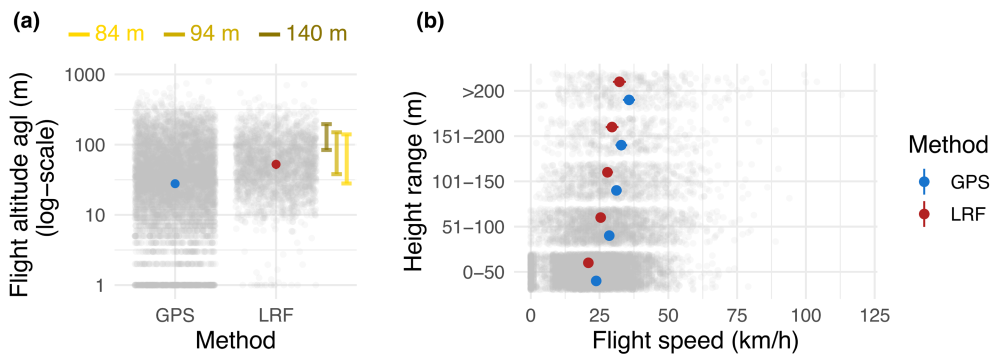

FIGURE 2 Model estimates of flight altitude with 95% CI depending on method (a) and of flight speed depending on method and height range (b). Grey dots: Localisations (GPS: *N* = 6792, LRF: *N* = 2511). T-bars: Height range of a wind turbine Vestas V112-3.0 MW with different hub heights.

speed increased with increasing height range above-ground level (Figure 2b) from 23.7 km/h at 0–50 m (95% CI: 22.5–25.1 km/h) to 35.7 km/h above 200 m (95% CI: 33.5–37.9 km/h) within GPS method and from 20.9 km/h (95% CI: 19.4–22.5 km/h) to 32.2 km/h (95% CI: 29.8–34.6 km/h) within LRF method, respectively.

3.2 | Influence of weather on individual flight activity

Individual hourly flight activity increased with increasing wind speed and decreased slightly with temperature (Figure 3a,b). Furthermore, flight activity decreased when weather conditions got wet (humidity, rain probability, weather status: rainy or foggy, Figure 3d,e,i). The CI of the estimated effects of wind direction, horizontal and vertical visibility as well as air pressure included both negative and positive effects; therefore, effect sizes for these variables remain unclear (Figure 3c,f,g,h).

3.3 | Influence of weather on flight altitude and flight speed

Flight altitude decreases with increasing wind speed (Figure 4a), humidity (Figure 4d), probability of rain (Figure 4e) and only marginally with decreasing air pressure (Figure 4g). There is almost no effect of wind direction (Figure 4c), but an increase of flight altitude with increasing horizontal visibility (Figure 4f). Temperature (Figure 4b) and vertical visibility (Figure 4h) show a curved relationship with flight altitude, with highest altitudes at average values. Flight altitude is higher during dry weather conditions than during rainy or foggy conditions (Figure 4i). There were no distinct effects of the weather

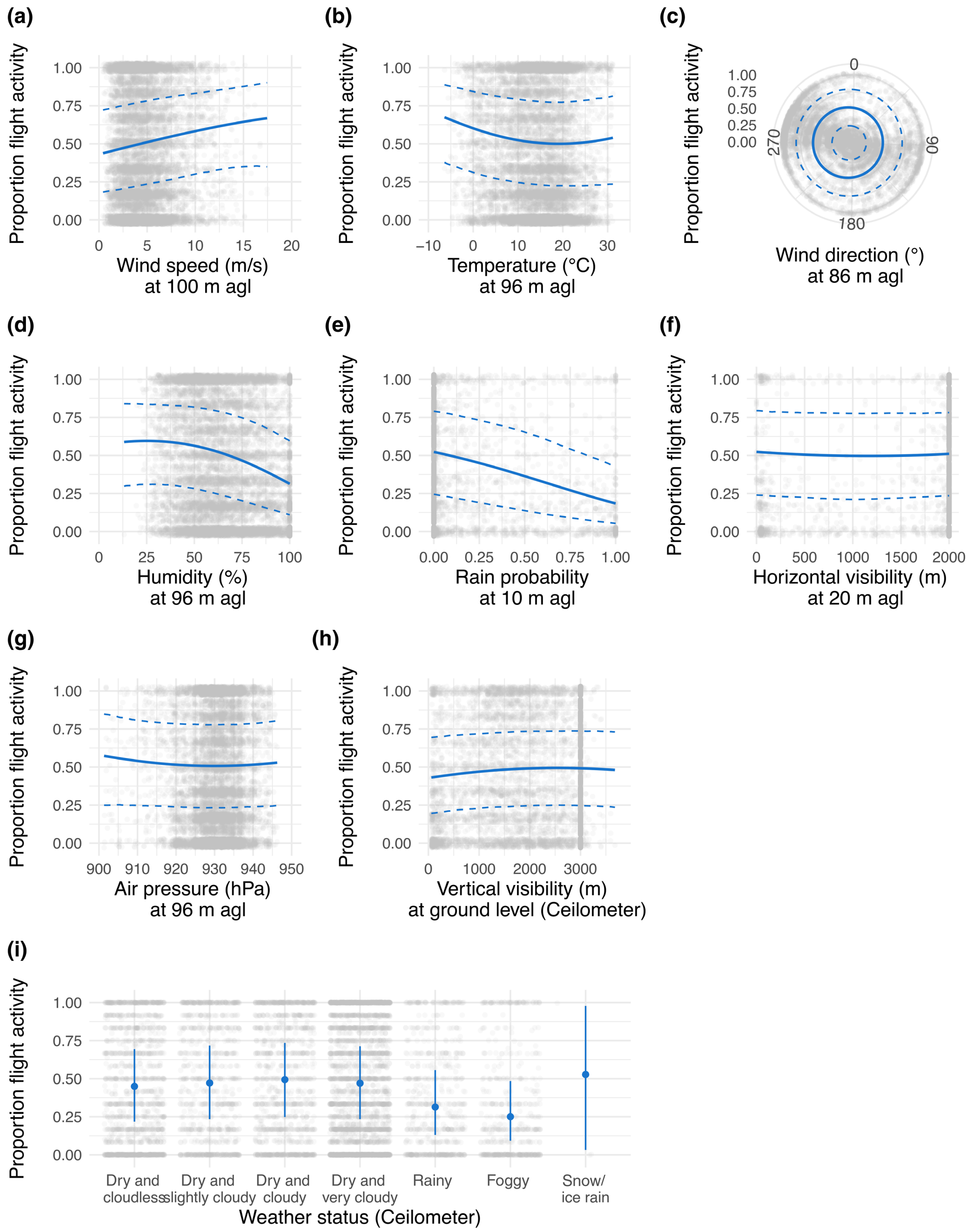

FIGURE 3 Proportion of individual flight activity depending on weather variables (a-i). Grey dots: Hourly proportion values of flight activity (N = 10,408, GPS-data). Blue dots with vertical bars are predicted values from the model keeping all other predictors at their means with 95% CI.

variables on flight speed (Appendix S6). The only effect worth mentioning is that the flight speed slightly decreased with increasing wind speed (Figure 4j).

3.4 | Influence of weather on probability of flying within a virtual rotor height range

Probabilities that Red Kites are flying within a virtual rotor height range are strongly depending on the measurement method and differed between hub height (Appendix S7). Probabilities are generally lower than 50% for all hub heights based on GPS-data and for a hub height of 140 m based on LRF-data. For hub heights of 84 and 94 m, the probabilities of flying within the virtual rotor height range based on LRF-data can reach up to 70%. The patterns of effects of weather variables on probabilities are very similar to the patterns of effects of weather variables on flight altitudes. Probabilities are, for example, decreasing with increasing wind speed, humidity and rain probability and increasing with increasing horizontal visibility.

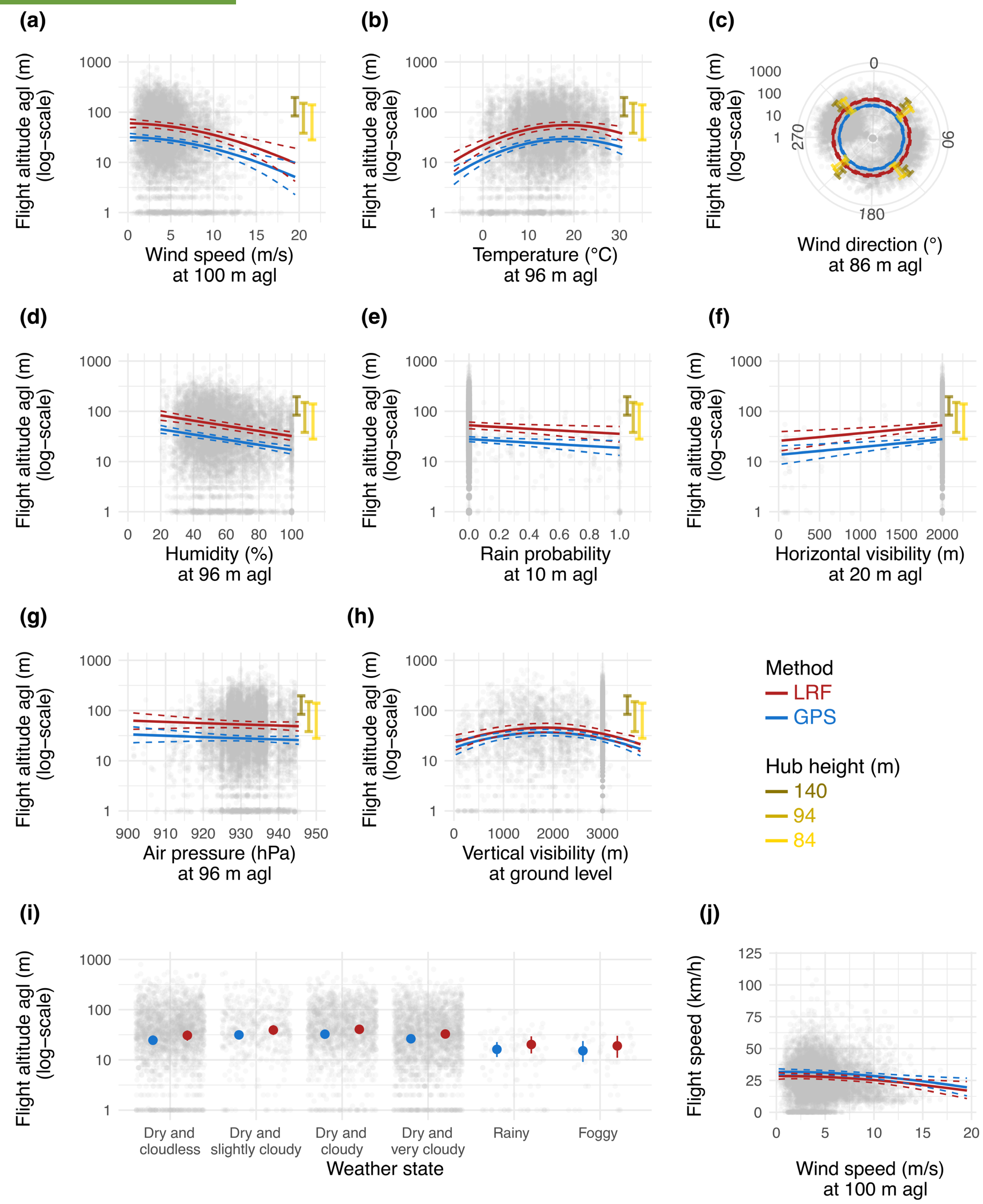

FIGURE 4 Model estimates of flight altitude (a–i) and of flight speed (j) with 95% CI depending on method and weather variables. Grey dots: Localisations (a–g: GPS [$N=6792$], LRF [$N=2511$]; h and i: GPS [$N=6792$], LRF [$N=2511$]; j: GPS [$N=6792$], LRF [$N=2360$]). T-bars: Height range of a wind turbine Vestas V112-3.0 MW at different hub heights.

4 | DISCUSSION

4.1 | Influence of measurement method on flight speed and flight altitude

Technical devices are essential to collect high-resolution data of flight trajectories in three dimensions to accurately determine flight speed and flight altitudes in relation to wind turbines. However, we must be aware that each technical device has advantages and disadvantages that need to be considered for interpretation of results. In this study, we used a military laser range finder (LRF) and satellite telemetry (GPS) to track Red Kites within their breeding area.

The flight speeds and flight altitudes resulting from the two measurement methods were different. The difference in flight speed appears to be quite small. But small differences in the parameters fed into collision risk models might have a strong influence on the results of collision risk calculations. In this context, it might be more appropriate to rely on a range of values together with statistical uncertainties instead of sticking on single mean values only.

Flight altitudes from GPS-data were about 25 m lower than flight altitudes from LRF-data. This difference is not explicable by the inaccuracy of measuring devices (cf. 2.2 and Appendix S3). There are several reasons that might contribute to this difference. GPS data are continuously collected and therefore cover all activity periods during all weather conditions. LRF-data cover only certain hours during a selection of days excluding extreme weather conditions, although we paid attention to balance observation hours and weather conditions as good as possible. Furthermore, the detection probability might be the same for the collection of all GPS-data but not for the collection of LRF-data. Detection probability for low flights observed with the LRF might have been lower than for higher flights because the background of low flying birds in relation to the observer position is often terrain (e.g. forest, meadows, crops) and not sky. It is reasonable that the optical detection and tracking of birds in front of a nonsky background is more difficult than in front of the sky (Ballester et al., 2024). Nevertheless, GPS-data are provided by four adult breeding birds only with an over representation of one individual, which also may have an influence on our results. Compared to this, more different individuals likely of different age classes and/or of nonbreeders are reflected in LRF-data (although we do not know the number of individuals). Such individuals might show a different flight behaviour compared to breeding birds. However, we expect that LRF-data also contain a remarkable proportion of tracks of untagged breeding birds, as there were usually three to five actively breeding pairs within a radius of 3 km around the test field. For the interpretation of flight altitudes of birds, generally given in studies, it is important to keep the measurement method in mind.

4.2 | Descriptive information on flight speed, flight altitudes and individual flight activity

We found an average flight speed of 27.2 km/h (=7.6 m/s), but this was dependent on the measurement method and the altitude above-ground level. Furthermore, we found that 50% of the localisations in flight (pooled over both methods) were lower than 37.3 m agl, 75% below 78.0 m agl, 90% below 140.0 m agl and 95% below 193.0 m agl. Individual flight activity (only GPS data) was highest between 9 am and 1 pm (UTC). Bruderer and Boldt (2001) tracked migratory movements of Red Kites using radar and measured ground speeds of 14–17 m/s for gliding flight and 7–21 m/s for mixed flight behaviour. Based on GPS data, Heuck et al. (2019) found that 72% of the localisations were less than 75 m agl, 81% less than 100 m and depending on breeding phase 18.3% to 29.0% of the localisations were within a height range of 80–250 m agl. Pfeiffer and Meyburg (2022) also used GPS data to analyse individual flight activity and flight altitudes of Red Kites in Germany (Thuringia). They found a median flight altitude of 45 m with a mean of 71 m agl. Flight activity also strongly depended on hour of day, with a peak between 9 am and 1 pm (UTC). Recent studies analysed a large pool of movement data collected at different locations in Germany by GPS, LRF, Radar or camera-based detection systems and found mean flight speed values close to 8.33 m/s or 9.2 m/s (Mercker et al., 2023; Reichenbach et al., 2023). The distributions of the values of the other flight parameters were also very similar to ours. All in all, despite differing collection methods and analyses as well as topographical differences, our values and distribution patterns are quite similar to the results found in other studies, which supports the representativity of our study.

4.3 | Influence of weather variables on flight parameters

Compared to previous years, where atmospheric visibility at meteorological stations was usually assessed by the eye of human observers, technical progress is increasingly allowing for automated and objective visibility measurement (Li et al., 2016; WMO, 2018). Atmospheric visibility, together with fog, is known to influence the flight behaviour of migrating birds (e.g. Becciu et al., 2021). But visibility might also influence the flight behaviour of birds on their breeding grounds. This is important, especially in the context of bird collisions at wind turbines, as it is supposed that collision risk is higher during conditions of poor visibility. To our knowledge, there is a lack of studies investigating the flight behaviour of birds within their breeding area in relation to visibility.

There were no distinct effects of horizontal or vertical visibility on the individual flight activity of the Red Kites. However, Red Kites flew less and at lower altitudes during wet weather conditions or fog represented by the influences of humidity, rain probability and weather status (rainy or foggy) compared to arid weather conditions (dry, no rain or fog). Furthermore, the flight altitude decreased with decreasing horizontal visibility. Finally, the probability that Red Kites in our breeding area fly within the virtual height range of wind turbine rotors (Vestas V112 3.0 MW) was different depending on hub height/ground clearance and was lower during wet weather conditions, fog or low horizontal visibility compared to dry weather conditions or clear horizontal visibility.

Interestingly, the influences of horizontal and vertical visibility on individual flight activity were quite weak, although there was an influence of rain and fog. The rain could be expected to reduce horizontal and vertical visibility, but our meteorological data show that during rain (weather status 'rain' of the ceilometer and 'rain probability' measured by the sensor at the meteomast) only vertical visibility is limited, while horizontal visibility is not (Appendix S8). When the weather status 'fog' is registered by the Ceilometer, both visibilities are clearly limited. We assume that visibility has to be clearly reduced in both directions to relevantly influence flight behaviour of Red Kites. In our study, visibility was rarely limited to an extent (e.g. fog) that might have been relevant for the birds. More data are needed to better understand the relationship between flight behaviour and visibility conditions, as well as the relationships between visibility and meteorological parameters.

In principle, the influence of all weather variables on the tested flight parameters was quite weak. This is in concordance with Heuck et al. (2019) who also found only weak relationships between the flight parameters of Red Kites and the weather variables. We found a positive relationship between individual flight activity and wind speed, not only by us but also by Pfeiffer and Meyburg (2022). Here, one must be aware that only data during daylight were included which represent a limited range of meteorological conditions. A large amount of for example strong winds (Appendix S9) or cold temperatures are not reflected in the data set, as birds are not active during the night or are outside of the breeding area when such conditions occur. Furthermore, in our study individual flight activity is only based on GPS data reflected by four birds with one individual overrepresented. The variation between individuals is high, which is represented by the wide credibility intervals. Therefore, the effects on individual flight activity must be interpreted carefully and more data are needed. But all in all, this means that during daylight within the breeding area, Red Kites are flying during almost all weather conditions.

Interestingly, flight altitudes decreased with increasing wind speed. Such an effect was also found by Heuck et al. (2019) and Pfeiffer and Meyburg (2022). The explanation of Pfeiffer and Meyburg (2022) is that increasing wind speeds promote orographic updrafts, which enable birds to conduct energy-saving flights at low altitudes instead of using thermal updrafts where birds reach high flight altitudes. Such an effect might also explain our findings.

In conclusion, Red Kites were flying at different altitudes during all weather conditions that occurred on their breeding grounds throughout the day during the entire season. Thus, collisions might occur under all constellations of weather variables at any wind turbine size.

4.4 | Hub height and ground clearance

Given by the altitudinal distribution of localisations, it is clear that probabilities for being within a rotor height range are increasing with decreasing hub heights, respectively, ground clearance of wind turbines in our case. In conclusion, it seems to be beneficial at least for Red Kites to increase the ground clearance of wind turbines. However, this could increase the risk of collisions for other bird species that usually move at higher altitudes above-ground level (e.g. during migration; Bruderer et al., 2018). Finally, there is simply no general optimum size of wind turbines (ground clearance, hub heights, rotor diameters) as the airspace is used by numerous species of birds, bats, and insects.

4.5 | Relationship between bird collisions and flight activity

Bird collisions are assumed to be a result from complex interactions between species characteristics (social behaviour), site (landscape, weather), and wind farm features (Marques et al., 2014). Especially inclement weather is often reported in relation to collisions of birds at human-made structures (Kerlinger et al., 2010). Our study shows that birds were flying less during wet weather conditions, but if they are flying under these conditions, a collision might be more probable because rotor blades might be less visible for birds than under clear weather conditions. As the real-time detection of collision events is not trivial, there is a lack of knowledge on the relationships between collision events, weather variables and other possible factors leading to collisions. This might be one reason why the true number of collisions within a wind farm is often not well predicted by collision risk estimations which are based on flight activity (De Lucas et al., 2008; Masden & Cook, 2016; Mercker et al., 2023; Morant et al., 2024).

Due to this lack of knowledge, the application of the mitigation hierarchy (May et al., 2017) is still an important concept. In the first step, the construction of wind turbines within habitats of species sensitive to wind turbine collisions should be avoided. In a second step, mitigation measures should be taken into account to reduce the number of collisions. As it might be difficult to get enough empirical data on the circumstances of collision events in combination with weather variables and other possible factors, real-time tracking of flight movements of raptors close to wind turbines combined with a shut-down on demand (McClure et al., 2021) could be an earlier available approach to reduce the number of collisions.

4.6 | Representativity of the study

Although the number of GPS-tagged Red Kites was small to analyse individual flight activity, the number of localisations (GPS and LRF) to investigate flight speed and altitudes within our study area was high. Therefore, we are confident that our results and conclusions are representative of comparable landscapes with similar weather conditions. Our results are one piece of the puzzle within the topic of bird collision mitigation, but more data need to be analysed (e.g. LIFE EUROKITE) as a basis for developing generalisable shutdown regimes suitable for raptors.

AUTHOR CONTRIBUTIONS

Janine Aschwanden, Herbert Stark and Felix Liechti conceived the ideas and designed methodology. Additionally, Herbert Stark collected the data and Janine Aschwanden analysed the data and wrote the manuscript. Janine Aschwanden, Herbert Stark and Felix Liechti contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

Janine Aschwanden declares no conflict of interest. Herbert Stark is a freelancer temporally employed by the ZSW. Felix Liechti is a consultant of the Swiss Birdradar Solution AG (SBRS). Both entities are working independently on the development of automatic anti-bird collision systems with a focus on large birds, to which H. Stark and F. Liechti are only marginally contributing their expertise.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study are available in the vogelwarte.ch Open Repository and Archive http://doi.org/10.5281/zenodo.11242680 (Aschwanden et al., 2024a) and in the Movebank Data Repository, https://doi.org/10.5441/001/1.338 (Aschwanden et al., 2024b).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Map test site and capture method for Red Kites.

Appendix S2. LRF-tracks.

Appendix S3. Accuracy of flight altitude.

Appendix S4. Variable 'weather status'.

Appendix S5. Altitudinal distribution and distribution of flight speed.

Appendix S6. Influence of weather variables on flight speed.

Appendix S7. Influence of weather variables on probability of flying within a virtual rotor height range.

Appendix S8. Relationships between selected weather variables (horizontal and vertical visibility, weather status, rain probability and humidity).

Appendix S9. Median wind speed during day and night per month.

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