WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

UNIVERSITÄT OSNABRÜCK

Potential collision risk of a threatened wader with wind turbines - an analysis based on high-resolution flight behaviour data

Master Thesis

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Münster, September 2023

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Abstract

Goals of energy transition towards more sustainability are leading to an accelerated expansion of wind power in many countries. Wind farm construction undoubtedly changes conditions of landscape and thus breeding habitats for many bird species. Besides all existing challenges to stop the decline of many endangered grassland birds, these developments add additional pressure on bird populations. Since land is a finite resource in Central Europe, elaborated concepts for climate protection measures are needed, which do not counteract with species conservation. Therefore, this study evaluated flight behaviour of 51 tagged Eurasian Curlews (*Numenius arquata*) concerning potential collision risk with wind turbines in NW Germany. GPS tracking data recorded in breeding season 2021 were used to evaluated (i) general information like flight activity and flight altitude per day, (ii) positional overlaps with wind turbines as well as (iii) avoidance behaviour in a vertical scale. The results revealed variations of flight behaviour throughout the day and between sexes. Low flight activity was indicated, with females spending 5.2 minutes and males 6.4 minutes per day. Average flight altitude was measured at 8 m above ground level. Further, a correlation was found associating longer flight distances with higher flight altitudes. Although the birds spent relatively little time in flight per day, the vertical overlap with the rotor height range (RHR) was 49%. Especially females showed more flight activity and performed higher flight altitudes than males at night, which can be attributed to nocturnal movements towards roosting sites. The study also discovered vertical avoidance behaviour in birds passing wind turbines with significant lower flight altitude near wind turbines. Nevertheless, there is a potential risk of collision due to large overlaps between flight altitudes and, in particular, smaller wind turbines with a low rotor tip height. Since most flights within breeding territories were conducted at low altitudes, the construction of taller wind turbines could be an appropriate measure to reduce the risk of collision. To prevent horizontal overlaps, prescribed distance criteria between turbines and breeding sites should be introduced. Further, restoration of high-quality habitats could divert the birds' attention away from turbines and reduce the need for long-flight distances including high flight altitudes.

Keywords: Eurasian Curlew *Numenius arquata*, collision prone species, GPS tracking data, flight altitude, vertical avoidance behaviour

1. Introduction

Facing challenges of climate change, many European countries take efforts to modify their energy production towards a higher degree of sustainability (Kaldellis & Zafirakis 2011, Tabassum-Abbasi et al. 2014, IPCC 2021). In Germany wind energy is the most important supplier in the field of renewable energies, with a high expansion rate in the last two decades (IEE 2019, UBA 2022). However, establishment of on- and offshore facilities is not without conflict. Concerning wildlife, especially birds are threatened in different ways: Direct impacts such as collisions with rotor blades or the vortex can affect species populations through increased mortality rates (Krijgsveld et al. 2009, Grünkorn et al. 2016). Moreover, many species evade wind turbines as disruptive elements, an indirect impact which results in abandonment of breeding territories and a reduction of available breeding habitats as well as staging sites on migration (Drewitt & Langston 2006). Grassland birds are affected in particular, as preferred habitats in open landscapes overlap with areas which suits to the demands of potential wind farm locations (Busch et al. 2017).

This circumstance increases the pressure on declining populations of many endangered species, such as the Eurasian Curlew (*Numenius arquata*, hereafter Curlew) (Pearce-Higgens et al. 2012). In Europe, this wader species breeds predominantly on agricultural grasslands and arable fields (Bauer et al. 2005, Silva-Monteiro et al. 2021). Intensive use of farmland as well as loss and fragmentation of original habitats like bogs, heathlands and wetlands resulted in a steep and critical population decline since the second half of the 20th century (Keller et al. 2020). Thus, Curlew is classified as *Near Threatened* on the European Red List (Birdlife International 2023). In Germany, total population size is estimated at 3,600–4,800 breeding pairs (Gerlach et al. 2019) and categorised as *Critically Endangered* in the national red data book due to a decline of 40% in the last five decades (Hötker et al. 2007, Ryslavy et al. 2020). The majority of the population occurs in the north-western lowlands, including parts of the federal states of Lower Saxony, Bremen and North-Rhine Westphalia (Grüneberg et al. 2013, Krüger et al. 2014).

Regarding the impacts caused by wind turbines, both direct and indirect effects are confirmed to have an influence on Curlew populations. The birds are assessed to be sensitive to wind farms by disturbance displacement and barrier movement effects (Langston & Pullan 2003) as well as threatened by on- and offshore collision during migration (Jiguet et al. 2021, Schwemmer et al. 2022). Further, it is known that turbines are usually avoided in the breeding sites (Pearce-Higgins et al. 2009). An extrapolation based on the distribution of breeding territories and wind turbine sites revealed that 4.1% of the Curlew population in Germany is potentially disturbed by wind farms, indicating that wind energy imposes a considerable pressure on the breeding population (Busch et al. 2017). However, additional decline due to the impact of wind power expansion has not been quantified. Dealing with a long living bird species that can have high survival rates as an adult (Robinson et al. 2020), strong negative population effects could thus be expected (Leopold et al. 2015).

Since the availability of land is limited in Germany, conflicts of interests between utilisation of wind power and further needs as conservations are predictable. Future research should focus on concepts, which reconcile goals of climate protection with those of conserving biodiversity. In order to achieve this, compatibility of wind power expansion and protection of collision prone species is highly important. If basic conditions of flight behaviour in the breeding sites are better known, more accurate decisions about the strategic placement of turbines can be ensured. Substantial knowledge of movement patterns is crucial to minimise potential collision risks. Especially, municipalities of districts and counties across Germany are interested in comparable insights to adapt spatial planning in their responsibility. Derived management implications could help to improve conservation efforts for this threatened wader species.

To assess the risk emanating from wind turbines and to develop measures to reduce it, fundamental and detailed knowledge of Curlews' flight behaviour is required. Therefore, this study aims to evaluate the interactions between Curlews and wind turbines at the breeding sites, including an assessment of the potential collision risk based on flight behaviour data to which the birds are exposed.

Recently, GPS tracking has proven useful to collect various information like data on migrating, foraging, resting or breeding behaviour in relatively short time (Vasilakis et al. 2016, Schwemmer et al. 2016, Schaub et al. 2020). In this study, high-resolution data, recorded in 2021, were used to evaluate the flight behaviour based on 51 GPS tagged Curlews breeding in NW Germany.

On a first step, flight activity, flight altitude, flight speed, track length, track duration as well as number of performed flights per day were determined. In addition, it was tested whether flight distances had an effect on flight altitudes and thus on the potential risk of collision. On a second step, flight behaviour was related to wind turbines and consequences for the potential risk of collision were derived. Finally, it was examined whether evasive behaviour takes place by changing flight altitudes in vicinity of wind turbines. The latter would indicate a potential strategy to mitigate collision risks. Based on the findings of this work, possible measures to reduce collision risks were derived and discussed.

2. Methods

2.1 Study area and wind turbine sites

The study was conducted in NW Germany, in the Federal States of Lower Saxony, North Rhine-Westphalia and Bremen. This region represents the main distribution area of Curlew in Germany (Gedeon et al. 2014). In spring 2020 and 2021, a total number of 86 birds was tagged in 23 subareas across a transect of approximately 250 km length, ranging from the Wadden Sea islands in the north to the Westphalian Basin in the south (Fig. 1). Breeding habitats of the studied Curlews comprise natural dune and marsh grasslands in coastal areas and different types of agricultural inland grasslands (Kämpfer & Fartmann 2022).

Data on wind turbines were provided by the Ministry for Food, Agriculture and Consumer Protection of Lower Saxony (ML 2019), the Senator for Climate Protection, Environment, Mobility, urban development and housing, State of Bremen (SKUMS 2020) and the State Office for Nature, Environment and Consumer Protection North-Rhine Westphalia (LANUV 2022).

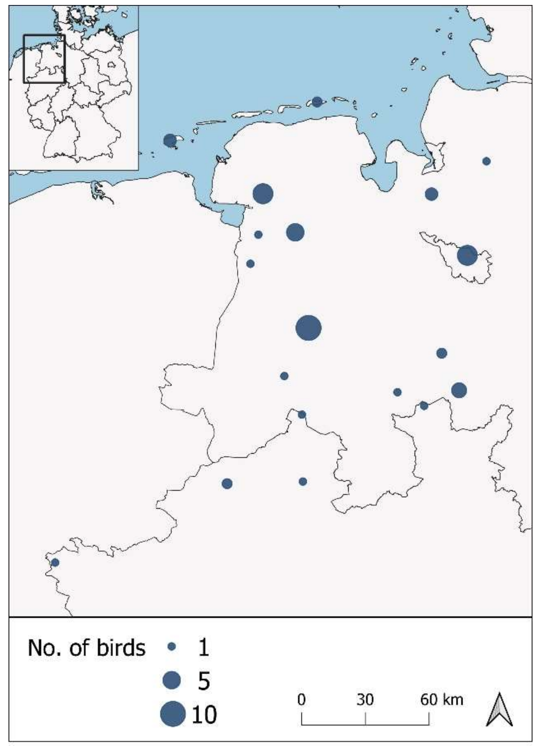

Figure 1 Distribution of the studied birds' breeding grounds (n=51) in NW Germany. Size of circles correspond to the number of tagged individuals (see legend).

Offshore wind turbines were excluded as this study is up to evaluate a correlation along breeding sites which are terrestrially located. Among onshore wind turbines, there were large differences in terms of hub height and rotor diameter. Small turbines with a total height of less than 50 m and a power output of less than 50 kW were excluded as those constructions pose a low risk due to their size and do not represent a conventional wind energy production facility in Germany (BWE 2011, MU 2021). The minimum rotor tip height of each turbine was calculated using technical characteristics such as hub height and rotor diameter. In order to achieve that each wind turbine is considered as a potential threat to the birds, the rotor height range (hereafter RHR) was then defined by the space between the total minimum and maximum height of the rotor sphere. This area was considered as a danger zone, in which the birds are threatened to be hit by rotor blades or impaired by vortex. To consider potential injuries of passing birds without being directly hit (e.g. barotrauma), an additional buffer of 5 m in both vertical directions was added (Barclay et al. 2007). Furthermore, a horizontal buffer of 200 m was placed around each turbine, to assess interaction with passing birds in an overlap zone (Vasilakis et al. 2016). Turbines located close to each other were not grouped into wind farm polygons, so that bird overflights were recorded individually for each turbine.

2.2 GPS tracking

Curlews were caught between late April and early June in 2020 and 2021, using a clap net on their nests. The birds were trapped while incubating for at least two weeks to minimise the risk of clutch abandonment. Body weight and bill length were measured to determine the sex of each individual according to Summers et al. (2013). All caught birds were marked with metal rings set by Institute of Avian Research "Vogelwarte Helgoland" and equipped with solar-powered GPS GSM transmitters (Ornitela OT-10 3G). In 2021, all individuals got additional colour rings for a better identification in the field. The backpack mounted tags were attached to the birds' body using a breast harness (Thaxter et al. 2014, Schwemmer et al. 2021). With a weight of 10 g the device was at maximum 1.7% of the birds' body mass (Kämpfer et al. 2023), which did not exceed the recommended load limit (Kenward 2001, Bodey et al. 2018). Without external disturbances such as technical errors, premature loss of the transmitter or death of the bird, shelf life is expected for two to three years until the bracket detaches by itself.

The study is based on data of breeding season in 2021. According to the average arrival and departure time of Curlews in their breeding territories, recorded GPS fixes between February 21 and July 23 were considered (Currie et al. 2001, Kämpfer et al. 2023). Since some studied birds were caught during breeding season 2021, an average residence time was determined on basis of individuals that were already equipped with transmitters in 2020 (n=23) and thus provided flight data throughout the whole season 2021.

Data were stored in the online platform Movebank (www.movebank.org). Raw data collection included time (UTC), instantaneous speed (km/h), acceleration (m/s^2), geographical position (x, y), altitude above sea level (m) and horizontal dilution of precision. The flights of the birds were considered by placing a buffer of 10 km around each nest. The radius was chosen based on a study from UK, in which a maximum activity range of breeding birds was on average 9.6 km offside their nesting sites (Bowgen et al. 2022). GPS fixes were generally recorded at 300 second intervals, except for flying birds. Here, the recording rate increased to 1–3 seconds. The switch was triggered by a 'flight detection', a setting that recognized fast movement and thus adjusted recording frequency. A battery charge level of at least 50% was a precondition for this process. Including in-flight and non-flight movements (3,767,660 GPS fixes), just 0.13% of the data that turned up in the nest-buffer selection failed to meet this condition, as solar radiation could maintain the energy supply of the battery almost permanently throughout the breeding season.

Out of 86 tagged birds, 71 individuals provided GPS data throughout breeding season 2021. Among them, high-resolution flight behaviour data were recorded by 51 individuals. The flight detection did not work properly for all transmitters, consequently, there was a lack of required information in 20 tagged birds.

Non-flight fixes were removed from the dataset, as those fixes did not represent flight behaviour and were therefore not relevant for the assessment. Outliers were detected by a sudden flight altitude difference of at least 5 m between two instantaneous tags of a flying bird (Schwemmer et al. 2022). According to the manufacturer, the accuracy of coordinates increases with higher transmission frequency (Ornitela pers. com.). Consequently, an inaccuracy and thus a scattering of coordinates was expected especially in take-off moments of a flight when transmission frequency just changed.

To exclude outliers, first, flight altitude was averaged for each flight. All fixes outside the 1.5 interquartile range of these flights were then excluded. A total of 8,980 fixes was affected, which amounts to 0.5% of the flight data. Among the outliers, 94.5% belonged to the first three tags after take-off, which is due to the transmission frequency change.

As the dataset contained short-term flight tracks, a threshold was introduced that excluded flights less equal 10 seconds to determine appropriate flight movements. Flights with a duration below this threshold were categorised as extended jump behaviour or minimal distance flights, which, however, activated the 'flight detection' of the transmitters but did not pose a potential threat with regard to collisions with wind turbines. A large amount of individual flight tracks lasted exactly 10 seconds (34%). This circumstance gave reason to suppose that the 'flight detection' was set to a fixed record time after activation by motions. Altogether, 53% of all tracks were recognised as non-proper flights, which, however, accounted for a proportion of only 4.9% of flight fixes.

All affected fixes were excluded from the investigation. Moreover, first and last detected flight tracks within the 10 km nest buffers at the beginning and the end of the breeding season were excluded, representing arrival and departure movements on migration.

2.3 Data analysis

Data processing and statistical analysis were performed with R (version 4.3.0, R Core Team 2023). For spatial references R packages 'sp' (Bivand & Pebesma 2013) and 'sf' (Pebesma 2018) were used. Statistical models were conducted using 'MuMIn' (Barton 2023) and 'lme4' (Bates et al. 2015) packages. Plotting was completed with 'ggplot2' (Wickham 2016) and visualisation as well as raster data adaption with QGIS (version 3.20.3, QGIS 2021). To prevent outliers from affecting the results, median instead of mean values were applied in all calculations of the study.

2.3.1 Flight behaviour

Data with high recording rates (1-3 seconds) were used, to determine several parameters of the birds' flight behaviour per day, including the general flight activity and the distribution of flight activity per hour. The actual flight altitude of the birds above ground level was calculated using a digital elevation model (DEM) to subtract ground level from the flight altitude above sea level. For each federal state, DEM were provided by the respective state authorities (ML 2019, SKUMS 2020, LANUV 2022) and calibrated to a 10x10 m raster. Due to inaccuracy of the vertical precision of the GPS fixes and obviously low flight height behaviour, the latter consisted to a considerable extent of negative values. These negative flight altitudes were not removed in order to avoid skewed bias as the entire data would have changed towards higher flight altitudes, combined with a loss of low flight altitudes (Péron et al. 2020, Schaub et al. 2020, Schwemmer et al. 2022).

For the evaluation of spatial data, knowledge about the accuracy of flight data was important. While horizontal precision was recorded by the transmitters, information on vertical precision was not available. The manufacturer gives an accuracy around 20 m of the elevation data of the transmitters (Ornitela pers. com.), excepted occasionally occurring outliers. Horizontal dilution of precision, recorded for each GPS position, was 1.1 ± 0.4 on average, indicating a high accuracy in horizontal GPS positions based on the geometry of available satellites (Langley 1999). In order to get a precise deviation of the vertical accuracy in flight altitudes, a calculation was completed, using the position of stationary birds to compare recorded altitudes above sea level with elevation information of the DEM at corresponding positions. As short logging intervals cause a high position accuracy (Poessel et al. 2018, Péron et al. 2020), transmission data with activated 'flight detection' (recording rate 1–3 seconds) were used. To obtain data of not flying birds, only data with a speed indication below 3.6 km/h were selected. This threshold was used as an additional condition to distinguish between flying and not flying birds (Kämpfer et al. 2023). High recording rates of stationary birds could be caused by specific motions on the ground, which triggered a malfunction and activated the 'flight detection'.

Flight speed, recorded for each GPS fix, was averaged for all flight data. Track length was detected by the distance between consecutive GPS fixes of corresponding flights and duration was calculated by the time between the first and the last timestamp of a flight. Further, the average number of flights that has been accomplished per bird and day was computed as flight frequency. For all calculations, differences in flight behaviour between the sexes were determined and analysed using the Mann-Whitney U test, as the data were not normally distributed.

2.3.2 Flight distances

To assess the dependency between flight distance and flight altitude, both parameters were compared, using a generalised linear mixed model (GLMM; Korner-Nievergelt et al. 2015; Zuur et al. 2017) with flight altitude as response variable, track distance as predictor and bird ID as random factor to correct for individual differences. In advance, the Euclidean distance between take-off and landing spots was computed of each flight. To perform a regression analysis of negative-binomial distributed flight altitude data, negative values were excluded for this analysis.

2.3.3 Vertical overlap

To evaluate vertical overlap between flying Curlews and wind turbine rotors, flight altitude was compared to the RHR of wind turbines in the study area. To investigate whether the height of wind turbines affects the overlap, newer turbines were considered separately. Information about the age of the facilities was collected in different years in the three federal states. Accordingly, the period for consideration was set from the time when most current information was available, which referred to constructions built since 2018. RHR intervals were set into relation to the flight altitude of all flight tracks. The proportion of fixes laying inside each danger zone of the rotors as well as corresponding time was then calculated. It was derived from the percentage of flight fixes in the RHR in relation to the flight activity. Additionally, distribution of flight altitudes throughout the day and differences between sexes were included.

2.3.4 Horizontal overlap

To identify an area posing a potential threat to passing Curlews, the intersection of flight tracks and wind turbine sites was realised by a buffer, covering a radius of 200 m around each facility. The proportion of fixes inside the 200 m buffers and the number of affected flights was then calculated. One individual of the studied birds was breeding within the buffer of a wind turbine, resulting in not representative flight distributions. The flight data was influenced by the proximity of the nesting site. The calculation of the proportion of the horizontal overlap was done both, including and excluding this bird.

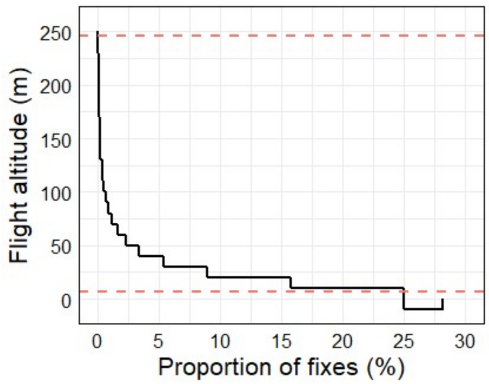

Figure 2 The proportion of fixes assigned to Curlews' flight altitude above ground level in bins of 10 m. Flight altitudes above 250 m (0.2%) and below -10 m (3.8%) are not shown. The two red horizontal lines describe the rotor height range of wind turbines in the study area, including a vertical buffer of 5 m in both directions (7–246 m).

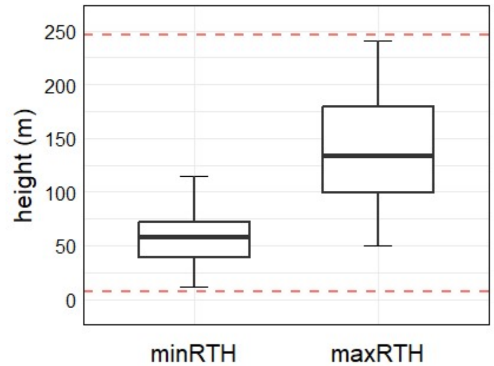

Figure 3 Proportion of minimum and maximum rotor tip height of wind turbines in the study area. The two red horizontal lines describe the rotor height range, including a vertical buffer of 5 m in both directions (7–246 m).

2.3.5 Vertical avoidance behaviour

For the assessment of intersections between Curlews and the potential danger zone of wind turbines, flight tracks that crossed the 200 m buffers of the turbines were tested for changes in flight altitude of Curlews. For this purpose, flight altitudes were compared inside and outside the buffers, using a GLMM with flight altitude as response variable, inside/outside buffer as binomial predictor and bird ID as well as flight ID as random factors. Due to the models' incompatibility with negative values, flight altitudes below ground level were excluded for this analysis.

3. Results

The dataset included 1,609,935 useable GPS flight fixes, which were composed of 27,919 separated flight tracks. Curlews were present in their breeding territories for 92 ± 35.7 days on average. During the study period no collisions with wind turbines were observed among the studied birds. Sex ratio was 24 females and 27 males. Total data transmission varied between 257 and 200,465 GPS fixes per bird throughout the whole study period, without significant difference between sexes. The comparison between altitude information of stationary birds and the DEM was completed considering 957,380 fixes with a vertical precision of 10.9 ± 17.5 m. Consequently, the vertical inaccuracy of the GPS fixes was supposed to be about 11 m.

The selection of wind turbines resulted in 7,103 facilities, distributed in the entire study area. Due to the large number of different construction types, the RHR extended over a wide range between 7 m and 246 m above ground level, including a vertical buffer of 5 m in both directions (Fig. 3). The RHR of newer facilities built since 2018 shifted slightly upwards, to 13 and 246 m.

3.1 Flight behaviour

Curlews spent only a short time flying and stayed on the ground most of the day. The average flight time per day was 5.7 minutes. No significant difference in flight activity was found between the sexes (Table 1). However, flight activity was not evenly distributed throughout the day.

Table 1 Median values (± standard deviation) of different flight behaviour parameters of Curlews (n=51) per day within a radius of 10 km around the nests during breeding season 2021. Differences between females and males were tested using the Mann–Whitney U test. Significance levels are indicated as follows: n.s. P > 0.05, * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001

Parameter	Median ± SD	Range	P
Flight activity (min)	5.7 ± 5.4	1.4 - 23.7	
Female	5.2 ± 4.2	1.9 - 22.7	n.s.
Male	6.4 ± 6.1	1.4 - 23.7	
Flight altitude (m above ground level)	8 ± 9.3	-2 - 46	
Female	13 ± 10.9	-1 - 46	**
Male	4 ± 5.7	-2 - 19	
Distance of single flights (m)	205.8 ± 828.4	0.3 - 14,406.6	
Female	220.5 ± 1,025.4	4.6 - 14,406.6	***
Male	201.2 ± 737.3	0.3 - 12,475.8	
Track length (m)	334.2 ± 1,170.5	43.1 - 27,051.3	
Female	349.4 ± 1,339.4	43.1 - 27,051.3	***
Male	327.7 ± 1,097.8	43.8 - 22,644.3	
Duration of single flights (sec)	31 ± 88.1	10 - 2,183	
Female	31 ± 101	10 - 2,183	n.s.
Male	30 ± 82.6	10 - 2,010	
No. of flights	7 ± 10.5	1 - 91	
Female	5 ± 5.2	1 - 34	***
Male	10 ± 12.4	1 - 91	
Flight speed (km/h)	11.4 ± 3.9	3.6 - 37.8	
Female	11.9 ± 3.8	3.6 - 36.7	***
Male	11.1 ± 3.9	3.6 - 37.8	

While males showed a higher flight activity between 4 am and 7 pm, females flew comparatively more in the evening hours and at night (Fig. 4). With 10 ± 12.4 flights per day, males performed approximately twice as many flights as females with 5 ± 5.2 flights on average (Table 1). Average flight altitude of Curlews was 8 ± 9.3 m above ground level. A significant difference in flight altitude was found between females and males (Table 1). The distribution of flight altitudes was wide ranging between -137 and 457 m above ground level. In total, 29.1% of the fixes were recorded below ground level. These negative altitudes averaged at -5 m. Considering the accuracy of 11 m, 88% of the negative flight altitudes were within the corresponding tolerance range between -11 and 0 m to the allocated ground level.

3.2 Flight distances

GLMM analysis showed a significant correlation in dependence on flight distances and flight altitudes (Fig. 6). This means that birds soared and flew at higher altitudes due to extended flight distances. It was found that flight distances of females were significantly longer than those of males. (Table 1). Regarding the occurrence of extended flights throughout the day, highest distances were recognised between 3–4 am and 7–8 pm by females (Fig. 8).

3.3 Vertical overlap

49.6% of all GPS flight fixes were recorded within the RHR and in 52.6% of flights, flight altitude reached the potential danger zone of the rotors at least once. This corresponds to a duration time in the potential danger zone of 2.8 minutes per day. Considering only newer turbine types with higher RHR, the proportion of GPS fixes within the potential danger zone decreased to 37.1% of GPS fixes and 35.7% flights that reached the danger zone at least once. Accordingly, the duration time per bird and day dropped to 2.1 minutes. Throughout a day, highest flight altitudes were measured at night, especially in female individuals (Fig. 5).

3.4 Horizontal overlap

Out of 51 studied birds, 16 individuals (10 females and 6 males) showed flights, which intersected the 200 m buffer around the wind turbine towers. 101,392 GPS flight fixes were recorded near wind turbines, representing 2,858 flight tracks and accounting for 6.3% of the total flight data. The proportion of flight fixes of individual birds within the buffer varied between 0.005 and 48.1%. The bird, which nested inside the 200 m buffer of a wind turbine, accounted for 95.1% of the flight fixes around wind turbines. For other individuals, only 4,970 GPS fixes were recorded in 209 flight tracks, representing 0.35% of the flight data.

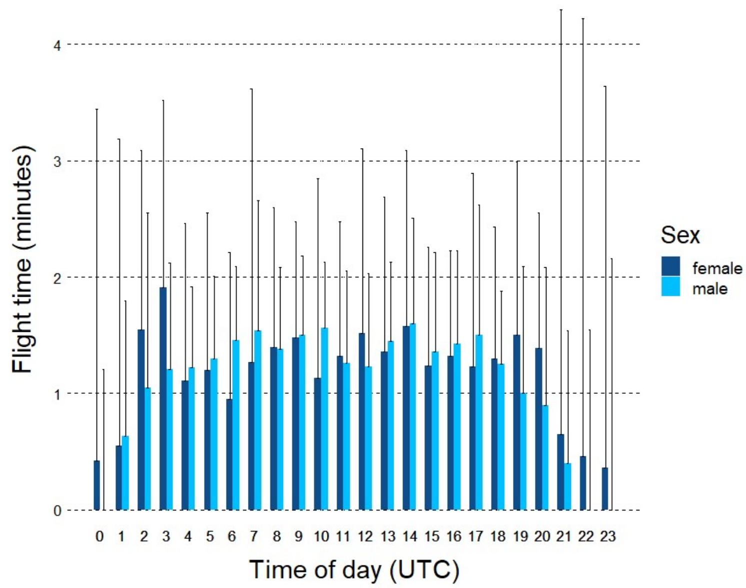

Figure 4 Curlews' hourly distribution of flight activity and standard deviation throughout the day during breeding season for females (red, n=24) and males (blue, n=27).

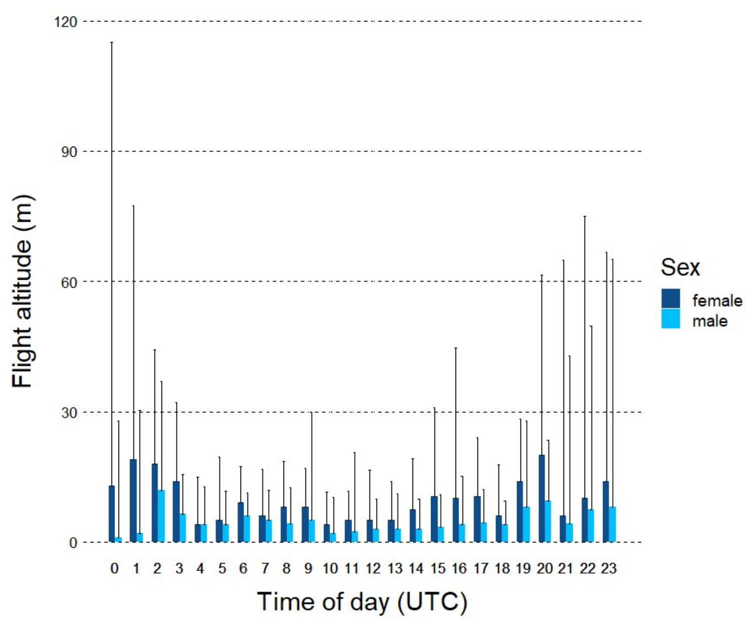

Figure 5 Curlews' hourly distribution of flight altitude and standard deviation throughout the day during breeding season for females (red, n=24) and males (blue, n=27).

3.5 Vertical avoidance behaviour

The result of GLMM comparing flight altitudes inside the 200 m buffers and corresponding tracks outside those buffers revealed a difference in flight altitudes. At 9 ± 21.4 m, the flight altitudes in the turbine buffers were significantly lower than the flight altitudes outside the buffers, which were 22 ± 37.7 m (Fig. 7). The bird which was breeding inside the 200 m buffer showed an identical adaption of flight altitudes inside and outside the buffer zones with lower flight heights in the buffer.

4. Discussion

The evaluation of the transmitter data showed varying flight activity of Curlews throughout the day. While most flights occurred during day, especially females performed more flights at night. Although the time the birds spent in flight was generally low, the vertical overlap with the RHR was comparatively high at 49%, which is due to the low minimum rotor tip height of many wind turbines. Moreover, the dependence of flight altitude and flight distance showed that the home range of the birds in the breeding area has a decisive influence on the potential collision risk by higher altitudes with increasing distances. In response to the presence of wind turbines, the birds adjusted their flight heights to lower ranges in order to avoid collisions.

4.1 Flight behaviour

Flights were performed in an average flight altitude of 8 ± 9.3 m and with an average flight speed of 11.4 ± 3.9 km/h. Compared to flight information collected during migration, the birds moved both lower and slower in the breeding sites. Diurnal migration patterns across land contained median flight altitudes of 335 ± 1,154 m in autumn and 576 ± 809 m in spring. Thereby, a mean flight speed of 56.3 ± 20.3 km/h was measured (Schwemmer et al. 2022). For further classification of the results, comparable information on the flight behaviour of other wader species in their breeding territories can be used. For this purpose, information on the flight behaviour of Piping plover (*Charadrius melodus*) is available, a tiny wader from North America, which reaches an average flight altitude of 2.6 m above ground and an average speed of 33.8 km/h (Stantial 2014). Compared to Curlew, mating flights are carried out at considerable low-level altitudes.

The large amount of Curlews' non-flight activity can be derived from foraging, breeding and comfort behaviour, which takes place on the ground and dominates the daily operations in this stage of the year. Flight activity was predominantly performed in short term actions, with a flight duration of 31 ± 88.1 seconds and a precise track length of 334 ± 1,170.5 m on average (Table 1). Movements can essentially be attributed to shifts between foraging or roosting spots, disturbance responses or mating interactions. The majority of total flights and total duration concentrated during daylight hours, which is in line with Curlews being diurnally active during breeding season (Bauer et al. 2005). However, differences were found in flight activity between male and female birds as well as between daytime and nighttime (Fig. 4). Males generally showed higher flight activity, attributed to mating displays and more territorial behaviour, while females' activity was lower due to a higher proportion of incubating time (Bauer et al. 2005). Moreover, females flew at higher altitudes (Fig. 5) and performed longer flight distances between take-off and landing spots throughout the day (Fig. 8). The occurrence and extent of nocturnal flights might be due to incubating alternations in which the dayshift usually is taken by females and the nightshift by male birds (Currie et al. 2001). Evening and night peaks in females' flight behaviour could thus be explained by visits of roosting places in varying distances apart from the nesting sites. Upon closer inspection of the transmitter data, flight movements of certain individuals confirm regular visits of wetlands, shallow water ponds and rewetted grasslands at night (Kämpfer, unpublished data). Thereby, it is important to mention that standard deviation of night generated data was predominantly high, indicating that variability within the flight activity of females was greater than that of males (Fig. 4). Similar nocturnal movement patterns were previously found in a study in the UK, where tagged Curlews moved further away from the nests at night than during day (Ewing et al. 2017).

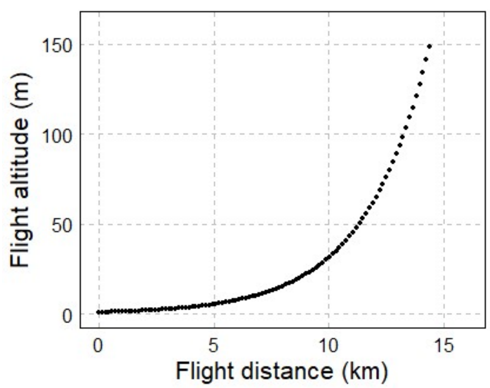

Figure 6 The distribution of flight altitudes with increasing flight distances between take-off and landing spot. For the visualisation, flight distance as predictor variable was divided into a sequence of 100 intervals. Flight altitudes were then assigned to the corresponding values.

4.2 Flight distances

Curlews' flight altitudes were influenced by flight distances. The flight distance was simultaneously conditioned by the location of intended destinations in the breeding areas. The further away those locations were, the longer flights had to be performed. In this process, the flight altitude increased equally to the covered distance (Fig. 6). This affects the potential collision risk, which is determined in a vertical context by the extent of the overlap between flights and the RHR. There is thus a connection between ranging distance of the birds' flights and potential conflicts with wind turbines. According to availability of resources, home range size is related in particular to habitat quality (Ponjoan et al. 2012). Hence, birds which breed in degraded landscapes are more threatened than birds in high quality habitats, as they need to enlarge their home range size to maintain appropriate breeding conditions (Séchaud et al. 2022). If urgent resources are available in the proximity of the breeding sites, birds have no need to cover long distances to forage or roost further afield, maintaining smaller home range sizes and thus avoiding flights in high altitudes. In this case, highest distances were performed in the evening hours and at night, indicating flight movements between roosting and nesting sites by females. This demonstrates that availability and proximity of appropriate roosting sites seems to be the most important factor in terms of performed flight distances. As the flight altitude is affected by this factor, it also links to potential collision risks.

4.3 Overlap with wind turbines

The low flight activity of the birds suggested a low proportion of stays in the RHR. More precisely, a low collision risk due to a quantitatively low probability of intersection with turbines could mistakenly be assumed. The average flight altitude (8 ± 9.3 m) indicated a small overlap of approximately 1 m, related to the RHR (7–246 m) (Fig. 2). However, average values should be considered with caution, as it is important to emphasise that half of the flight fixes (49%) as well as performed flights (53%) lay inside the danger zone of the rotors and thus enhance the potential collision risk. Comparing turbine constructions installed since 2018, the vertical overlap of the taller facilities with an upshifted RHR of 13–246 m obviously decreased. Only 37% of the flight fixes and 35.7% of flights overlapped, a decline of 12% in fixes and 17% in flights. Hence, wind turbines with higher RHR are expected to decrease collision risk due to lower crossing frequency in the danger zone of the rotors.

On the horizontal scale the proportion of flights overlapping with turbines must be considered from different points of view: Out of 28,212 independent flights, 2,858 tracks crossed the 200 m buffer which correspond to 10.1% of the flight movements. Excluding the bird that was breeding in a buffer and thus showed inevitably a large number of flights due to the proximity of the nest, a comparatively small proportion of 0.8% overlapping fixes remained. This result could be influenced by the high number of selected breeding sites in protection areas, which ensures that there are usually fewer wind turbines in the immediate vicinity due to legal requirements. Further research on this topic is needed to survey movement patterns in detail.

4.4 Vertical avoidance behaviour

For birds facing wind turbines a response of vertical flight motions was observed, detecting a correction into lower altitudes (Fig. 7). With regard to the impact of a potential collision risk, this response can be assessed cautiously positive, as the birds obviously perceive wind turbines as obstacles and react specifically to them. However, the case of a verified collision during migration showed that Curlews obviously cannot always evade collisions (Jiguet et al. 2021).

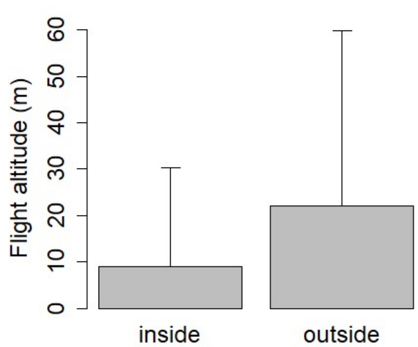

Figure 7 The difference between flight altitudes and standard deviation inside and outside the 200 m buffers around wind turbines. Flight information were provided by Curlews that intersected the buffers at least once during breeding season (n=16).

While the vertical avoidance behaviour might reduce the potential collision risk, it could have a far-reaching negative impact in terms of increasing evasive effects and thus barrier effects. For Curlew population, this could lead to habitats being avoided and abandoned due to construction of wind turbines. A corresponding assessment was also found for Curlew migration patterns in the Baltic and North Sea with strong small-scale avoidance responses on a vertical and horizontal scale at offshore wind farms (Schwemmer et al. 2023). It must be emphasised that this impact is likely to be even more hazardous than the loss of individuals through collisions (Langston & Pullan 2003).

Based on the results, the collision risk is essentially determined by the height of wind turbines and performed flight distances of the birds (Fig. 6). This confirms the need for prescribed distance criteria between wind turbines and breeding sites.

5. Implications for conservation

The results of this study point out that especially small wind turbines with a low minimum rotor tip height increase the overlap with the RHR (Fig. 2). Furthermore, the birds' vertical avoidance behaviour stresses a response by reducing their flight altitude (Fig. 7). Accordingly, larger facilities with an uplifted rotor hub and a larger non-swipe zone between ground level and RHR could counteract to this reaction and decrease the potential collision risk. Turbine constructions should be adapted, a trend that is in line with the economic and technical development towards larger facilities (McKenna et al. 2015). It is important to emphasise that the results of this study only apply to breeding Curlews. Migration patterns across land indicate that Curlews move much higher, increasing the proportion of overlap with the RHR into higher ranges (Schwemmer et al. 2022).

Based on the hypothesis that home range and thus distance of performed flights is related to the habitat quality, also measures for habitat improvements could be used to direct the interest of Curlews away from already installed turbines nearby the nests. Comparable compensatory measures are already used to avoid casualties of other bird species like Red Kites (*Milvus milvus*). In this context, distraction by creation of attractive foraging spots was realised in a controlled agricultural management area apart from wind farms, as Red Kites prefer recently mowed grasslands (Blew et al. 2018). Similar regulating measures could be established by improving habitat quality of Curlews' breeding sites through the creation of shallow water ponds or rewetted grasslands as foraging and roosting sites.

Beyond that, the planning of wind turbine construction sites should be adapted to the requirement of occurring Curlew breeding territories. Therefore, facilities should not be placed between nesting sites and roosting spots, which must be considered as the main driver of long-distance flights. A selection of areas with high habitat quality should be highlighted in preliminary studies during construction, which is certainly important in order to find appropriate wind farm locations and increase environmental sustainability. Further, prescribed distance criteria between wind turbines and breeding sites should be introduced to reduce the probability of an overlap of the birds' home range with wind turbines.

In conclusion, this study presents valid data towards flight behaviour of Curlews in their breeding territories, thereby completing urgently needed knowledge of a highly threatened bird species impacted by expansion of wind power. It is recommended that more extensive research should be carried out. This includes in particular horizontal avoidance behaviour in flight as well as calculation of collision models according to Band et al. (2007), which could allow accurate measurements of local loss rates in precisely definable study areas such as existing or planned wind farm sites.

6. Acknowledgements

I would like to thank Prof. Dr. Hanna Meyer and Prof. Dr. Thomas Fartmann for supervising this study. A special thanks goes to Dr. Steffen Kämpfer, who substantially supported me in writing this thesis. He helped me dealing with large data structures as well as statistical analyses and kindly responded to countless of questions in an amazingly short time. Further, I would like to thank Jonas Linke for valuable comments on the first version of this manuscript and all persons from the Biodiversity and Landscape Ecology Group of University Osnabrück and the Institute for Wetlands and Waterbird Research e.V. (IWWR), who were involved in the Curlew tagging project. The Ministry for Food, Agriculture and Consumer Protection of Lower Saxony, the Senator for Climate Protection, Environment, Mobility, urban development and housing, State of Bremen and the State Office for Nature, Environment and Consumer Protection North Rhine-Westphalia made this evaluation viable by providing information of wind turbine locations as well as digital elevation models.

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Appendix

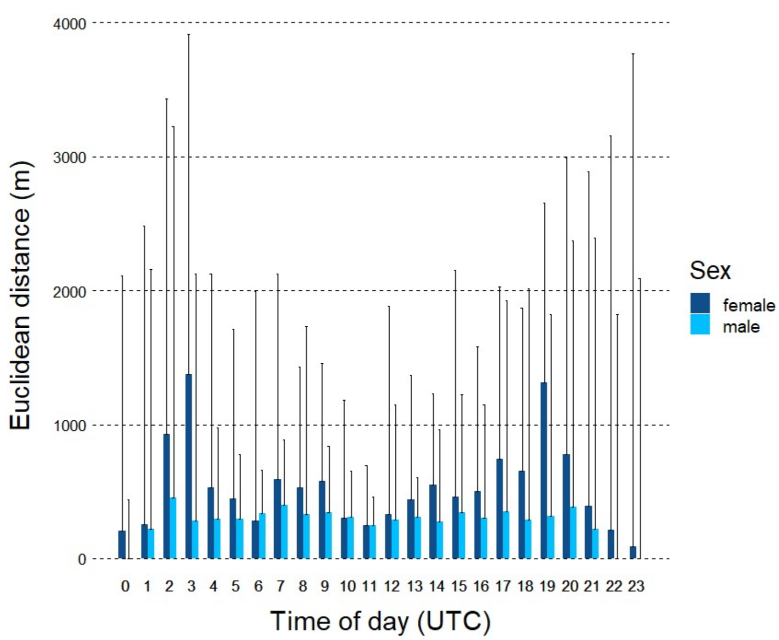

Figure 8 Curlews' hourly distribution of flight distance and standard deviation throughout the day during breeding season for females (red, n=24) and males (blue, n=27).

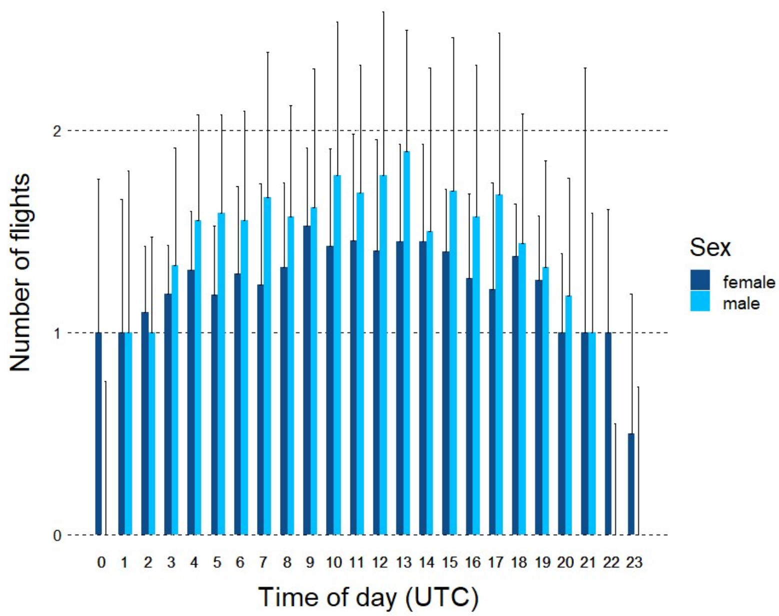

Figure 9 Curlews' hourly distribution of flight frequency and standard deviation throughout the day during breeding season for females (red, n=24) and males (blue, n=27).

Declaration of Academic Integrity

I hereby confirm that this thesis, entitled

Potential collision risk of a threatened wader with wind turbines
- an analysis based on high-resolution flight behaviour data

is solely my own work and that I have used no sources or aids other than the ones stated. All passages in my thesis for which other sources, including electronic media, have been used, be it direct quotes or content references, have been acknowledged as such and the sources cited. I am aware that plagiarism is considered an act of deception which can result in sanction in accordance with the examination regulations.

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