Biological Conservation 220 (2018) 228–236

Contents lists available at ScienceDirect

Biological Conservation

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

Bird collisions at wind turbines in a mountainous area related to bird movement intensities measured by radar

Janine Aschwanden*, Herbert Stark, Dieter Peter, Thomas Steuri, Baptiste Schmid, Felix Liechti

Swiss Ornithological Institute, Seerose 1, 6204 Sempach, Switzerland

A R T I C L E I N F O

Keywords:
Carcass search
Bird radar
Echo classification
Nocturnal migration
Avoidance
Mitigation

A B S T R A C T

Bird collisions at wind turbines are perceived to be an important conservation issue. To determine mitigation actions such as temporary shutdown of wind turbines when bird movement intensities are high, knowledge of the relationship between the number of birds crossing an area and the number of collisions is essential. Our aim was to combine radar data on bird movement intensities with collision data from a systematic carcass search.

We used a dedicated bird radar, located near a wind farm in a mountainous area, to continuously record bird movement intensities from February to mid-November 2015. In addition, we searched the ground below three wind turbines (Enercon E-82) for carcasses on 85 dates and considered three established correction factors to extrapolate the number of collisions.

The extrapolated number of collisions was 20.7 birds/wind turbine (CI-95%: 14.3–29.6) for 8.5 months. Nocturnally migrating passerines, especially kinglets (*Regulus* sp.), represented 55% of the fatalities. 2.1% of the birds theoretically exposed to a collision (measured by radar at the height of the wind turbines) were effectively colliding.

Collisions mainly occurred during migration and affected primarily nocturnal migrants. It was not possible to assign the fatalities doubtlessly to events with strong migration. Fresh-looking carcasses were found after nights with both strong and weak bird movement intensities, indicating fatalities are not restricted to mass movement events (onshore). Rather, it is likely that an important factor influencing collision risk is limited visibility due to weather conditions. Local and regional visibility should be considered in future studies and when fine-tuning shutdown systems for wind turbines.

1. Introduction

Over the past 15 years, wind power installations have increased steadily across Europe (EWEA European Wind Energy Association, 2016). Due to the greenhouse gas reduction target 2020 (European Commission, 2010), this increasing trend will likely continue in coming years, as wind energy is renewable and CO_2-neutral. Negative impacts of conventional industrial wind turbines on avifauna are widely discussed and of global concern (Dai et al., 2015; Wang et al., 2015; Smith and Dwyer, 2016). The topic of bird collisions at wind turbines is considered to be of particular importance, as is the assessment of potential mitigation measures (Marques et al., 2014; May et al., 2015; Smith and Dwyer, 2016).

The temporary shutdown of wind turbines during high bird movement intensities might be an option to reduce the collision risk (Liechti et al., 2013). To define mitigation actions within the framework of approval processes for wind energy developments, the relationship between the number of birds crossing an area and the number of collisions must be known. Furthermore, knowledge about this relationship might improve siting of wind farms in general, which again decreases the number of necessary shut-down events. An investigation of the relationship between the number of birds crossing an area and the number of collisions requires continuous, quantitative data on diurnal and nocturnal bird movements within the height interval of the wind turbines as well as simultaneous monitoring of collision victims. Radar systems are suitable to record bird movement intensities continuously during day and night (Eastwood, 1967; Bruderer, 1997a, 1997b). However, estimates of absolute intensities require radar systems calibrated for bird detection, taking into account the bird-size specific detection probability and surveyed volume (Schmaljohann et al., 2008). In addition, it must be assured that small birds like warblers are detected and distinguished from similar sized large insects.

For determining the number of bird collisions, carcass searches have to be systematic and numbers must be corrected for the detection probability, which depends on search efficiency, persistence time of carcasses and the probability of a carcass lying within the searched area

* Corresponding author.
E-mail address: janine.aschwanden@vogelwarte.ch (J. Aschwanden).

https://doi.org/10.1016/j.biocon.2018.01.005
Received 22 June 2017; Received in revised form 19 December 2017; Accepted 3 January 2018

(Korner-Nievergelt et al., 2015). The accuracy of a carcass search study increases with increasing frequency of searches, narrow transects and a large surveyed area. Collection and analysis of this type of continuous data is extremely labour-intensive and time-consuming. Up to now, published studies of seasonal and altitudinal distributions of bird movement intensities in relation to wind farms (Bruderer and Liechti, 2004) or of carcass searches including small birds are rare (Johnson et al., 2002; Grodsky et al., 2013; Hull et al., 2013; Grünkorn et al., 2016). Likewise, studies combining radar data with carcass searches are uncommon. Krijgsveld et al. (2009) and Welcker et al. (2017) made an approach into this direction but used radar systems with limited bird detection abilities, during a limited number of days.

The present study investigates the relationship between the number of flying birds at risk and the number of bird collisions at a wind farm location in the Swiss Jura mountains. The first aim was to estimate theoretical collision risk by monitoring the intensity of diurnal and nocturnal bird movements within and above the height interval of three nearby located wind turbines. The second aim was to simultaneously conduct a systematic carcass search with a high detection probability to achieve a reliable estimate of the true number of fatal collisions. The correction factors search efficiency and persistence time were experimentally determined by placing test carcasses of wild birds in the field. The third aim was to link the number of birds theoretically at risk with the estimated absolute number of collisions to determine a collision rate and to infer an avoidance rate, respectively. The results of this study will provide information critical to the discussion of bird collisions at wind turbines and potential mitigation measures. Additionally, the aspect of wind turbines in mountainous areas is addressed.

2. Methods

2.1. Study area

This study was conducted in the Jura Mountains of northwest Switzerland, in a region near the French border known as “Franches Montagnes”. The wind farm was erected in 2010 at “Le Peuchapatte” (47°12′N, 6°57′E) and consists of three wind turbines of the type Enercon E-82 E2/2.3 MW (Fig. 1) placed at altitudes between 1125 and 1180 m above sea level (asl, tower feet). The wind turbines are 600–700 m apart, placed along the axis of the main bird migration direction (about 230°, Bruderer and Liechti, 1990). The turbines have a rotor diameter of 80 m and a hub height of 108 m, resulting in a total height of nearly 150 m (including rotor blades). They are illuminated by a permanent red light at middle height of the tower and by a flashing red light on the hub. For 95% of the study duration, the turbines were rotating with at least 5 rounds per minute which is a rotor tip speed of at least 77 km/h. The landscape is hilly with a mosaic of forest and agricultural land (mainly grassland and pastures).

2.2. Radar investigation

2.2.1. Radar measurements, analysis and bird movement intensity

The radar system was located close to the farm “Le Roselet”, at 1050 m asl (47°13′28”N, 7°00′24″E), about 3.5 km northeast of the wind farm site, along the axis of the main bird migration direction. The radar location is about 100 m lower in elevation compared to the wind farm. This ensured that radar measurements were not significantly contaminated with ground clutter and were fully covering the height interval of the wind turbines. Based on a radar study conducted in the region 2010/2011 (mean values published in Liechti et al., 2013), we are confident that the bird movement intensity measured at “Le Roselet” corresponds to the general bird movement intensity of the region (broad front migration). Bird movements were recorded automatically and continuously between 26 February 2015 and 17 November 2015 (265 days) with a fixed-beam radar of the type BirdScanMT1 (Bruderer et al., 2012). General details on fixed-beam radar measurements are given in Komenda-Zehnder et al. (2010) and details specific to the study in the online Appendix A1.

Radar data were processed by tailor-made software. Extracted targets were classified automatically as birds or non-birds based on the maximum reflectivity and the temporal pattern of the reflectivity (echo signature). In the case of single flying birds the echo signature corresponds to wing-beat pattern (Zaugg et al., 2008; Bruderer et al., 2010). After separating birds from non-birds (mainly insects), hourly bird movement intensities per km (birds * km^{-1} * h^{-1}) were calculated for height intervals of 50 m up to a height of 2550 m above ground level (agl). Bird movement intensities are equivalent to migration traffic rates according to Schmaljohann et al. (2008), but additionally including non-migratory bird movements. They are defined as the number of birds crossing a virtual line of 1 km length per hour. For the calculation of bird movement intensities we took into account a size-class-specific detection probability and surveyed volume of the radar device (Schmaljohann et al., 2008). From the altitudinal distributions, we extracted the number of birds flying within the height range of the wind turbines. During the day, birds often aggregate in flocks, which are represented as a single echo in radar data. Therefore, the diurnal bird movement intensity values should be considered as the minimum number of birds flying at a given time (Bruderer, 1997a). The time of civil twilight was used to distinguish between diurnal and nocturnal bird movement intensities.

2.2.2. Theoretical number of birds exposed to collisions

To calculate the theoretical number of birds exposed to collisions, we first estimated the number of birds flying across a virtual window 200 m in height and 1 km in width (Fig. 2), situated within the altitudinal range of the wind turbines (1150 to 1350 m asl). We then calculated the proportion of this area covered by one wind turbine, which included the surface area of the three rotor blades (not the swept area) plus the part of the tower protruding above the trees. Together, this constituted an area of roughly 500 m^2 and corresponded to 0.25% of the total area of the virtual window. Assuming that birds crossed this virtual window area randomly distributed, did not show any avoidance behaviour and were able to pass through the space between the rotor blades unoffended, 0.25% of the birds would theoretically be exposed to collisions. We expect this to be the minimum theoretical number of birds exposed to a collision risk; mainly because diurnal bird numbers are minimum numbers (see Section 2.2.1).

2.2.3. Carcass search, ground cover and X-ray analysis

We searched the ground below all three wind turbines for carcasses on 85 days between March 1, 2015 and November 15, 2015. On average a search was done every 2.8 days with search intervals of 2–7 days (online appendix A2). For carcass searches, it is recommended (Gauthreaux, 1996; Hull and Muir, 2010) and common (Johnson et al., 2002; Krijgsveld et al., 2009; Grodsky et al., 2013) to consider an area within a radius that is roughly equivalent to the total height of a wind turbine (in our case 140 m). When searching the entire recommended area is not possible due to not searchable ground cover (e.g. forest, shrubs) or financial constraints, collision calculations need to be corrected for the area not searched by considering the probability of a carcass lying within the searched area. Our searches covered a radius of 100 m (69 dates) or of 50 m (16 dates, online Appendix A2).and so the area not included in the search (up to 140 m), was considered afterwards in the analysis to calculate the correction factor “probability of a carcass lying within the searched area” (see Section 2.2.4). All searches were conducted by the same two observers, each on alternate days. For each search, one observer walked along parallel transects spaced 5 m apart below all three wind turbines during one day. The length of the transects underneath all three wind turbines summed up to a distance of about 15 km (100 m radius) and about 4.8 km (50 m radius), respectively.

80% of the searched area (radius 100 m) was grassland. The

Fig. 1. Two of the three wind turbines at “Le Peuchapatte” (Aug. 25, 2015, ©Swiss Ornithological Institute).

remaining 20% was covered by forest and was not included in the searches. Local farmers were contracted by the Swiss Federal Office of Energy to keep the grass as short as possible. The wind turbine areas were mown and used as cattle pastures. At each search, ground cover was estimated (online appendix A3) visually based on the categories “snow”, vegetation “short” (0–5 cm), vegetation “medium” (5–10 cm) and vegetation “long” (> 10 cm). For the examination of carcasses that appeared intact, we used a mobile x-ray apparatus Gierth TR 90 - Battery 90/20 (software: Veterinary Solutions).

2.2.4. Search efficiency, persistence time and probability of a carcass lying within the searched area

We tested the correction factors “search efficiency” and “persistence time” by placing test carcasses of wild birds belonging to different size

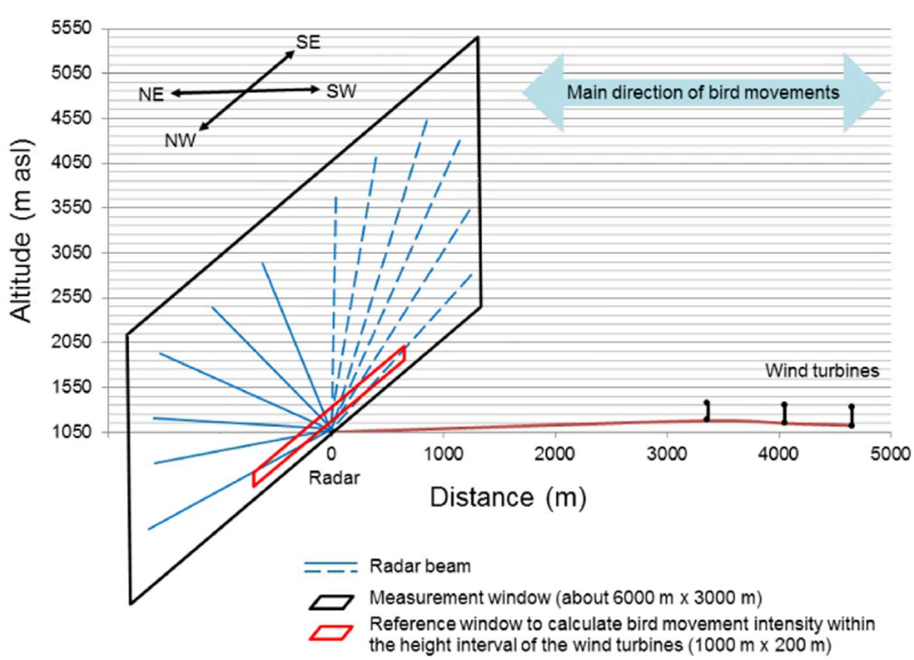

Fig. 2. Experimental layout and principle of the sequential radar measurements with the radar beam set to different elevations. For small birds, the maximal range of the radar beam is about 3 km. Bird movement intensities were calculated based on radar data for the height interval of the wind turbines and up to 3550 m asl.

classes (small [Wren to Hawfinch], medium [Common Swift to Common Kestrel], large [Wood Pigeon to Grey Heron]) on the search area under the three wind turbines in regular intervals distributed over the study period (online Appendices A2, A4 and A5). The test carcasses were non-euthanised wild birds that died at a bird care centre. The placing of test carcasses for assessing search efficiency was done in the early morning of a search day, without informing the person doing the carcass search. Test carcasses were marked by cutting some feathers. Correction factor calculations and all subsequent statistical analyses were conducted in R 3.2.2 (R Development Core Team, 2015) and BUGS (Lunn et al., 2013). Credibility intervals were estimated according to Bayes based on flat prior distributions. A detailed description of the method and statistical analysis is given in the online Appendices A4 and A5.

We considered the third correction factor, "probability of a carcass lying within the searched area", because searches for collision fatalities did not cover the whole area up to a radius of 140 m, where fatalities could also occur. The applied correction factor is based on the distance distribution of fatalities below a wind turbine (for details see online Appendix A6). We used the estimated distance distribution of fatalities as calcultated by Grünkorn et al. (2016). Their estimated distance distribution includes values for wind turbines with a total height of 140 m and is based on larger sample sizes than available in our study.

2.2.5. Extrapolation of the number of collision victims and absolute collision rate

We used the function "estimateN" from the R-package "carcass" (Korner-Nievergelt et al., 2015) to estimate the effective number of collisions based on the total number of found victims. Extrapolation is based on daily persistence time and search efficiency plus their associated statistical uncertainty, as well as the probability of a carcass lying within the searched area. The analysis is based on probability calculations according to Bayes and estimates statistical uncertainty of the final result with Monte Carlo simulations (MCMC). Finally, we calculated the average number of collisions per wind turbine from the extrapolated number of collisions.

3. Results

3.1. Pattern of bird movement intensities

The mean bird movement intensity across the study period (all heights up to 3550 m asl) was 60 birds*km^{-1}*h^{-1} during the day (standard deviation SD 75, number of days $N = 265$ daily mean values) and 540 birds*km^{-1}*h^{-1} at night (SD 780, $N = 263$). Bird movement intensities (Fig. 3 and Table 1) were highest during spring (March 8 to May 31) and autumn (Aug. 16 to Nov. 7). These periods correspond to the well-known temporal pattern of migration. Up to 3550 m asl, weekly mean intensities fluctuated between 40 and 950 birds*km^{-1}*h^{-1} in spring (Feb. 26–May 31), 8–60 birds*km^{-1}*h^{-1} in summer (June 1–Aug. 15) and 25–880 birds*km^{-1}*h^{-1} in autumn (Aug. 16–Nov. 17). The fluctuations in relation to the height interval of the wind turbines were between 8 and 140 birds*km^{-1}*h^{-1} in spring, 4–15 birds*km^{-1}*h^{-1} in summer and 3–370 birds*km^{-1}*h^{-1} in autumn, and strongly correlated with the total movements (all heights, $r = 0.84$, $N = 39$ weekly means). Averaged over the study period for the height interval of the wind turbines, the diurnal mean intensity was 15 birds*km^{-1}*h^{-1} (SD 20, $N = 265$); and the nocturnal mean intensity was 125 birds*km^{-1}*h^{-1} (SD 210, $N = 263$). Bird movement intensities per date are given in the online Appendix A7.

Bird movement intensities decreased with increasing altitude (Fig. 4). The proportion of birds moving within the height interval of the wind turbines was somewhat larger during the day (26%) than during the night (23%). Thus, nocturnal migration was slightly shifted to higher altitudes compared to diurnal migration.

3.2. Collision victims and correction factors

3.2.1. Species composition and condition of carcasses

In total we found 51 bird remains, which ranged in condition from single feathers to intact-looking carcasses. Similar to Hull et al. (2013), we decided to count only remains of > 10 feathers as collision victims (online Appendix A8). Finally, we used 20 out of the 51 remains for the extrapolation. 13 of the 20 selected carcasses were "intact" and 7 consisted only of loose feathers and/or feather clumps. 11 of the 20 carcasses belonged to the genus *Regulus* (Table 2). Eight of the intact carcasses were investigated by X-ray-analysis. Six of the eight carcasses had obvious fractures (broken legs, broken neck, torsion of legs, see online Appendix A9).

3.2.2. Relation to bird movement intensities

Of the 20 carcasses, all except for three (Common Swift, Fieldfare and a Song Thrush), were found during periods with elevated bird movement intensities (7 in spring and 10 in autumn, Fig. 3). We assume that most of the victims were migrants because they were found during their typical migration periods. As we did not know the age of a carcass (time passed since the collision event), we divided them into two age categories. Fresh-looking as well as predated carcasses were estimated to be no older than 3 days, while remains which appeared more

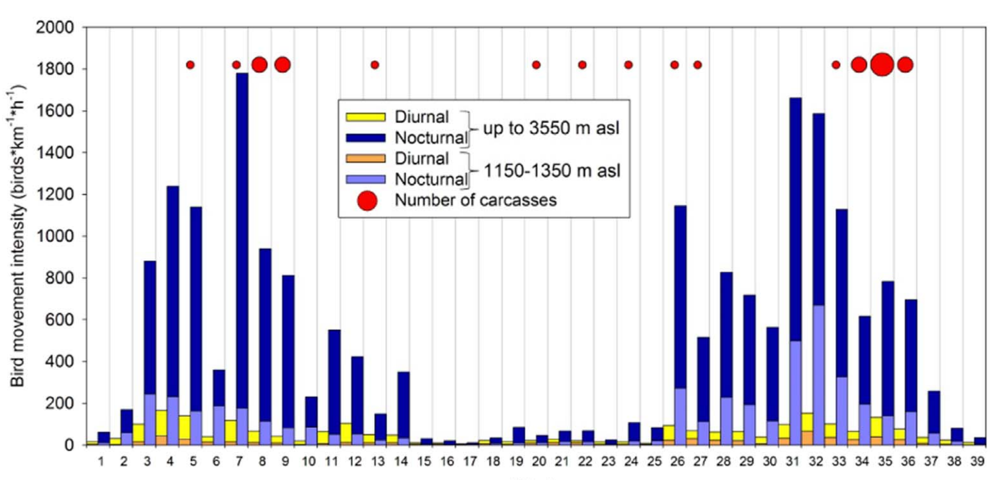

Fig. 3. Mean diurnal and nocturnal bird movement intensity per week within the height interval of the wind turbines (1150–1350 m asl) and in total up to 3550 m asl. Dots above the bars mark the number of collision victims per week (small = 1, medium = 2, large = 3).

Table 1
Mean bird movement intensities (birds * km^{-1} * h^{-1}) per season, time of the day and height interval.

Height interval and value	Spring (26 Feb.–31 May)			Summer (1 June–15 Aug.)			Autumn (16 Aug.–17 Nov.)			Total study period (26 Feb.–17 Nov.)		
	Day	Night	24 h	Day	Night	24 h	Day	Night	24 h	Day	Night	24 h
Total[a]												
Mean	75	670	370	15	55	35	75	800	440	60	540	300
SD[b]	90	880	465	10	45	25	70	800	430	75	780	415
200 m[c]												
Mean	15	110	60	6	10	8	25	225	125	15	125	70
SD	20	150	80	5	10	6	30	275	150	20	210	110
N[d]	95	95	95	76	75	75	94	93	93	265	263	263

[a] All height intervals up to 3550 m above sea level (asl).
[b] Standard deviation of daily mean values.
[c] Within the height interval including the wind turbines (1150–1350 m asl).
[d] Number of valid daily means.

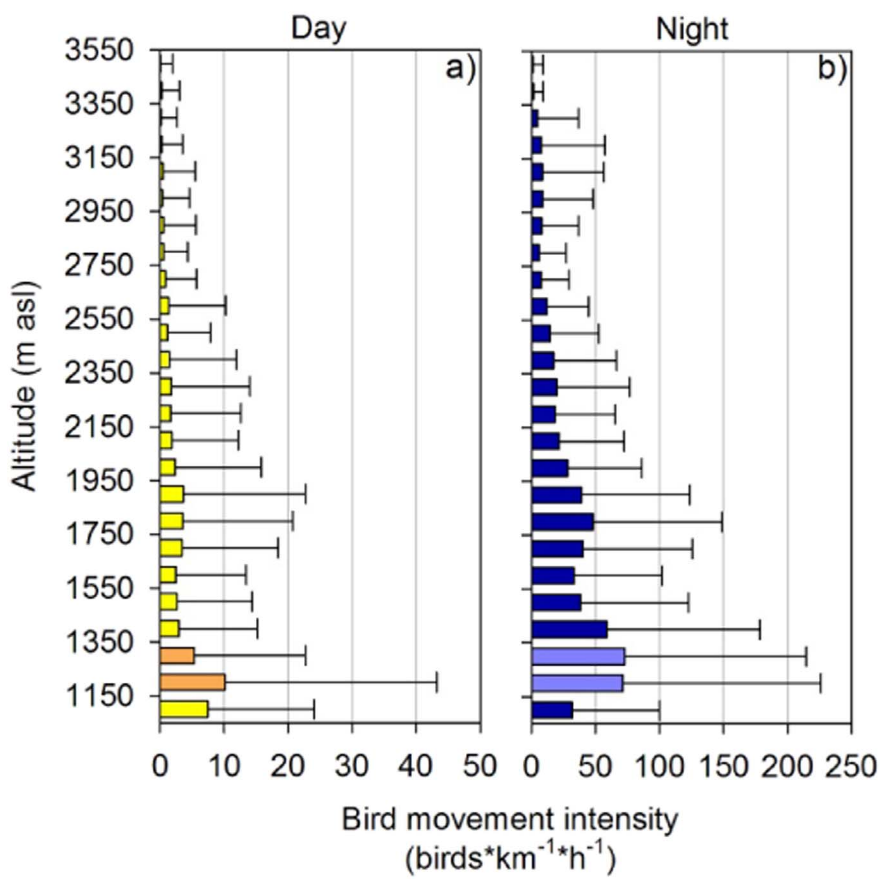

Fig. 4. Altitudinal distribution of diurnal (a) and nocturnal (b) mean migration intensity with standard deviation of daily mean values (T-lines) measured from 1050 m to 3550 m (asl) between Feb. 26 and Nov. 15, 2015. The differently coloured bars indicate the height intervals where the wind turbines are located.

Table 2
Species list, numbers of collision victims and condition of the bird remains found below the three wind turbines (s = small, m = medium, l = large).

Common name (size class)	Scientific name	Number	Proportion (%)	Condition
Common firecrest (s)	*Regulus ignicapilla*	7	35	Intact, fresh or old
Goldcrest (s)	*Regulus regulus*	2	10	Intact, fresh
Unknown kinglet (s)	*Regulus sp.*	2	10	Feather spot/clump
Mallard (l)	*Anas platyrhynchos*	2	10	Feather clumps
Mistle thrush (m)	*Turdus viscivorus*	1	5	Feather spot
Common swift (m)	*Apus apus*	1	5	Feather spot
Fieldfare (m)	*Turdus pilaris*	1	5	Feather spot
Song thrush (m)	*Turdus philomelos*	1	5	Feather spot
European robin (s)	*Erithacus rubecula*	1	5	Intact, fresh
Eurasian blue tit (s)	*Cyanistes caeruleus*	1	5	Intact, fresh
Common grasshopper warbler (s)	*Locustella naevia*	1	5	Intact, old

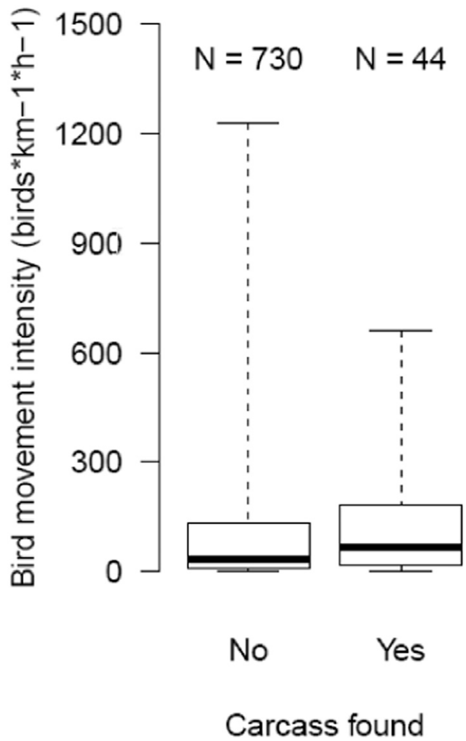

Fig. 5. Bird movement intensities at 3 days prior to finding a carcass and for 3-days-periods without finding a carcass. The horizontal line in a box is the median, the lower end of a box is the 25% and the upper end the 75% quartile and the dashed lines outside of the boxes mark the range of the data. N is the number of bird movement intensity values.

weathered were estimated to be at least 3 days old. The median of the distribution of bird movement intensities (Fig. 5) for the 3 day periods prior to finding a fresh or predated carcass tended to be higher (68 birds*km^{-1}*h^{-1}) than for the 3 days periods when no carcasses were found (33 birds*km^{-1}*h^{-1}, Mann-Whitney-Wilcoxon Test, $W = 13{,}445$, $p = 0.07$).

3.2.3. *Search efficiency, persistence time and probability of a carcass lying within the searched area*

The overall search efficiency based on the test carcasses was 0.81 (95% credibility interval, CI-95%: 0.57–0.93). The search efficiency

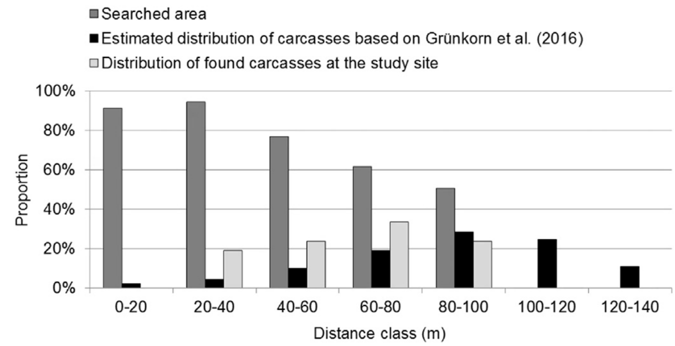

Fig. 7. Proportion of the searched area per distance class (circular rings), the estimated proportion of carcasses per distance class based on Grünkorn et al. (2016) and the distribution of found carcasses per distance class at the study site.

decreased for small and medium-sized test carcasses with increasing height of the vegetation (Fig. 6). Large test carcasses were always found, irrespective of vegetation height.

To calculate the persistence time, a test carcass was valued as removed, when < 10 feathers were left on a spot. Probability of finding a test carcass or a feather spot (10 or more feathers) one day after exposition was 0.93 (CI 95%: 0.91–0.94). This means, that the mean overall persistence of a test carcass in the field was 14 days (CI-95%: 11.1–17.7). Common scavengers detected by camera traps were fox, domestic cat, crow, common buzzard and red kite.

Due to the distribution of areas covered by forest, the proportion of the searched area per distance class decreased with increasing distance to the wind turbines (Fig. 7). The estimated distance distribution of carcasses found by Grünkorn et al. (2016) showed that the proportions of carcasses per distance class get larger with increasing distance to the wind turbine up to the distance class 80–100 m and then decrease. Combining distance dependent proportions of searched area and carcass distribution resulted in a final probability of a carcass lying within the searched area of 0.4.

3.3. *Collision rate and avoidance*

When taking into account search efficiency, persistence time and the probability of a carcass lying within the searched area, the estimated number of collision victims for all three wind turbines together was 62 (median, CI-95%: 43–89) for the duration of the study period. Therefore, the estimated bird collision rate per wind turbine was 20.7

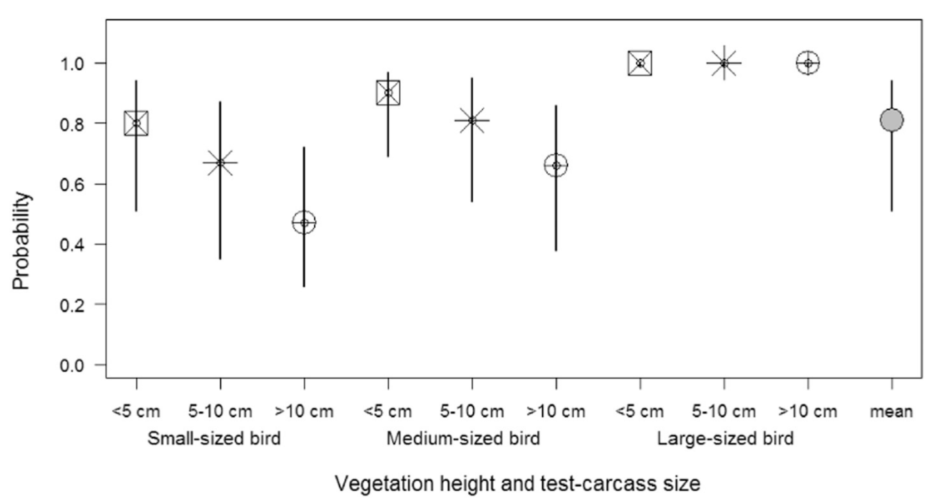

Fig. 6. Search efficiency (symbols) depending on vegetation height and size of the test carcass with the general mean search efficiency (grey dot) and the 95% credibility interval (black lines). All large-sized test carcasses were found in all vegetation heights. Three of the 65 test carcasses were placed on snow. We included them into the category vegetation height < 5 cm.

(median, CI-95%: 14.3–29.6).

We estimated that at least 1.65 million birds per km had crossed the region during the study period (all heights). Of these 1.65 million, 390,500 were moving within the height interval of the wind turbines. Following our simple theoretical concept of estimating collision risk, 0.25% or 976 victims per wind turbine would have been expected. The estimated 21 bird collisions per wind turbine make up 2.1% (median, CI-95%: 1.5–3.0%) of the theoretically expected 976 victims, calculated from the bird movement intensities measured by radar. Thus, we conclude that roughly 98% of the birds exposed to a collision risk avoided a collision.

4. Discussion

Because bird migration rates can vary by orders of magnitude within a matter of days (e.g., Erni et al., 2002), accurate quantification of bird movement intensity requires a radar device which is calibrated for bird detection (Schmaljohann et al., 2008), as well as continuous measurements over a representative time period. As such, the inferences that can be drawn from previous studies using radar to quantify bird collision risk are limited due to much shorter study durations (2 to 14 days per study site) and lack of echo identification (Krijgsveld et al., 2009; Welcker et al., 2017). To our knowledge, this is the first study combining quantitative bird movement data derived by a dedicated bird radar with an intense carcass search over almost one year.

We invested a lot of effort into the carcass search study to increase the detection probability for carcasses and the accuracy of the statistical extrapolation of the number of collision victims. We think this aim was successfully reached because our extrapolation factor of three was relatively low (see Table 3), and resulted in 62 estimated collisions from 20 found carcasses around three wind turbines. The detection probability for carcasses results from linking the three correction factors search efficiency, persistence time and probability of a carcass lying within the searched area (Korner-Nievergelt et al., 2015). In our study, the search efficiency was high (0.81) due to the combination of short vegetation and narrow transects. Daily persistence time was high (0.93) meaning that persistence time of carcasses was longer than the intervals between searches. Only the probability of a carcass lying within the searched area was relatively low (0.4) compared to the probabilities of the two other correction factors. This probability was calculated including data provided by Grünkorn et al. (2016). They estimated based on empirical data that a relatively large proportion of carcasses is outside of the search radius of 100 m for wind turbines with heights of 140–160 m (incl. rotor). We strongly assumed that this must be also true for the wind turbines of our study (Grünkorn et al., 2016).

Perhaps because gulls and raptors are frequently documented fatalities from onshore wind farms in Europe (Grünkorn et al., 2005; Krijgsveld et al., 2009; Grünkorn et al., 2016; Welcker et al., 2017), research and discussion about avian victims of turbine collisions has been focused primarily on large birds up to this point (Marques et al., 2014). In our study, however, passerines smaller than thrushes constituted the majority (70%) of victims found, with the only large birds being two mallards. It is quite likely the different species composition of turbine victims observed in our study compared to previous studies in Europe is due to differences in land cover and topography, both of which are known to influence the distribution of bird movements (Kerlinger, 1989; Bruderer and Jenni, 1990; Bruderer and Liechti, 1999). Thus, the results of bird collision studies in agricultural lowland areas, where most such research has been conducted within Europe, may not be transferable to mountainous, forested regions like our study area. Our results are similar to what has been found at wind farms in the USA, where most of the collision victims were small passerines (Johnson et al., 2002; Grodsky et al., 2013; Erickson et al., 2014) or even nocturnally migrating small passerines (Kunz et al., 2007). Especially in wind farms on forested hills, small passerines were frequently victims of fatal collisions. The topographical situation there might be similar to the one in our study. Our study clearly shows that collision risk for nocturnally migrating (small) passerines at onshore wind farms is not necessarily lower than for other bird groups. Indeed, isolated findings of small passerine collision victims occur repeatedly in Europe (Dürr, 2017). Although we had test carcasses of small passerines to determine search efficiency and persistence time, test carcasses of kinglets were not available. Due to their very small size, search efficiency and persistence time for kinglets might be lower than for other small passerine species which would in turn mean that we underestimated the collision risk for these birds. We believe the impact of onshore wind turbines on small nocturnally migrating passerines should be generally reassessed.

That no clear relationship was found between peak bird movement intensities and bird collisions suggests other factors are more important in determining collision risk. One such factor could be reduced visibility due to bad weather conditions, which has been linked to increased collision risk for birds in other studies (Johnson et al., 2002; Marques et al., 2014; Grünkorn et al., 2016). In the present study, although visibility was not measured systematically, a post-hoc examination of images from camera traps revealed limited visibility in the 72 h prior to finding 8 out of 12 fresh-looking or predated carcasses. Thus, out of the 12 cases 2/3 of the collisions might be related to conditions of poor visibility (mist, fog, drizzling rain).

In addition, the constant lights on the wind turbines might attract nocturnal migrants, an effect which is likely more pronounced during periods with limited visibility. Interestingly, in our study, half of the collision victims were kinglets (*Regulus* sp.), which have also been found to be frequent collision victims in other regions. In Canada, the golden-crowned kinglet (*Regulus satrapa*) was among the most common victims found at wind farms (Zimmerling et al., 2013), and in Europe kinglets often collide with illuminated tall buildings (Haupt, 2009).

Table 3
List of references with absolute collision rates per wind turbine, total number of carcasses found and the extrapolation factor deduced of those numbers.

Reference and type	Country and landscape	Size (m), number of searched turbines	Collision rate per turbine per time period	Total number of carcasses found	Extra-polation factor
Review					
Marques et al., 2014	various	Various	0–40/year	Various	Various
Dai et al., 2015	various	Various	0.003–35/year	Various	Various
Wang et al., 2015	various	Various	0.02–20.5/year	various	Various
Study					
Grodsky et al., 2013	USA, flat, agriculture	118, 29	0.026/day	20	13
Krijgsveld et al., 2009	NL, flat, agriculture	100–111, 14	28 (19–68)/year	14	28
Welcker et al., 2017	D, flat island	100, 65	4.1/3.5 months	41	6.5
Johnson et al., 2002	USA, forested hill	52.5–74, 91	0.98–4.45/8 months	55	1.6–7.3
Bull et al., 2013	NZL, hilly coast	107, 24	4.64–5.83/year	53	2.1–2.6
Zimmerling et al., 2013	CAN, various	117–136, na[a]	8.2 (± 1.4)/year	na	na

[a] Information not available.

Kinglets have also been found in small numbers at wind farms in the Netherlands (Krijgsveld et al., 2009) and in Northern Germany (Grünkorn et al., 2016; Welcker et al., 2017).

A comparison of the absolute collision rate with values from other studies is difficult. Locations of wind farms, methodologies of data collection and statistical analysis differ considerably from study to study. However, our collision rate per turbine is within the range found in other studies (cf. Table 3).

For the calculation of the number of birds theoretically at collision risk, we applied a simple concept based on the area covered by the frontal projection of the surface of a wind turbine (see methods). Our number of birds theoretically at risk and data on absolute collision rates are pooled over the different species and bird-size classes (small to large), as it is not possible to extract species specific bird movement intensities depending on bird-size class from the radar data. Furthermore, we do not have information on flight speeds or high resolution data on flight heights. Therefore, our data are not suitable to calculate a useful theoretical collision risk based on the well-known Band-model (Band et al., 2007; Band, 2012a, 2012b) or similar models (Masden and Cook, 2016). Nonetheless, in order to get an impression of the values, we calculated a theoretical collision risk for some species based on the basic Band-model (without avoidance, Band, 2000, see online Appendix A10). We included a range of flight speeds given in Bruderer and Boldt (2001). The theoretical collision risks estimated by the Band-model for the different flight speeds are rather higher (Kinglets 0.0026–0.0037), intermediate (Robin 0.0022–0.0031) or lower (Song thrush 0.0018–0.0021) than our theoretical collision risk pooled over all species (0.0025).

Avoidance rate was not directly measured in this study, but was inferred based on the measured collision rate and the number of birds theoretically at risk. Thus, the avoidance rate given in this study summarizes the avoidance behaviour from the macro-, meso- and micro scale (May, 2015). The value is pooled over different bird-size classes and should not be used directly as parameter of avoidance in the Band-model which is specific for the species and their body sizes. Furthermore, it is not immediately comparable to studies where avoidance behaviour was determined based on flight tracks recorded by radar within and around offshore wind farms (Desholm and Kahlert, 2005; Plonczkier and Simms, 2012). In our study we waived measuring within the area of the turbines, because detection probability is strongly affected by the echoes of the wind turbines itself. Thus, with the current radar technique, proper quantitative comparisons between areas around and within wind farms are critical. It is a reasonable assumption that birds migrating over land effectively avoid wind turbines, and that visibility conditions might have a strong impact on collision rates. In order to rigorously examine the relationship between visibility conditions and collision rates, we recommend future studies record local and regional visibility in a standardized way in parallel with carcass searches and measurements of bird movement intensities. Another critical aspect to be considered is the potential attraction by artificial light sources mounted on the wind turbines (van Doren et al., 2017).

5. Conclusions

Most of the collision victims at our study site in the Swiss Jura mountains were nocturnally migrating small passerines, half of them kinglets. Collisions were related to migration season. However, within migration seasons, it was not possible to assign the carcasses clearly to spikes in migratory movements. There were some indications that impaired visibility due to meteorological conditions might increase collision risk. Our study clearly shows that collision risk for nocturnally migrating small passerines at onshore wind farms is not necessarily lower than for other bird groups. We conclude that results of carcass searches should always be interpreted within the context of the specific study area (topography, species involved, type and size of wind turbines) and weather conditions. Furthermore, visibility should be considered in future studies of bird movements in relation to collisions and when fine tuning shutdown systems for wind turbines mitigating bird collision risks.

Acknowledgements

The study was mainly financed by the Swiss Federal Office of Energy (SFOE), contract SI/501139-01, and partly by the Federal Office for the Environment (FOEN), contract 00.0293.PZ/M382-1188. We thank the environmental consulting office NATURA biologie appliquée Sàrl, the veterinaries A. and T. Wagner, the foundation "Stiftung für das Pferd" and the consulting office KohleNusbaumer. Furthermore we thank numerous collaborators of the Swiss Ornithological Institute, which substantially contributed to the success of the study. Special thanks go to G. Pasinelli, S. Werner and S. Lüpold as well as three reviewers who helped to improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2018.01.005.

References

Band, B., 2000. Windfarms and Birds: Calculating a Theoretical Collision Risk Assuming no Avoiding Action. Guidance Document. Scottish Natural Heritage.
Band, B., 2012a. Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Windfarms. (SOSS Report).
Band, B., 2012b. Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Windfarms — With Extended Method: Worked Example.
Band, W., Madders, M., Whitfield, D.P., 2007. Developing field and analytical methods to assess avian collision risk at wind farms. In: de Lucas, M. (Ed.), Birds and Windfarms - Risk Assessment and Mitigation. Servicios Informativos Ambientales/Quercus, Madrid, pp. 259–275.
Bruderer, B., 1997a. The study of bird migration by radar. Part 1: the technical basis. Naturwissenschaften 84, 1–8.
Bruderer, B., 1997b. The study of bird migration by radar. Part 2: major achievements. Naturwissenschaften 84, 45–54.
Bruderer, B., Boldt, A., 2001. Flight characteristics of birds: I. Radar measurements of speeds. Ibis 143, 178–204.
Bruderer, B., Jenni, L., 1990. Migration across the Alps. In: Bird Migration. Cambridge University Press, Cambridge, pp. 60–77.
Bruderer, B., Liechti, F., 1990. Richtungsverhalten nachtziehender Vögel in Süddeutschland und der Schweiz unter besonderer Berücksichtigung des Windeinflusses. (German with English abstract and figure legends). Der Ornithologische Beobachter 87, 271–293.
Bruderer, B., Liechti, F., 1999. Bird Migration across the Mediterranean. In: Slotow, R. (Ed.), Adam, N. Proc. Int. Ornithol. Congr, Birdlife South Africa, Durban, pp. 1983–1999.
Bruderer, B., Liechti, F., 2004. Welcher Anteil ziehender Vögel fliegt im Höhenbereich von Windturbinen? Der Ornithologische Beobachter 101, 327–335.
Bruderer, B., Peter, D., Boldt, A., Liechti, F., 2010. Wing-beat characteristics of birds recorded with tracking radar and cine camera. Ibis 152, 272–291.
Bruderer, B., Steuri, T., Aschwanden, J., Liechti, F., 2012. Vom militärischen Zielfolgeradar zum Vogelradar. Der Ornithologische Beobachter 109, 157–176.
Bull, L.S., Fuller, S., Sim, D., 2013. Post-construction avian mortality monitoring at Project West Wind. New Zealand Journal of Zoology 40, 28–46.
Dai, K., Bergot, A., Liang, C., Xiang, W.-N., Huang, Z., 2015. Environmental issues associated with wind energy - a review. Renew. Energy 75, 911–921.
Desholm, M., Kahlert, J., 2005. Avian collision risk at an offshore wind farm. Biol. Lett. 1, 296–298.
Development Core Team, R., 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
van Doren, B.M., Horton, K.G., Dokter, A.M., Klinck, H., Farnsworth, A., 2017. High-intensity urban light installation dramatically alters nocturnal bird migration. Proc. Natl. Acad. Sci. U. S. A. 114, 11175–11180.
Dürr, T. Auswirkungen von Windenergieanlagen auf Vögel und Fledermäuse. update Feb. 6, 2017. http://www.lugv.brandenburg.de/cms/detail.php/bb1.c.312579.de.
Eastwood, E., 1967. Radar Ornithology. Methuen, London.
Erickson, W.P., Wolfe, M.M., Bay, K.J., Johnson, D.H., Gehring, J.L., 2014. A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. PLoS One 9, e10749.
Erni, B., Liechti, F., Underhill, L.G., Bruderer, B., 2002. Wind and rain govern the intensity of nocturnal bird migration in central Europe - a log-linear regression analysis. Ardea 90, 155–166.
European Commission, 2010. Wind Energy Developments and Natura 2000. (Guidance Document).
EWEA European Wind Energy Association, 2016. Wind in Power. 2015 European

Statistics.
Gauthreaux, S.A., 1996. Suggested practices for monitoring bird populations, movements and mortality in wind resource areas. In: PNAWPPM-II (Ed.), Proceedings of National Avian-Wind Power Planning Meeting II. Prepared for the Avian Subcommittee of the National Wind Coordinating Committee by RESOLVE, Inc., Washington, DC, and LGL, Ltd., King City, Ontario, pp. 88–110.
Grodsky, S.M., Jennelle, C.S., Drake, D., 2013. Bird mortality at a wind-energy facility near a wetland of international importance. Condor 115, 700–711.
Grünkorn, T., Diederichs, A., Stahl, B., Poszig, D., Nehls, G., 2005. Entwicklung einer Methode zur Abschätzung des Kollisionsrisikos von Vögeln an Windenergieanlagen. (Report in German). Landesamt für Natur und Umwelt Schleswig-Holstein, Bio Consult SH, Hockensbüll D.
Grünkorn, T., von Rönn, J., Blew, J., Nehls, G., Weitekamp, S., Timmermann, H., Reichenbach, M., Coppack, T., Potiek, A., Krüger, O., 2016. Ermittlung der Kollisionsraten von (Greif-)Vögeln und Schaffung planungsbezogener Grundlagen für die Prognose und Bewertung des Kollisionsrisikos durch Windenergieanlagen (PROGRESS). (German with English abstract). BioConsult SH GmbH & Co.KG, Husum; ARSU GmbH, Oldenburg; IfAÖ Institut für Angewandte Ökosystemforschung GmbH, Rostock; Lehrstuhl für Verhaltensforschung Universität Bielefeld, Bielefeld.
Haupt, H., 2009. Der Letzte macht das Licht an! - Zu den Auswirkungen leuchtender Hochäuser auf den nächtlichen Vogelzug am Beispiel des „Post-Towers“ in Bonn. (German with English summary and legends). Charadrius 45, 1–19.
Hull, C.L., Muir, S., 2010. Search areas for monitoring bird and bat carcasses at wind farms using a Monte-Carlo model. Australas. J. Environ. Manag. 17, 77–87.
Hull, C.L., Stark, E.M., Peruzzo, S., Sims, C.C., 2013. Avian collisions at two wind farms in Tasmania, Australia: taxonomic and ecological characteristics of colliders versus non-colliders. N. Z. J. Zool. 40, 47–62.
Johnson, G.D., Erickson, W.P., Strickland, M.D., Sheperd, M.F., Sheperd, D.A., Sarappo, S.A., 2002. Collision mortality of local and migrant birds at a large-scale wind-power development on Buffalo Ridge, Minnesota. Wildl. Soc. Bull. 30, 879–887.
Kerlinger, P., 1989. Flight Strategies of Migrating Hawks. University of Chicago Press, Chicago.
Komenda-Zehnder, S., Jenni, L., Liechti, F., 2010. Do birds captures reflect migration intensity? - trapping numbers on an Alpine pass compared with radar counts. J. Avian Biol. 41, 434–444.
Korner-Nievergelt, F., Behr, O., Brinkmann, R., Etterson, M.A., Huso, M.M.P., Dalthorp, D., Korner-Nievergelt, P., Roth, T., Niermann, I., 2015. Mortality estimation from carcass searches using the R-package carcass - a tutorial. Wildl. Biol. 21s, 30–43.
Krijgsveld, K.L., Akershoek, K., Schenk, F., Dijk, F., Dirksen, S., 2009. Collision risk of birds with modern large wind turbines. Ardea 97, 358–366.
Kunz, T., Arnett, E.B., Cooper, B.M., Erickson, W.P., Larkin, R.P., Mabee, T., Morrison, M.L., Strickland, M.D., Szewezak, J.M., 2007. Assessing impacts of wind-energy development on nocturnally active birds and bats: a guidance document. J. Wildl. Manag. 71, 2449–2486.
Liechti, F., Guélat, J., Komenda-Zehnder, S., 2013. Modelling the spatial concentrations of bird migration to assess conflicts with wind turbines. Biol. Conserv. 162, 24–32.
Lunn, D., Jackson, C., Best, N., Thomas, A., Spiegelhalter, D., 2013. A practical introduction to Bayesian analysis. In: The BUGS Book. CRC Press, Boca Raton U.A..
Marques, A.T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M.J.R., Fonseca, C., Mascarenhas, M., Bernardino, J., 2014. Understanding bird collisions at wind farms. An updated review on the causes and possible mitigation strategies. Biol. Conserv. 179, 40–52.
Masden, E.A., Cook, A., 2016. Avian collision risk models for wind energy impact assessments. Environ. Impact Assess. Rev. 56, 43–49.
May, R.F., 2015. A unifying framework for the underlying mechanisms of avian avoidance of wind turbines. Biol. Conserv. 190, 179–187.
May, R., Reitan, O., Bevanger, K., Lorentsen, S.H., Nygård, T., 2015. Mitigating wind-turbine induced avian mortality: sensory, aerodynamic and cognitive constraints and options. Renew. Sust. Energ. Rev. 42, 170–181.
Plonczkier, P., Simms, I.C., 2012. Radar monitoring of migrating pink-footed geese: behavioural responses to offshore wind farm development. J. Appl. Ecol. 49, 1187–1194.
Schmaljohann, H., Liechti, F., Bächler, E., Steuri, T., Bruderer, B., 2008. Quantification of bird migration by radar - a detection probability problem. Ibis 150, 342–355.
Smith, J.A., Dwyer, J.F., 2016. Avian interactions with renewable energy infrastructure: an update. Condor 118, 411–423.
Wang, S., Wang, S., Smith, P., 2015. Ecological impacts of wind farms on birds: questions, hypotheses, and research needs. Renew. Sust. Energ. Rev. 44, 599–607.
Welcker, J., Liesenjohann, M., Blew, J., Nehls, G., Grünkorn, T., 2017. Nocturnal migrants do not incur higher collision risk at wind turbines than diurnally active species. Ibis 159, 366–373.
Zaugg, S., Sapporta, G., van Loon, E., Schmaljohann, H., Liechti, F., 2008. Automatic identification of bird targets with radar via patterns produced by wing flapping. J.R. Soc. Interface 5, 1041–1053.
Zimmerling, J.R., Pomeroy, A.C., d'Entremont, M.V., Francis, C.M., 2013. Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments. Avian Conservation and Ecology 8, 13.