Science of the Total Environment 954 (2024) 176551

Contents lists available at ScienceDirect

Science of the Total Environment

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

Effects of wind turbine dimensions on the collision risk of raptors: A simulation approach based on flight height distributions

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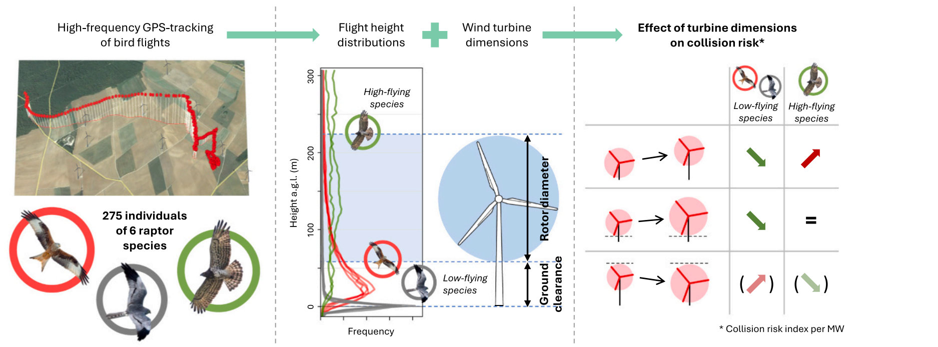
https://doi.org/10.1016/j.scitotenv.2024.176551

Available online 30 September 2024

H I G H L I G H T S

- Simulations indicated wind turbine dimensions can affect collision risk of raptors.
- Effects were species-specific due to varying flight height distributions.
- Collision risk could be reduced by informed selection of wind turbine dimensions.
- Increasing ground clearance reduced simulated collision risk in 5/6 study species.
- Using larger but fewer turbines reduced collision risk per MW in 5/6 species.

G R A P H I C A L A B S T R A C T



A R T I C L E I N F O

Editor: Rafael Mateo

Keywords:
Bird conservation
Energy transition
Environmental impact assessment
Flight behaviour
Renewable energy
Wind turbine size

A B S T R A C T

Wind energy development is a key component of climate change mitigation. However, birds collide with wind turbines, and this additional mortality may negatively impact populations. Collision risk could be reduced by informed selection of turbine dimensions, but the effects of turbine dimensions are still unknown for many species.

As analyses of mortality data have several limitations, we applied a simulation approach based on flight height distributions of six European raptor species. To obtain accurate flight height data, we used high-frequency GPS tracking (GPS tags deployed on 275 individuals). The effects of ground clearance and rotor diameter of wind turbines on collision risk were studied using the Band collision risk model.

Five species had a unimodal flight height distribution, with a mode below 25 m above ground level, while Short-toed Eagle showed a more uniform distribution with a weak mode between 120 and 260 m. The proportion of positions within 32–200 m ranged from 11 % in Marsh Harrier to 54 % in Red Kite.

With increasing ground clearance (from 20 to 100 m), collision risk decreased in the species with low mode (−56 to −66 %), but increased in Short-toed Eagle (+38 %). With increasing rotor diameter (from 50 to 160 m) at fixed ground clearance, the collision risk per turbine increased in all species (+151 to +558 %), while the collision risk per MW decreased in the species with low mode (−50 % to −57 %).

These results underpin that wind turbine dimensions can have substantial effects on the collision risk of raptors. As the effects varied between species, wind energy planning should consider the composition of the local bird community to optimise wind turbine dimensions. For species with a low mode of flight height, the collision risk for a given total power capacity could be reduced by increasing ground clearance, and using fewer turbines with larger diameter.

1. Introduction

A key component of the strategies to reduce greenhouse gas emissions is the development of wind energy. For example, the European Union targets a total installed wind power capacity of 510 GW by 2030 (European Commission, 2022), which requires a more than twofold increase compared to 2022 (WindEurope, 2023). However, the expansion of wind energy may have detrimental effects on biodiversity. One of

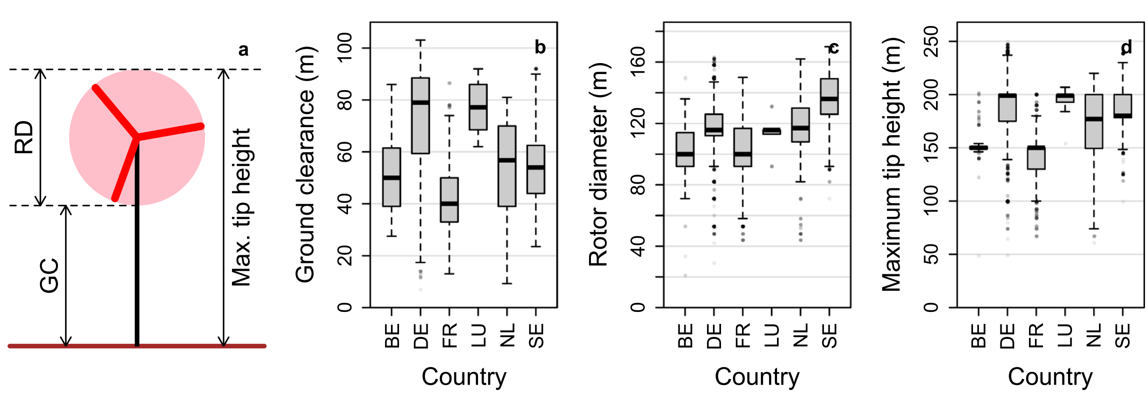


Fig. 1. (a) Illustration of the terms used in this study: GC = ground clearance; RD = rotor diameter. (b) to (d) Ground clearance, rotor diameter and maximum tip height of wind turbines constructed between 2015 and 2023 in Belgium, Germany, France, Luxemburg, The Netherlands and Sweden (n = 12,809 for ground clearance and maximum tip height, and 14,911 for rotor diameter).
Source: The Wind Power (2022, 2023).

the main impacts is that wind turbines cause lethal collisions of birds (Thaxter et al., 2017). This additional anthropogenic mortality may significantly impact bird populations (Bellebaum et al., 2013; Duriez et al., 2022).

To reduce the collision risk of birds with wind turbines, a variety of mitigation measures have been used, such as an informed site selection or wind turbine shut-down during periods with increased collision risk (Marques et al., 2014; Arnett and May, 2016). Another possible measure which has received limited attention so far is the informed selection of the wind turbine dimensions (hub height, rotor diameter), which determine the height range swept by the wind turbine rotors (Johnston et al., 2014). This rotor height range, delimited by the lowest and highest points the rotor blades can reach ("ground clearance" and "maximum tip height"; Fig. 1a), differs strongly between available wind turbine models. For example, in onshore wind turbines constructed since 2015 in six European countries, ground clearance varied between 10 and 100 m, and the rotor diameter between 40 and 170 m (Fig. 1). Over the past decades, there has been a clear trend towards increasing rotor diameters (Serrano-González and Lacal-Arántegui, 2016; Appendix 1: Figs. S1–2).

The selection of the rotor height range of wind turbines potentially has a large effect on collision risk, as birds use the vertical airspace in a non-uniform way (Ross-Smith et al., 2016; Pfeiffer and Meyburg, 2022). In addition, rotor diameter can be expected to affect collision risk as it determines the volume of the space where collisions can occur. Indeed, earlier studies found that the rate of bird collisions at a wind turbine was affected by different turbine size parameters, such as rotor diameter (Garvin et al., 2024), rated power (Thaxter et al., 2017; Huso et al., 2021), hub height (De Lucas et al., 2008; Loss et al., 2013), ground clearance (Garvin et al., 2024) and maximum tip height (Anderson et al., 2022). However, results were not always consistent, and studies either did not distinguish between bird species (De Lucas et al., 2008; Loss et al., 2013; Thaxter et al., 2017; Huso et al., 2021) or considered only a few species (Anderson et al., 2022; Garvin et al., 2024).

Moreover, the aforementioned studies were based on ground searches of carcasses around wind turbines, which implies several limitations: 1) as the different size parameters may be intercorrelated, it is difficult to disentangle their individual effects (Loss et al., 2013; Anderson et al., 2022); 2) the ability to detect effects of turbine dimensions may be limited due to a variety of confounding factors affecting collision risk at a turbine such as bird abundance, topography or habitat (Garvin et al., 2024); 3) analyses are restricted to available turbine models and to species which are already exposed to wind turbines within their distribution range; 4) the availability of the required high-quality fatality data, based on sufficient search effort (Ravache et al., 2024) and including species- and site-specific information on carcass persistence and carcass detectability, is limited. At the same time, the rapid expansion of wind energy implies that there is an urgent need to obtain information on the effects of turbine dimensions on collision risk for a range of bird species.

A promising complementary approach to carcass search studies is to assess the effects of turbine dimensions on collision risk in a theoretic way based on information on the birds' flight behaviour, mainly with respect to the flight height distributions (Johnston et al., 2014; Schaub et al., 2020). However, the study of flight height for this purpose has been notoriously difficult, as it requires a high level of accuracy in the height measurements. Methods like visual observations or bird-borne GPS tags generally imply large vertical errors, which require the use of complex modelling techniques to obtain unbiased flight height distributions (Johnston et al., 2014; Péron et al., 2020). A novel possibility to collect accurate flight height data is high-frequency GPS tracking, with GPS fixes taken at intervals of a few seconds, where the GPS module remains turned on between fixes. This "continuous mode" substantially reduces the error in GPS height data (Bouten et al., 2013; Schaub et al., 2023).

Here, we used an extensive high-frequency GPS tracking dataset to investigate the flight height distributions of six raptor species across 15 study areas in six European countries. Raptors (Accipitriformes) are particularly prone to wind turbine collisions (Beston et al., 2016; Thaxter et al., 2017). In Europe, 23 out of 30 breeding Accipitriformes species (Keller et al., 2020) have been reported as collision victims (including all six study species; Dürr, 2023) and Serratosa et al. (2024) found that wind turbine collisions already represented ca. 2 % of mortality events in migratory raptors in the African-Eurasian flyway in the past two decades. As raptors are long-lived and reproduce at a low pace, their populations are particularly sensitive to an increased mortality (Bellebaum et al., 2013; Beston et al., 2016).

Our main objective was to assess how the theoretical collision risk varied according to the ground clearance and rotor diameter of wind turbines in the six study species. Our study approach was based on a stochastic adaptation of the Band collision risk model (Band, 2000; McGregor et al., 2018). In this way, we took into account the overlap of the wind turbines' rotor height range with the birds' flight height distributions ("vertical overlap"), alongside technical parameters varying with rotor diameter, such as rotor rotation speed. Furthermore, we considered the increase of rated power of wind turbines with larger rotor diameters, to determine whether the collision risk for a given targeted power capacity can be minimised using a large number of small turbines or a small number of large turbines. Finally, we assessed the consistency of the results between study areas.

2. Materials and methods

2.1. Data collection

We collected flight height data using solar-powered GPS tags deployed on 275 individuals of six raptor species (Montagu's Harrier *Circus pygargus* [MoH; $n = 76$], Hen Harrier *C. cyaneus* [HH; $n = 51$], Marsh Harrier *C. aeruginosus* [MaH; $n = 29$], Common Buzzard *Buteo buteo* [CB; $n = 24$], Red Kite *Milvus milvus* [RK; $n = 93$] and Short-toed Eagle *Circaetus gallicus* [STE; $n = 2$]) in 15 study areas in France, Belgium, Luxembourg, The Netherlands, Germany and Sweden between 2009 and 2023 (Table 1). For the 21 species-area combinations (Appendix 1: Fig. S4), the number of individuals varied between 2 and 48 (median: 9; Table S3). 205 of the individuals were tagged as adults and 70 as nestlings (see Appendix 1 for details). Eleven different GPS tag models from the manufacturers *Milsar*, *Ornitela* and *UvA-BiTS* (Bouten et al., 2013) were used (Table S3). Tags weighed 9.7–26.3 g, i.e. 1.4–6.5 % of individual body weight (median: 2.9 %; mean: 3.2 %; SD: 1.0 %). The tags transferred the recorded data remotely, either using the GSM network (*Milsar*, *Ornitela*) or local antennas (*UvA-BiTS*).

Throughout this study, we exclusively relied on high-frequency GPS tracking data (GPS positions recorded at an interval of 2–3 s), with the GPS module operating in continuous mode (i.e., it remained turned on between successive fixes). This type of tracking data provides considerably more accurate height data than GPS data in standard mode, with mean absolute error of 1–7 m, as opposed to 4–30 m in standard mode (Bouten et al., 2013; Schaub et al., 2023). High-frequency data were collected mostly during manually set blocks of 1–4 h per day, and to a lesser extent using automatic geofences around areas of interest such as wind farms (see Appendix 1 for details).

The dataset was restricted to 15 defined study areas (Appendix 1: Fig. S4), which are used by the study species for breeding. The tagged CB were year-round residents within the study areas, while all MoH, MaH and STE (trans-Saharan migrants) and most HH and RK (partial migrants) left the study areas outside the breeding season. No further spatial restrictions were applied; hence the dataset included GPS positions in different habitats and both outside and inside wind farms (but note that the majority of the positions were outside wind farms).

The study areas were dominated by agricultural or semi-natural open habitat with a varying proportion of woodland. The topography varied from flat polder landscapes to hilly terrain and low mountains

Table 1
Overview of sample size and parameters of flight height distributions per species. Parameter estimate: value across all data; range in brackets: first and third quantile of values per individual (minimum and maximum for STE). ind. = individuals (number of individuals with ≥5 h of flight data in brackets); pos. = positions, prop. = proportion, IQR = inter-quartile range, RHR = general rotor height range (32–200 m a.g.l.).

	Montagu's Harrier	Hen Harrier	Marsh Harrier	Common Buzzard	Red Kite	Short-toed Eagle
n study areas	6	2	4	3	5	1
Time period	2009–23	2012–23	2012–23	2021–23	2019–23	2021–23
n ind. (≥5 h)	76 (54)	51 (21)	29 (19)	24 (15)	93 (70)	2 (2)
n GPS pos.	1,906,493	386,371	892,025	356,742	3,826,726	47,519
Time span (h)	1554.2	300.4	747.9	294.9	3188.9	39.6
Mode (m)	2.5 (2.5–2.5)	2.5 (2.5–2.5)	2.5 (2.5–2.5)	7.5 (7.5–7.5)	22.5 (17.5–27.5)	127.5 (127.5–252.5)
Mode prop. (%)	36.9 (30.4–44.7)	24.1 (20.9–29.2)	34.4 (23.4–34.2)	9.4 (7.7–11.1)	6.1 (4.7–7.5)	2.0 (1.3–2.6)
Median (m)	4.0 (2.2–6.4)	7.2 (4.0–10.0)	3.0 (3.0–7.5)	37.4 (36.0–41.8)	51.3 (44.4–73.3)	187.9 (155.2–287.9)
IQR (m)	11.6 (7.0–16.9)	32.6 (16.6–47)	11.0 (11.0–27.5)	82.0 (77.5–95.5)	89.9 (65.8–132.5)	204.3 (126.0–266.0)
Prop. RHR (%)	12.1 (8.8–14.2)	20.6 (13.0–26.2)	11.4 (10.4–16.1)	46.1 (42.5–51.2)	54.2 (48.9–59.5)	47.7 (28.1–61.1)

(Table S1). All six study species typically forage in open habitats. MoH, HH and MaH nest on the ground in agricultural fields, reedbeds, shrubland or woodland clearings, while CB, RK and STE nest in trees, often close to the woodland edge (del Hoyo et al., 1994).

2.2. Data processing

All data processing and analyses were performed in *R* 4.0.3 (R Core Team, 2020). The dataset was restricted to flight positions only, based on the instantaneous GPS ground speed recorded alongside each GPS location (see Appendix 1 for details). The GPS altitude obtained from the tags was height above mean sea level, which we transformed into height above ground level (termed height a.g.l. hereafter) by applying the *Shuttle Radar Topography Mission* global digital elevation model with a resolution of 30 m (NASA JPL, 2013). Despite the high accuracy in the GPS tracking data, negative heights a.g.l. were recorded to some extent. To avoid introducing biases (Péron et al., 2020), these negative height data were kept in the dataset. See Appendix 1 for additional information on the processing of the GPS height data.

The final dataset encompassed 7,415,876 in-flight GPS positions, i.e. 6126 h of recorded flight movements (Table 1). Per individual, the timespan varied between <0.1 and 200.4 h (median: 10.7 h; mean: 22.3 h). For all parts of the analysis where individual differences were considered, individuals with <5 h of flight data (n = 94) were omitted (Table 1).

2.3. Comparison of flight height distributions

To compare flight height distributions, we derived the following five parameters per species, per species-area combination and per individual bird: mode (centre of the 5 m bin with the highest proportion of positions), proportion of mode (proportion of positions in the bin of the

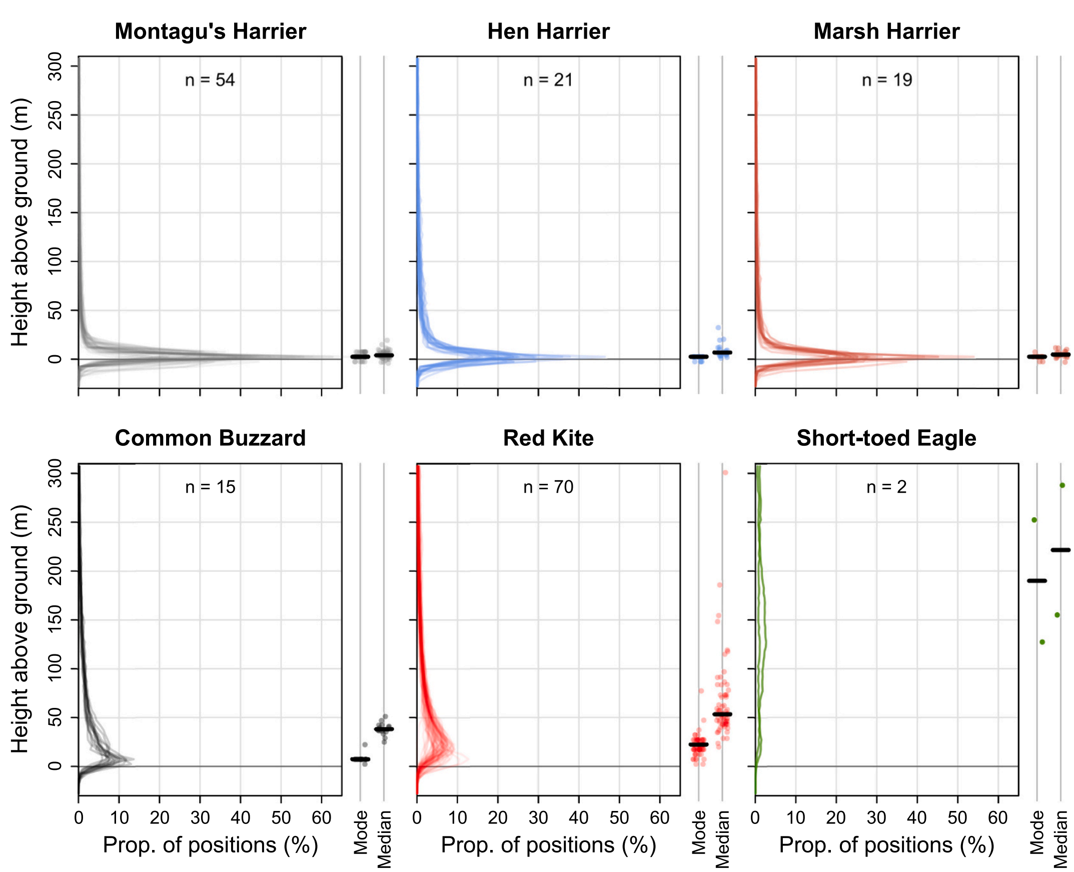


Fig. 2. Flight height distributions per species in height bins of 5 m. Every line represents one individual bird; the mode and median per individual are indicated right of the panels (thick horizontal line indicating medians across individuals). Prop. = proportion.

mode), median, interquartile range and the proportion of positions within 32–200 m a.g.l. ("general rotor height range" encompassing the rotors of most modern wind turbines; see Appendix 1).

Due to difficulties to fit parametric models to the flight height distribution parameters (Fig. 2), we applied non-parametric Kruskal-Wallis rank-sum tests (*R* function *kruskal.test*) to test differences in the five distribution parameters between species and between study areas within species (see Appendix 1 for details).

2.4. Wind turbine models and scenarios

For information on available wind turbine models and wind turbines installed in the six study countries, we relied on the databases provided by The Wind Power (2022, 2023). For later use in the collision risk index (see below), we built Generalized Additive Models (GAM) for the relationships of mean rotation speed (revolutions per minute), blade width and rated power with rotor diameter (see Appendix 1 for details).

For the analysis of the effect of wind turbine dimensions on collision risk, we set up a range of hypothetical wind turbine models by combining ground clearances of 10–120 m (increments of 5 m) and rotor diameters of 40–170 m (increments of 10 m; 322 combinations in total). Note that we extended the range of ground clearances somewhat beyond the dimensions of operating onshore wind turbines (Fig. 1b) to cover possible future developments.

To structure the comparison of collision risk amongst the wind turbine models, we applied three "scenarios": 1) ground clearance varied at fixed rotor diameter; 2) rotor diameter varied at fixed ground clearance; 3) rotor diameter varied at fixed maximum tip height (implying simultaneous variation of diameter and ground clearance). The third scenario was included because it is common that maximum tip height is capped by legal regulations (e.g. to prevent impacts on aviation), while the wind industry commonly strives for a maximisation of the maximum tip height due to the increased wind yield (Hau, 2006). As fixed values, we primarily focussed on one example for each of the three scenarios: for diameter and ground clearance (scenarios 1 and 2), we used the medians across wind turbines constructed since 2015 in the six countries (120 and 60 m, respectively). For maximum tip height (scenario 3), we primarily considered 150 m as fixed value, as this represents a common statutory limit in France and Belgium (Fig. 1d).

Throughout, we applied an "all other things being equal" approach, i.e. while ground clearance or rotor diameter were varied, the geographic location of the wind turbine, environmental factors, bird abundance and bird behaviour were assumed to be equal.

2.5. Collision risk index

For each combination of hypothetical wind turbine models and study species, we derived a collision risk index (CRI) based on the Band collision risk model (CRM; Band, 2000), estimating the expected number of collisions given a range of bird- and wind-turbine-related input parameters. In this way, the CRI did not only integrate the vertical overlap between wind turbine rotors and flight height distributions, but also technical characteristics such as rotation speed and blade width, which are correlated with rotor diameter (Appendix 1: Fig. S3). The Band CRM consists of two stages: stage I estimates the expected number of rotor crossings N_{cross}, largely determined by bird density, vertical overlap and avoidance rate. Stage II estimates the collision probability per rotor crossing P_{coll}, based on rotation speed, blade width and flight speed, amongst others. The expected number of collisions are obtained using the formula $N_{coll} = N_{cross} \times P_{coll}$.

We defined the CRI for a given combination of wind turbine dimensions as the expected number of collisions per year for one turbine in an area with a bird density of 0.1 flying individuals per km^2, assuming the default avoidance rate of 98 % (SNH, 2018). Note that the choice of these two parameters affected the absolute CRI value, but not the relative change in CRI between wind turbine models, our focus of interest. The following input parameters were modified according to the wind turbine model: ground clearance, rotor diameter, flight speed, rotation speed and blade width. The latter two were assumed to only vary with rotor diameter. The CRM calculations were performed using the function *band_crm* from the *R* package *stochLAB* (Caneco et al., 2022). See Appendix 1 for additional details and an overview of the input parameters used.

To obtain confidence intervals, we adapted the "stochastic collision risk model" (sCRM; McGregor et al., 2018; Caneco et al., 2022) to our study question. Stochasticity was only included for those input parameters which could affect the relative difference of collision risk between wind turbine models, i.e. flight height distribution for the effect of ground clearance, and flight height distribution, rotation speed and blade width for the effect of rotor diameter (see Appendix 1 for details). Per wind turbine model, 500 stochastic replicates were produced; the mean across replicates was used as estimate of the CRI, and the 2.5 and 97.5 % quantiles as limits of the 95 % confidence interval.

As the rated power (or nameplate capacity) of a wind turbine typically increases with the rotor diameter (Fig. 3d), we also computed the CRI per power for scenarios 2 and 3. The rated power for each hypothetical turbine model was determined based on the GAM described above (including stochasticity; see Appendix 1). The CRI per power allowed comparing situations where the same total power capacity is achieved using wind turbines of different diameters, implying different numbers of turbines. As turbine density is negatively correlated with rotor diameter for technical reasons, the choice between fewer larger or more smaller turbines is a realistic situation whenever a wind farm is planned in a limited designated area, or when an existing wind farm is repowered (Huso et al., 2021).

3. Results

3.1. Flight height distributions

In MoH, HH, MaH, CB and RK, the flight height distributions were clearly unimodal (Fig. 2). The mode was lowest in the three species of harriers (2.5 m), followed by CB (7.5 m) and RK (22.5 m; Table 1). In STE, the flight height distributions deviated from the other species, being relatively uniform (Q1: 115 m; Q3: 320 m; Table S8) with an indistinct mode at 127.5 and 252.5 m in the two tracked individuals. Medians and interquartile ranges were lowest in the harriers, intermediate in CB and RK and highest in STE (Table 1; see Appendix 2: Tables S6–7 for results of Kruskal-Wallis tests). The proportion of positions within 32–200 m a.g.l. varied between 11 and 21 % in the harriers and between 46 and 54 % in CB, RK and STE (Table 1). Between study areas, the variation in the distribution parameters was generally smaller than between species (Appendix 2: Figs. S8–10; Tables S6–8).

3.2. Effect of wind turbine dimensions on collision risk

The collision risk index (CRI) per wind turbine varied considerably between hypothetical turbine models in all species (Fig. 3), the highest CRI being 12.1–13.5 times higher than the lowest. Also regarding the CRI per power, there was large variation between turbine models in the five species with low mode of flight height (MoH, HH, MaH, CB and RK; termed "low-mode species" hereafter; highest CRI per power 12.1–17.0 times higher than lowest), while variation was relatively small in STE (highest 1.5 times higher than lowest). In relative terms, the effect of wind turbine dimensions was similar for the low-mode species, whereas STE showed a distinctly diverging pattern throughout (Fig. 4). The effects of ground clearance and rotor diameter on CRI were similar across study areas for the five species with data available from ≥2 areas (Appendix 2: Figs. S16–18).

3.2.1. Ground clearance

With increasing ground clearance at fixed rotor diameter (scenario

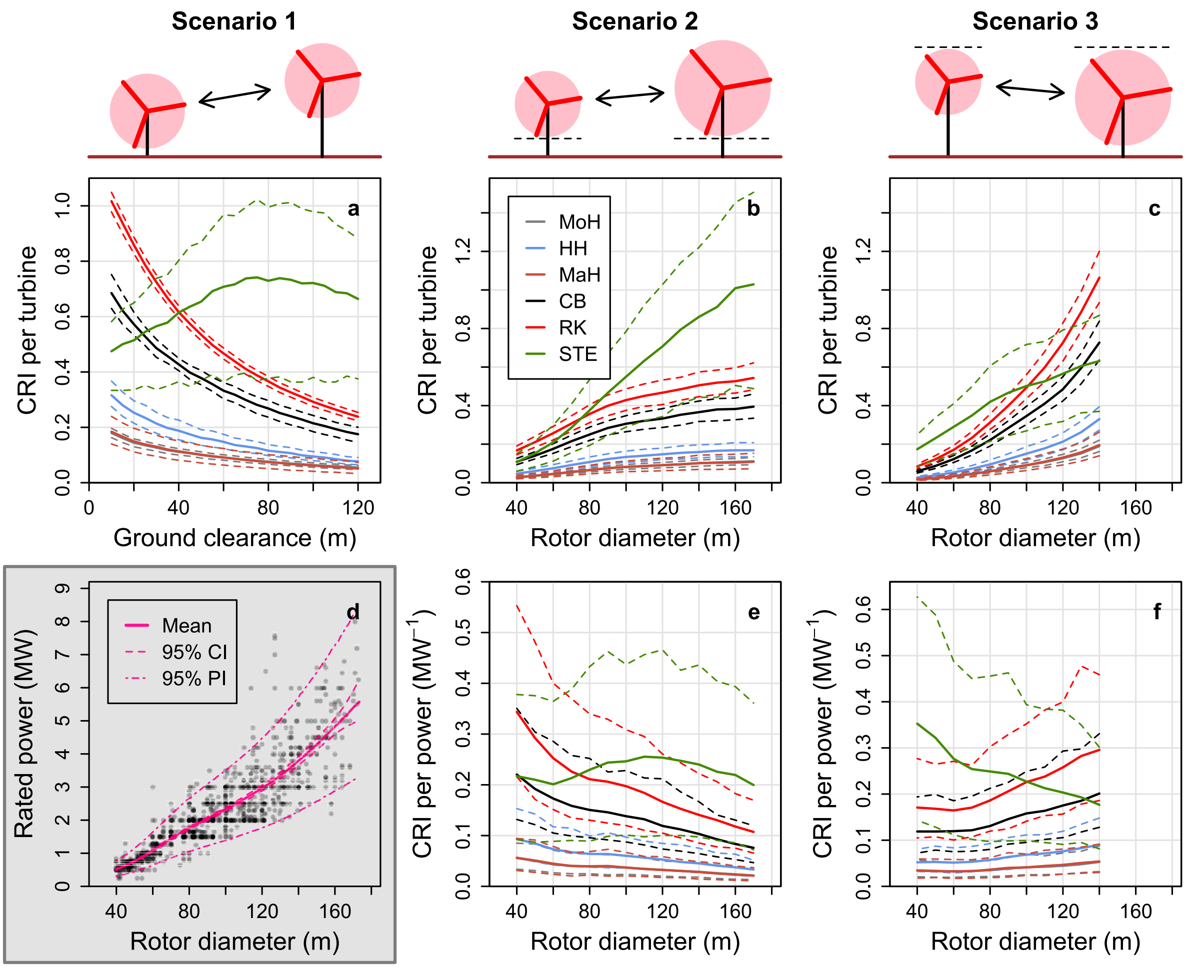


Fig. 3. Effect of ground clearance and rotor diameter of wind turbines on collision risk. Panels refer to wind turbines with 120 m diameter (a), 60 m ground clearance (b, e) or maximum tip height of 150 m (c, f). Thick lines indicate means and dashed lines 95 % confidence intervals (CI). Note that lines for MoH and MaH lie on top of each other. (d) Relationship of rated power with rotor diameter for onshore wind turbines. Points: individual wind turbine models ($n = 1360$); lines: predictions from a Generalized Additive Model. MoH = Montagu's Harrier, HH = Hen Harrier, MaH = Marsh Harrier, CB = Common Buzzard, RK = Red Kite, STE = Short-toed Eagle; CRI = collision risk index; PI = prediction interval.

1), the CRI per turbine decreased in the five low-mode species (Fig. 3a), regardless of the selected level of the rotor diameter (Fig. S11). In STE, CRI increased continuously with increasing ground clearance at small rotor diameters (below ca. 80 m), whereas at larger diameters, CRI peaked around 50–90 m ground clearance (Figs. 3a, S11). For a turbine with 120 m diameter, the relative change in CRI from 20 to 100 m ground clearance was significant in all species (−56 to −66 % in the low-mode species; +38 % in STE; Fig. 4; see Table S9 for confidence intervals and additional pairwise combinations).

3.2.2. Rotor diameter

The effect of rotor diameter on collision risk at fixed ground clearance (scenario 2) was influenced by two opposite trends: on the one hand, the number of rotor crossings (stage I of Band CRM) increased strongly with increasing diameter; on the other hand, the probability of colliding per rotor crossing (stage II of Band CRM) decreased (Appendix 2: Fig. S15), mainly as a consequence of reduced rotation speed (Appendix 1: Fig. S3). The resulting CRI per turbine increased with increasing diameter in all six species for all levels of ground clearance (Figs. 3b, S11; e.g. increase by 151–558 % when increasing the diameter from 50 to 160 m at a ground clearance of 60 m; Table S9).

As the mean rated power increased with increasing diameter (Fig. 3d), the CRI per power decreased with increasing diameter in the low-mode species (Figs. 3e, S12). In STE, this was also the case when ground clearance was large (above ca. 90 m; Fig. S12). With smaller ground clearance, CRI per power in STE peaked at diameters of 90–140 m (Fig. 3e). In all species, confidence intervals for the CRI per power were wide (Fig. 3e), reflecting the large variation in rated power for a given rotor diameter (Fig. 3d). Nevertheless, for a turbine with 60 m ground clearance, the relative difference in CRI per power between a diameter of 50 and 160 m was significant in all low-mode species (−50 to −57 %), while it was not for STE (Fig. 4; Table S9).

With increasing rotor diameter at fixed maximum tip height (scenario 3), the CRI per turbine increased in all species (Figs. 3c, S13). In the low-mode species, this increase was stronger than in the fixed ground clearance case (scenario 2; Fig. 3b, c), reflecting that an increased rotor diameter at fixed maximum tip height implies a decreased ground clearance. The CRI per power increased with increasing diameter in the low-mode species, while it decreased in STE (Figs. 3f, S14). The relative change in CRI per power between a diameter of 50 and 130 m for a turbine with 150 m maximum tip height was close to significant in both the low-mode species (+51 to +78 %) and STE (−35 %; Fig. 4; see Table S9 for confidence intervals).

4. Discussion

4.1. Flight height distributions

High-frequency GPS tracking allowed us to describe the flight height distributions of six raptor species during the breeding season. Based on

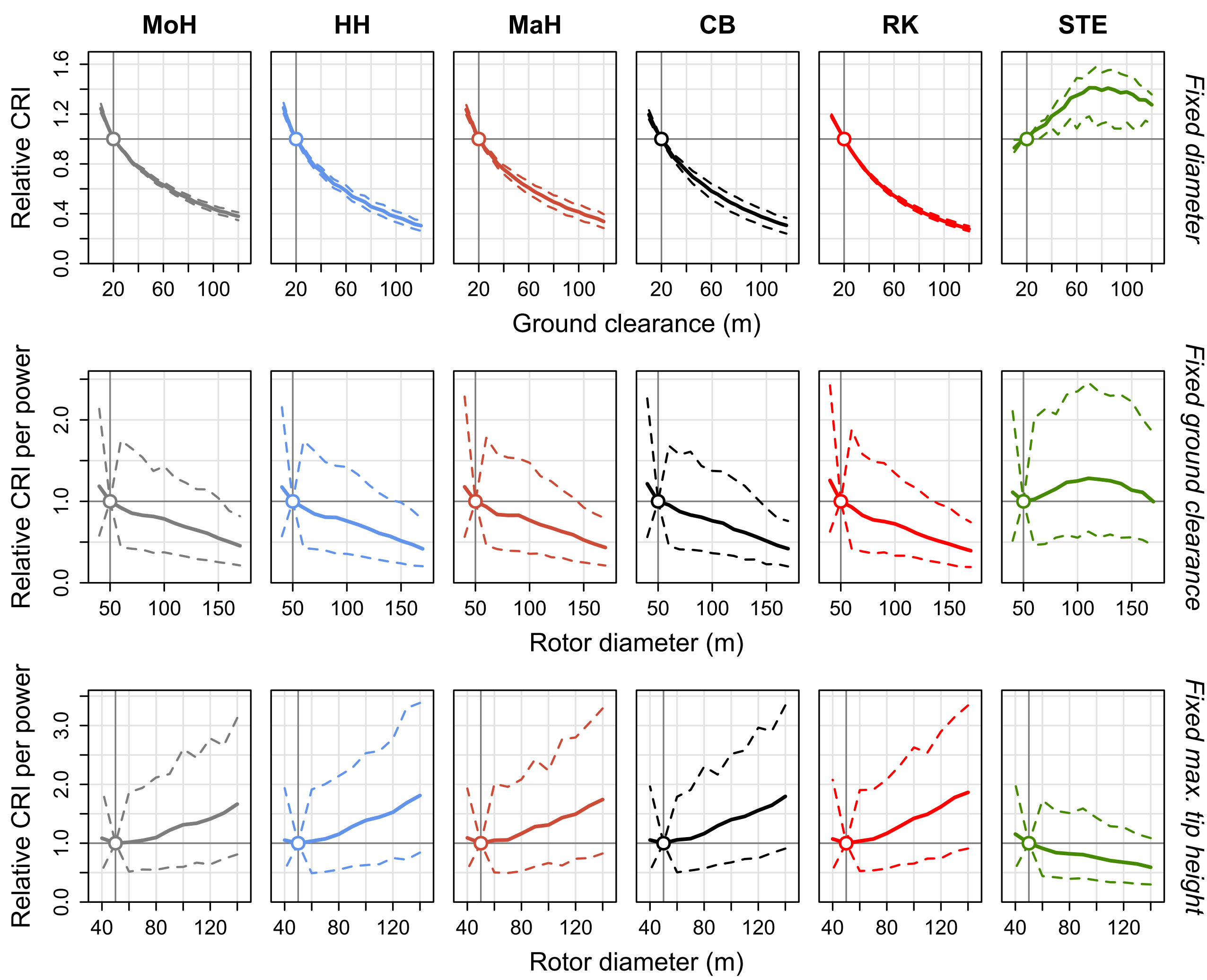


Fig. 4. Effect of ground clearance and rotor diameter of wind turbines on collision risk relative to a reference level (thick vertical line). Panels show either collision risk index per turbine (first row) or per rated power (second and third row), and refer to wind turbines with 120 m diameter (first row), 60 m ground clearance (second row) or maximum tip height of 150 m (third row). Thick lines indicate means and dashed lines 95 % confidence intervals. MoH = Montagu's Harrier, HH = Hen Harrier, MaH = Marsh Harrier, CB = Common Buzzard, RK = Red Kite, STE = Short-toed Eagle.

the mode of the flight height distributions, the six species were separated into two groups: Montagu's Harrier (MoH), Hen Harrier (HH), Marsh Harrier (MaH), Common Buzzard (CB) and Red Kite (RK) showed clearly unimodal distributions with a mode at low height (below 30 m a.g.l.), while Short-toed Eagle (STE) showed a more uniform distribution with a weak mode at 120–260 m. These differences can be explained by the species' behaviour, with harriers hunting while flying low above the vegetation, CB and RK more often soaring at higher height, but predominantly foraging at heights below 50 m, and STE regularly searching for prey from 100 m and above (del Hoyo et al., 1994). Earlier studies on MoH, HH and RK reported similar results (Wilson et al., 2015; Grajetzky and Nehls, 2017; Pfeiffer and Meyburg, 2022), but comparison between studies is hampered by differences in tracking methods and in the parameters reported (e.g. Shamoun-Baranes et al., 2006). Amongst the large number of recent GPS-tracking studies on birds, surprisingly many did not report the shape of the flight height distributions (e.g. Péron et al., 2017; Tikkanen et al., 2018), which is however essential to assess the effect of wind turbine dimensions on collision risk, as demonstrated here.

It is important to emphasise that the flight height distributions presented here are only representative of the birds' local movements during the breeding season. We expect different distributions during migration, presumably with a larger proportion of time at greater heights (Spaar and Bruderer, 1997) and a less pronounced mode, which in turn might alter the effect of wind turbine dimensions on collision risk. At the same time, it is noteworthy that we found only little variation in flight height distributions between study areas. The average flight height distributions across weather conditions and habitats during the breeding season can thus be seen as a basic characteristic of a species associated with its morphology and ecology. At a finer spatial and temporal scale, it is likely that flight height distributions vary according to factors like habitat, topography, weather or time of the day (Shamoun-Baranes et al., 2006; Pfeiffer and Meyburg, 2022; Vignali et al., 2022). These effects were beyond the scope of the present study but would be a valuable subject for future research, which would allow to refine the recommendations on wind turbine dimensions (see below) with respect to habitat and topography, and provide indications for the temporary shut-down of wind turbines.

For STE, our study included data from only two individuals. However, we are confident that the large differences in the overall shape of the flight height distributions between STE and the other five study species are genuine, as we generally found small individual variation within species. Moreover, additional GPS-tagged STE individuals from other areas not included in this study showed similar, uniform flight height distributions with a relatively high mode (Appendix 3). Nevertheless, it would be valuable to extend the dataset on STE to confirm our results and to reduce the confidence intervals concerning the effect of turbine dimensions on collision risk for this species (Fig. 4).

4.2. Relevance of the simulation approach

In this study, we used data on flight behaviour in combination with a collision risk model, instead of mortality data from ground searches of carcasses around wind turbines, to assess the effects of wind turbine dimensions on collision risk. The theoretic flight behaviour approach has several advantages compared to mortality studies: 1) it allows to disentangle the effects of intercorrelated turbine size parameters (Loss et al., 2013); 2) the numerous confounding factors affecting the collision rate at a turbine (e.g. bird abundance or topography; Garvin et al., 2024) can be kept constant; 3) it can be applied to species which are not yet exposed to wind turbines; and 4) it does not depend on mortality data of sufficient quality with respect to search effort and information on carcass persistence and detectability, which are currently of limited availability.

However, a disadvantage of the flight behaviour approach is that little reliable information is available on the avoidance of wind turbines by birds, i.e. one of the aspects of flight behaviour determining collision risk. Here, we made the assumption that avoidance is independent of wind turbine dimensions. In practice, this is not necessarily the case: for example, the size and rotation speed of turbines could affect the capacity of birds to detect and avoid the rotor blades (Blary et al., 2023), and behaviours which might make birds more susceptible to collisions such as foraging or display flights could be predominantly performed within certain height ranges (Hoover and Morrison, 2005). Therefore, the effects of turbine dimensions on avoidance should be a priority for future studies.

Moreover, our approach depends on the reliability of the Band collision risk model, especially concerning the effect of rotor diameter (depending more strongly on the probability of collision per rotor crossing estimated by the model than the effect of ground clearance; Appendix 2: Fig. S15). The Band model was deemed mathematically sound, but validating its outcomes has remained difficult due to the lack of reliable data on species-specific avoidance rates, an important input parameter (Chamberlain et al., 2006). Given the inherent advantages and disadvantages of the approaches based on either mortality or flight height data, we argue that they should be seen as complementary, and it would be ideal if studies using both approaches were available on the same species.

For integrating energy production in our analysis, we only considered the rated power of wind turbines. However, turbines do not continuously operate at their rated power: amongst others, turbines stand still when wind speed is insufficient or during maintenance operations. The ratio between the mean realised power and the rated power ("capacity factor"; Hau, 2006) could vary with turbine dimensions. For example, when ground clearance increases at fixed rotor diameter (and fixed rated power), the capacity factor can be expected to increase due to increased wind speeds at higher height above ground (Hau, 2006). Therefore, as pointed out by Huso et al. (2021), it would be valuable to include information on the capacity factor in future studies by standardising the collision risk per unit of energy produced.

4.3. Species-specific effects of wind turbine dimensions

For the five low-mode species, we found that collision risk decreased with higher ground clearance. The collision risk per power decreased with larger rotor diameter if ground clearance was fixed, but tended to increase at fixed maximum tip height. STE showed the opposite trend in these three scenarios, as a consequence of the higher mode compared to the other five species.

Earlier studies on other bird species, or where species were lumped, mostly found results similar to those for our low-mode species, regarding the effect of both ground clearance (Johnston et al., 2014; Garvin et al., 2024) and rotor diameter (Thaxter et al., 2017; Huso et al., 2021; Garvin et al., 2024) on the collision risk per turbine, and regarding the effect of rotor diameter on the collision risk per unit of power (Smallwood, 2013; Johnston et al., 2014; Thaxter et al., 2017; Garvin et al., 2024). However, Huso et al. (2021) found no differences in the collision rate per MW between turbines between 0.6 and 2.5 MW in a wind farm in North America.

In general, it can be presumed that flight height distributions with low mode are relatively common amongst bird species, aside from migratory and commuting flights. Low modes (< 30 m) have been found in other birds of prey such as White-tailed Eagle *Haliaeetus albicilla* (Buij et al., 2022), Golden Eagle *Aquila chrysaetos* (A. Hemery, pers. comm.) and Eagle Owl *Bubo bubo* (Grünkorn and Welcker, 2019), and a range of seabirds (Johnston et al., 2014; Ross-Smith et al., 2016). Distributions with high mode as in STE were found in vultures (R. Buij, pers. comm.; O. Duriez, pers. comm.; note the phylogenetical closeness between STE and Aegypiinae vultures; Lerner and Mindell, 2005). Intermediate types of flight height distributions might exist in other bird species. During migratory and commuting flights, higher modes and therefore an increase in collision risk with greater ground clearance at fixed rotor diameter, and with greater rotor diameter at fixed ground clearance, can be expected for many species (Krijgsveld et al., 2009; Stumpf et al., 2011). For future research, it should be a priority to provide accurate information on flight height distributions for as many species as possible, both for the breeding season and the migration and winter periods, so that these can be considered when decisions on wind turbine dimensions are made (see below).

In relative terms, the effects of turbine dimensions on collision risk were very similar between the five low-mode species in our study, but the absolute level of the collision risk index for the same turbine model differed considerably between these species (in line with the found differences in the proportion of positions within the general rotor height range). This, however, does not allow to draw conclusions on real-world interspecific differences in collision risk, as these will also depend on factors such as the proportion of time spent in flight and the avoidance rate, which were not considered here and may differ importantly between species (SNH, 2018; Schaub, 2024).

4.4. Practical implications

The large effects of ground clearance and rotor diameter on collision risk found here offer opportunities for reducing collision risk, which are applicable to the installation of new wind farms as well as the repowering of existing turbines. Installing wind turbines with higher ground clearance is likely to benefit a range of bird species (species with a low mode of flight height). Larger rotor diameters increased the simulated collision risk per turbine, but reduced the collision risk per power for these species, if ground clearance was not simultaneously reduced. This implies that the total collision risk may be mitigated by using fewer large-diameter turbines instead of more small-diameter turbines.

However, these conclusions do not apply to species with a high mode of flight height, and possibly don't hold in a migration context. In other words, there is no "one-size-fits-all" approach and careful consideration of the community of bird (and bat) species present in the given area of interest at different times of the year (breeding, migration, winter) is indispensable to determine which wind turbine design minimises collision risk across species and seasons. Moreover, we would like to emphasise that mitigating collision risk by an informed selection of wind turbine dimensions should not be seen as an alternative for the "horizontal" site selection accounting for the abundance and behaviour of collision-prone species (Marques et al., 2014), but rather as an additional lever to further reduce the residual risk.

During the planning process of a wind farm, the selection of a turbine model is complex, depending on local wind conditions, legal regulations, model availability and economical aspects. The collision risk index proposed here can be used as an additional layer to compare alternative wind farm designs involving (different numbers of) wind turbines of different models and optimise the planned wind farm both economically and ecologically. Aside from the ecological effects, higher ground clearance at fixed rotor diameter has the disadvantages of higher material and transport costs and increased landscape impact for humans. Currently, higher ground clearances are often inhibited by legal regulations on maximum tip height. In such cases, high ground clearance can only be achieved using a small rotor diameter, which might not be economically viable. These regulations appear to be especially strict in Belgium and France, where maximum tip height is often limited to 150 m or less (Fig. 1). We recommend that these regulations are reviewed given our findings on the potential of higher ground clearances to reduce collision risk for a range of bird species.

CRediT authorship contribution statement

Tonio Schaub: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Raymond H.G. Klaassen:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Caroline De Zutter:** Writing – review & editing, Funding acquisition, Conceptualization. **Pascal Albert:** Investigation. **Olivier Bedotti:** Writing – review & editing, Conceptualization. **Jean-Luc Bourrioux:** Investigation. **Ralph Buij:** Writing – review & editing, Investigation, Funding acquisition. **Joël Chadœuf:** Writing – review & editing. **Celia Grande:** Writing – review & editing, Investigation. **Hubertus Illner:** Writing – review & editing, Investigation, Funding acquisition. **Jérôme Isambert:** Investigation, Conceptualization. **Kjell Janssens:** Investigation. **Eike Julius:** Investigation. **Simon Lee:** Writing – review & editing, Investigation, Funding acquisition. **Aymeric Mionnet:** Writing – review & editing, Investigation. **Gerard Müskens:** Writing – review & editing, Investigation, Funding acquisition. **Rainer Raab:** Writing – review & editing, Investigation, Funding acquisition. **Stef van Rijn:** Writing – review & editing, Investigation, Funding acquisition. **Judy Shamoun-Baranes:** Writing – review & editing. **Geert Spanoghe:** Writing – review & editing, Investigation, Funding acquisition. **Benoît Van Hecke:** Investigation. **Jonas Waldenström:** Writing – review & editing, Investigation. **Alexandre Millon:** Writing – review & editing, Visualization, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

This study was partly funded by the energy company ENGIE (TS's PhD position and part of the GPS tracking work). However, the scientific orientation of the PhD project was directed by the partner universities (Aix-Marseille University and University of Groningen), and academic freedom in publishing the results was guaranteed by a partnership agreement. We certify that the results were not influenced by the company's economic interests.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank everyone involved in the local GPS tracking projects, amongst others A. Keller, C. Montégu, L. Boldt, A. Schlaich, B. Koks, J. Rougé and Werkgroep Roofvogels Noordoostpolder (see Appendix 4 for a full list of involved persons and organisations); Boralex, EDPR, Soler, natur&ëmwelt and SICONA for allowing data use for this study; all farmers and landowners who gave permission to access their land for fieldwork; R. Zydelis (*Ornitela*), P. Otulak (*Milsar*) and W. Bouten (*UvA-BiTS*) for support with the GPS tags; B. Nolet, C. Thaxter, S. Chamaillé-Jammes and A. Leriche for helpful advice; and four anonymous reviewers for valuable comments which improved the manuscript. TS' PhD position was co-funded by ANRT and ENGIE (Cifre grant 2020/0448). See Appendix 4 for information on funding for the local GPS tracking projects.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176551.

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