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Collision risk and micro-avoidance rates of birds with wind turbines in Flanders

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Capsule Local factors can lead to strong variation in mortality rate and collision risk that obscures possible effects of turbine size in wind farms.
Aims The impact of bird collisions was studied at eight land-based wind farm sites with a total of 66 small to large turbines in order to assess the mortality rate and collision risk.
Methods Searches for collision fatalities were performed under all turbines with a minimum search interval of 14 days. Mortality rate was calculated with corrections for available search area, scavenging and search efficiency. Flight movements of birds crossing five of the wind farm sites were recorded during a minimum of four days per site. Actual collision risk was then calculated as the number of collision fatalities relative to the average surveyed flight intensity.
Results Mortality rate was 21 birds per turbine per year on average. Most fatalities were local common species (e.g. gulls) but rarer species were also found (e.g. terns, raptors and waders). Collision risk of gulls was 0.05% and 0.08% on average for birds, respectively, flying at turbine and rotor height through the wind farms (0.09% and 0.14% maximum). Large gulls had a significant higher collision risk than small gulls at rotor height. Mortality rate and collision risk were not significantly related to turbine size. The results were integrated in a widely used collision risk model to obtain information of micro-avoidance, i.e. the proportion of birds that fly through the wind farm but avoid passing through the rotor swept area of the turbines. For gulls, this micro-avoidance was 96.1% and 96.3% on average for birds, respectively, flying at turbine and rotor height through the wind farms.
Conclusion The results indicate that local factors can lead to strong variation in mortality rate and collision risk that obscures possible effects of turbine size in wind farms. However, large turbines have more installed capacity (MW), so repowering wind farms with larger but fewer wind turbines, could reduce total mortality at certain locations.

Use of wind energy is growing rapidly worldwide. This is also the case in Flanders, the northern region of Belgium. However, wind power is not without its own potentially damaging consequences for nature conservation. Birds and bats can collide with wind turbines, or encounter the vortex wake behind the turbines. They can also become disturbed from breeding, resting and foraging areas, or during migration (Langston & Pullan 2003, Drewitt & Langston 2006, 2008, European Commission 2010, Birdlife Europe 2011).

In general, it is recommended not to build wind farms close to very important areas and migration routes of birds and bats (Langston & Pullan 2003, Birdlife International 2005, Drewitt & Langston 2006, Hötker *et al.* 2006, Everaert & Stienen 2007, LAG-VSW 2007, Drewitt & Langston 2008, Winkelman *et al.* 2008, Aarts & Bruinzeel 2009, Piela 2010, Birdlife Europe 2011). Site selection studies at a strategic level, including the use of vulnerability maps indicating important areas and migration routes, are therefore recommended to prevent potential significant effects on populations (Birdlife Europe 2011). In case of potential and significant risks for birds and bats, extensive impact assessments are needed (European Commission 2010).

However, in a significant number of cases there is a substantial lack of knowledge to produce reliable assessments of the potential impact of planned wind farms. Ferrer *et al.* (2012) recently found no clear relationship between predicted risk in environmental

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impact assessments and the actual recorded bird mortality at wind farms. A better understanding of the impact at existing wind farms, can improve the quality of impact assessment and advice for new locations. For example, at an international level, there is still an urgent need for more field data concerning actual collision risk, certainly in relation to differences between species and turbine size. The widely used collision risk model of Scottish Natural Heritage for estimating the mortality in planned wind farms (Band *et al.* 2007, and recent updates on www.snh.gov.uk) starts its calculation method with data – mostly from field surveys – of the number of birds flying through a 'risk window' (i.e. usually the entire site of the planned wind farm). Assuming a uniform distribution within the risk window, the number of birds flying through the area swept by the rotors of the turbines can be calculated. Assuming no avoidance action, the model then calculates the theoretical collision risk for birds flying through the rotor swept area, using several characteristics of the wind turbines and the birds. An additional correction for avoidance is then needed to assess final collision risk (Scottish Natural Heritage 2010). In the model, the proportion of birds taking action to avoid possible collisions (i.e. avoidance rate) is a combination of avoidance of the entire wind farm (i.e. macro-avoidance) and avoidance of the rotor swept area of individual turbines within the wind farm (micro-avoidance). The model still has some limitations in reliability because the accuracy in determining collision risk depends greatly on the application of flight avoidance rates and collision risks obtained from relatively few monitoring results at existing wind farms (Chamberlain *et al.* 2006, Drewitt & Langston 2006, National Wind Coordinating Collaborative 2010). More complex mixed models are also being developed for species groups for which the exact flight intensity is difficult to survey (Eichhorn *et al.* 2012, Korner-Nievergelt *et al.* 2013).

The Research Institute for Nature and Forest (INBO) started a small project in 2000 (with the financial support of the Flemish government), for monitoring the impact at existing wind farms throughout Flanders, to provide advice at project and regional level, and to review environmental impact assessments. A supporting study with regard to the risks for birds and bats for planned wind farms, including vulnerability maps for birds and methodological recommendations for impact assessments, was also made (Everaert *et al.* 2011, Everaert & Peymen 2013). The results of the monitoring were first presented in a report (Everaert 2008). The most important part of the monitoring was mortality and collision risk of birds flying through the wind farms. The main results and related analyses are presented here.

The main objective of this study, was to obtain more information on the number of collision fatalities (i.e. mortality rate) and actual collision risk (i.e. the number of collision fatalities relative to the average surveyed flight intensity) at wind farms in Flanders. An additional (more recent) objective was to integrate the actual collision risk results into the Scottish Natural Heritage current collision risk model to obtain information on micro-avoidance for birds that fly through the wind farm, so that this collision model can be further optimized.

METHODS

Study sites

The impact of bird collisions was studied at eight land-based wind farm sites in Flanders, with a total of 66 wind turbines (Fig. 1, Table 1).

The wind farm in Zeebrugge ('OZ', 24–25 turbines orientated in L-shaped line with 1500 m at the widest point) is situated alongside the North Sea coast in the port of Zeebrugge. The wind farm is build next to a peninsula with an important breeding colony of terns, and 2 km further in the port there is also a large breeding colony of gulls. There is distinct seasonal migration, but also regular flight movements of local birds during the whole year. For more information about this location, see also Everaert & Stienen (2007).

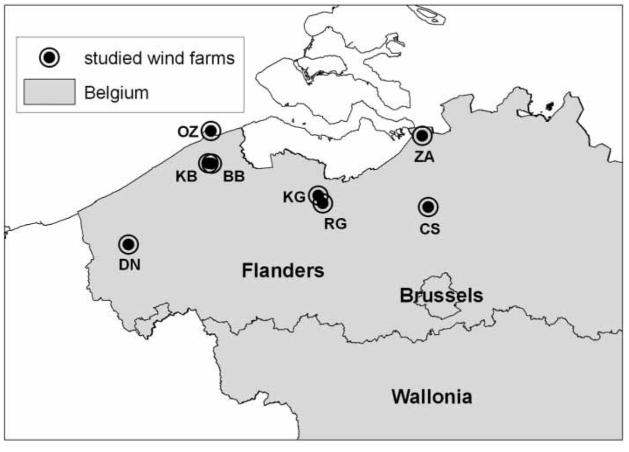

Figure 1. Studied wind farm locations in Flanders. See also Table 1.

Table 1. Summary of locations where systematic research for collision fatalities was performed.

	Number of wind turbines (*… = MW per turbine)[a]	Period of the fatality search	Radius (m) of theoretical search circle[b]	Interval (in days) between searches	Correction for available search area	Correction for search efficiency[c]	Correction for scavenging (predation)[c]
Oostdam, Zeebrugge (OZ)	10 (* 0.2) 12 (* 0.4) 2–3 (* 0.6) Mast = 23–55 Tip = 34–79 Rsa = 398, 908 and 1809	2001–2007	50 (test 70)	14 (and 1–2 in breeding season of the terns)	1.33–9.09	2: small birds (<pigeon) on peninsula. 1.16: terns on peninsula	7.14: small birds (<pigeon) 1.10: terns on peninsula
Boudewijnkanaal, Brugge (BB)	5 (* 0.6) 9 (* 0.6) Mast = 55 Tip = 79 Rsa = 1809	2001–2006 2002–2006	60 (test 90)	14	1.33	2: small birds (<pigeon)	4.35: small birds (<pigeon)
De Put, Nieuwkapelle (DN)	2 (* 0.8) Mast = 75 Tip = 100 Rsa = 1809	April 2005–March 2006	100	14	1.00	NA	NA
Centrale, Schelle (CS)	3 (* 1.5) Mast = 85 Tip = 120 Rsa = 3849	2002–2004	85 (test 120)	14	1.00–1.89	2: small birds (<pigeon)	20: small birds (<pigeon)
Kleine Pathoekeweg, Brugge (KB)	7 (* 1.8) Mast = 86 Tip = 121 Rsa = 3421	2005–2006	100 (test 110)	14	1.84–7.53	2: small birds (<pigeon)	4.35: small birds (<pigeon)
Rodenhuize, Gent (RG)	2 (* 2.0) Mast = 78 Tip = 118 Rsa = 5027	2004	100	14	1.77–2.84	NA	NA
Kluizendok, Gent (KG)	11 (* 2.0) Mast = 98 Tip = 135 Rsa = 3849	May 2005–April 2007	120	14	1.50–6.93	2: small birds (<pigeon)	3: small birds (<pigeon)
Zandvlietsluis, Antwerpen (ZA)[d]	2 (* 2.0) Mast = 98 Tip = 139 Rsa = 5281	February–October 2006	120	30	2.43–3.52	NA	NA

[a]Mast = hub height (m), Tip = highest point of moving blades (m) and Rsa = rotor swept area per turbine (m^2).
[b]Not the full area inside the search circle could be searched, see correction factor for available search area.
[c]NA = not applicable, because no small bird fatalities were found.
[d]The mortality result from this location was extrapolated for the whole year.

The two wind farms in Brugge ('BB' and 'KB', 14 and 7 turbines orientated in two parallel lines with about 660 m distance between the lines) are situated alongside a canal with industrial development, with important bird areas nearby (at about 2 km, including a wetland). There are regular flight movements of local gulls in relation to their roost, especially during winter, and some movements of local geese and waterfowl originating from nearby important bird areas.

The wind farm in Nieuwkapelle ('DN', 2 turbines) is situated at about 1 km from an important bird area (including a wetland) for both breeding and non-breeding birds holding large numbers of waterfowl during winter. Also during winter, there are some flight movements of local gulls and waterfowl, with a higher intensity at more than 1 km.

The wind farm in Schelle ('CS', 3 turbines orientated in a cluster) is situated alongside the Schelde river with a mix of industrial development and nature areas nearby. The Schelde is important for wintering waterfowl. Alongside the river, there are some flight movements of local gulls and waterfowl, and seasonal migration as well.

The wind farm at Rodenhuize in Gent ('RG', 2 turbines) is situated in an industrial area with some important bird areas (canal and docks) for wintering waterfowl further away at more than 1 km. There are no regular flight movements of birds over the site.

The wind farm at Kluizendok in Gent ('KG', 11 turbines orientated in two parallel lines with about 2000 m distance between the lines) is situated in an industrial area with some important bird areas (canals, docks and wetland) for wintering waterfowl nearby (waste land and a dock within 1 km). There are regular flight movements of local gulls and some movements of waterfowl.

The wind farm in Antwerpen ('ZA', 2 turbines) is situated in waste land next to an industrial area, with a pond where small numbers of waterfowl are present during winter, and with a breeding colony of gulls nearby. The Schelde river is also situated at about 1 km. There are some flight movements of local gulls and waterfowl.

Mortality rate

During the indicated period (Table 1), the area around all wind turbines was searched for collision fatalities, with a minimum search interval of 14 days, except for one location with a search interval of 30 days during 9 months. The radius of the search circle around the turbines (Table 1) was in most cases equal to the mast height × 1.1, as in Krijgsveld *et al.* (2009) and Winkelman (1992), up to the mast height × 1.2 (rarely × 1.6) or the tip height of the turbines (=highest point of the moving blades). The systematic searches within the search area were performed by one person (the author) who walked in parallel line transects with a distance of 4–6 m between the lines depending on the type of vegetation.

Only the obvious or probable collision fatalities were used to determine the mortality (birds with lacerations, wing injuries, head injuries, back injuries and signs of internal injuries which were certainly or probably caused by a collision). All useful information (date, possible date of collision, species, age, sex, place/distance in relation to the nearest turbine, wounds, etc.) was collected in a standardised database and spatially presented in a geographical information system (ArcGIS 9). The distance between the nearest wind turbine and the location of the found collision victims was measured with Leica Geovid 7 × 42 BDA binoculars with an integrated distance meter, or by counting the number of steps to the turbine.

Not all collision fatalities can be found: some end up in the water or dense vegetation and some are removed by predators. The estimated number of actual collision fatalities (see below) was therefore calculated using correction factors for available search area, scavenging (predation) and search efficiency, deduced from the formula as defined by Winkelman (1992):

$$N = Na \times Cz \times Cp \times Ce,$$

where N is the estimated actual number of collision fatalities, Na the found number of collision fatalities, Cz the correction factor for search area, =100/z, with z being the proportion of searched surface (in %) of the total surface which should have to be searched, Cp the correction factor for scavenging, =100/p, with p being the proportion of birds (in %) that were not removed by predators during a scavenging-test and Ce the correction factor for search efficiency, =100/e, with e being the proportion of birds (in %) that were found by the investigator.

At most locations, it was not possible to search the whole (theoretical) necessary search area around the turbines, because the area was not accessible or the vegetation was too dense. The correction factor for available search area (in comparison with the normal area that should be searched) for each wind turbine was calculated in ArcGIS with the most recent aerial photograph of the area, and was applied for all collision fatalities (all species).

At locations where at least one small bird (wingspan smaller than a pigeon) or at least one tern was found (because of the regional conservation concern), a correction factor for scavenging by predators was used. A scavenging test was performed at each location by placing a minimum of 20 fresh bird carcasses from bird rescue centres (combination of day-old Chicken chick *Gallus gallus domesticus*, Starling *Sturnus vulgaris*, Song Thrush *Turdus philomelos*, Blackbird *Turdus merula*, Chaffinch *Fringilla coelebs* and Robin *Erithacus rubecula*) within the search area. After the normal search interval period (mostly after 14 days) the presence of the carcasses was checked. During the study period, it was found that no correction factor for scavenging was necessary for larger birds in Flanders (Everaert 2008).

Based on extensive test results published by Winkelman (1992) at sites with similar vegetation in the Netherlands, a correction factor for search efficiency of 2 (50% of the birds were not found because of dense vegetation) was used for small-sized collision fatalities (wingspan smaller than a pigeon) that were found on non-uniform ground with tall grass or small bushes. Due to time constraints, this factor was not determined at the sites in Flanders and therefore might affect the reliability of this study. However, considering the similar vegetation at the sites in the Netherlands, it is expected that this uncertainty does not affect the general outcomes of this study.

The lack of statistical errors in the presented mortality rate estimation is partially compensated by the use of standard deviation in the results of several years (per location). In any case, the formula used to calculate mortality rate still has its limitations and there are now more complex and better formulas available (Huso *et al.* 2012, Korner-Nievergelt *et al.* 2013). For example, it was found that carcasses do not fall evenly and there is a higher concentration closer to the turbine tower (Huso *et al.* 2012). This means that mortality might have been over-estimated in this study. However, there are other factors that might have resulted in under-estimation, such as the possibility that collision fatalities were not found and not fully corrected in the estimation, and because of possible fatalities with no clear sign of a collision that were not taken into account in the analysis.

Flight movements and actual collision risk

At five wind farm locations (Zeebrugge, Brugge (2), Kluizendok Gent and Nieuwkapelle) where the turbines are all orientated in a line, flight movements of local gulls (in relation to nearby roosts) were surveyed during the day, including dusk and dawn. The birds flying through the wind farm (=crossing the line of turbines) and those flying nearby (zones up to 300 m and 1000 m outside of the wind farm) were recorded. The altitude (below, above and at turbine rotor height) of the birds was also estimated. The surveys were performed by one person (the author) with Swarovski 10 × 42 EL binoculars at a fixed point during a minimum of 4 days evenly spread over 4 months during winter. For each wind farm site, the average of the 4 days surveys was then extrapolated for the full 4 months period.

Most flight movements were clearly related to nearby daily used roosts, and it was estimated (Everaert 2008) that the flight behaviour of the local gulls was relatively constant. However, this extrapolation affects the reliability of the study results. The reported results should therefore be treated with caution and further study with better standard survey methodologies is recommended.

Actual collision risk for gulls flying through the entire wind farm was then calculated from the estimated actual number of collision fatalities (i.e. mortality rate) relative to the average extrapolated number of birds flying through the wind farm (i.e. surveyed flight movements of birds crossing a line of wind turbines) during 4 months in the winter period.

Information on micro-avoidance for use in collision risk modelling

Whilst the actual collision risk results from this study can be converted to 'non-collision' risks, it is important to note that in this reverse form, they do not reflect micro- and/or macro-avoidance rate as used in the collision risk model of Scottish Natural Heritage (see more information about this difference in Cook *et al.* (2012)). But micro-avoidance rates can be deduced from these actual collision risks, because in this case macro-avoidance is not relevant because the actual collision risks only relate to birds flying through the existing wind farm. Micro-avoidance in this case, is the proportion of birds that fly through the wind farm but avoid passing through the rotor swept area of the turbines.

To determine the micro-avoidance rate, the number of flight movements of birds crossing the risk window (i.e. entire wind farm) was set to a value whereby the number of collision fatalities (mortality rate) would be 1, using the actual collision risk that was calculated in Flanders. The model used was that of Band *et al.* (2007) for onshore wind farms with an update for stage 2 of the model (spreadsheet version 16 August 2013 on www.snh.gov.uk). In the model, the potential number of birds flying through the rotor swept area was then determined (assuming a uniform distribution within the risk window). Then the model calculated the theoretical collision risk for birds flying through the rotor swept area, assuming no avoidance. Micro-avoidance was then obtained from the difference in the outcome of the model and the collision fatality number set to '1'.

RESULTS

Mortality rate

The estimated collision fatality numbers (observed numbers with corrections for available search area, scavenging and search efficiency) varied substantially

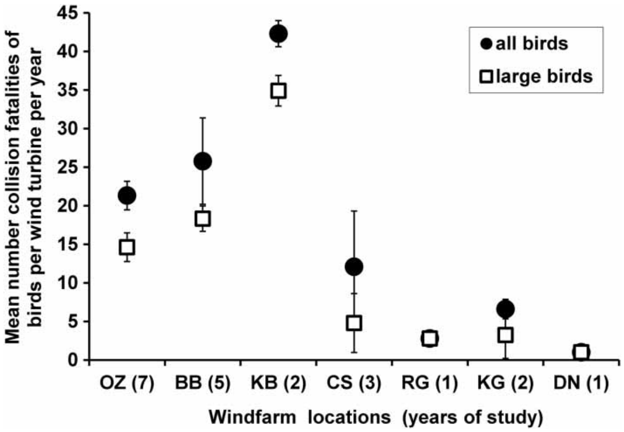

Figure 2. Average number of collision fatalities of birds per wind turbine per year for the wind farms in Flanders (±sd for data from several years). See also Table 1 for detailed information on the locations.

from 0 to 125 birds per individual turbine per year. The average mortality rate was 21 birds per turbine per year but the results between the eight wind farms varied substantially (Fig. 2). Mortality rate of large birds (=mostly gulls) was significantly different between the five sites with a minimum 2 years of study (one-way ANOVA, df = 4, $F = 4.8$, $P < 0.05$). Using the average number for all wind farms, it was calculated that for the 66 studied wind turbines, 1353 birds collided each year.

The wind farms Oostdam in Zeebrugge, Boudewijnkanaal and Kleine Pathoekeweg in Brugge and Zandvlietsluis in Antwerpen, had the highest mortality rates (Fig. 2), mainly because of the large number of colliding gulls. Most of the bird fatalities were locally common bird species like Black-headed Gull *Chroicocephalus ridibundus*, Common Gull *Larus canus*, Herring Gull *Larus argentatus*, Lesser Black-backed Gull *Larus fuscus*, Mallard *Anas platyrhynchos* and Starling *Sturnus vulgaris*. But also rare or even endangered species were found, like Grey Heron *Ardea cinerea*, Mediterranean Gull *Ichthyaetus melanocephalus*, Peregrine *Falco peregrinus*, Redshank *Tringa totanus*, Black-tailed Godwit *Limosa limosa*, Kentish Plover *Charadrius alexandrinus*, Woodcock *Scolopax rusticola* and Swift *Apus apus*. A complete species list can be found in Everaert (2008). In one wind farm (Oostdam Zeebrugge) next to a breeding colony of terns, there were also relatively large numbers of Common Terns *Sterna hirundo*, Sandwich Terns *Sterna sandvicensis* and Little Terns *Sternula albifrons* that collided with the wind turbines.

Actual collision risk

The calculated actual collision risk of small gulls was 0.03% on average (se = 0.01) for birds flying at wind turbine height, and 0.05% on average (se = 0.02) for birds flying at rotor height. For large gulls, the collision risk was 0.06% on average (se = 0.01) for birds flying at wind turbine height, and 0.11% on average (se = 0.02) for birds flying at rotor height (Table 2, Fig. 3). The difference in collision risk between small and large gulls at rotor height, was significant ($t = 3.3$, $n_1 = n_2 = 4$, $P < 0.05$ two-tailed). There was no significant relationship between the actual collision risk and rotor swept area of the turbines (Spearman rank correlation: $\rho = -0.1$, df = 7, $P > 0.05$; see also Fig. 3).

Information on micro-avoidance for use in collision risk modelling

Micro-avoidance rate of small gulls was 96.9% on average (se = 1.1) for birds flying at wind turbine height, and 97.3% on average (se = 0.8) for birds flying at rotor height. For large gulls, micro-avoidance rate was 95.3% on average (se = 1.3) for birds flying at wind turbine height, and 95.2% on average (se = 1.0) for birds flying at rotor height (Table 2). The difference in micro-avoidance between small and large gulls at both wind turbine and rotor height, was not significant ($t = -2.3$, $n_1 = n_2 = 4$, $P > 0.05$ two-tailed).

DISCUSSION

The results of this study should be treated with caution, because there are some methodological issues that might have affected the outcomes of the analysis. These issues mainly involve the corrections in the estimation of mortality rate, and the extrapolations due to the limited number of bird movement surveys. Nevertheless, the variation in mortality rates for the studied wind farms in Flanders was quite high. This is also the case in other wind farms across Europe: where correction factors for available search area, scavenging and search efficiency were applied, the average mortality was highly variable between almost zero and 63 birds per turbine per year (Table 3). The variation can be explained by different local factors including the characteristics of the development, the topography of the surrounding land, the habitats affected, the species and their behaviour and the number of birds present (Drewitt & Langston 2006, de Lucas *et al.*

Table 2. Collision risk and micro-avoidance rates for flying gulls, crossing one line of wind turbines, at rotor height and wind turbine height (=also below rotor height to ground level) during the day + night (24/24 h).

Location wind turbines: Species	Collision risk (%) at rotor height	Micro-avoidance (%) at rotor height	Collision risk (%) at wind turbine height	Micro-avoidance (%) at wind turbine height
Oostdam, Zeebrugge in 2001:[a] Herring Gull + Lesser Black-backed Gull	0.05	98.2	0.03	98.4
Boudewijnkanaal, Brugge in 2001:[b] Herring Gull	0.13	95.2	0.05	97.0
Boudewijnkanaal, Brugge in 2005:[c] Herring Gull	0.12	94.1	0.09	92.7
Boudewijnkanaal, Brugge in 2005:[c] Black-headed Gull	0.03	98.1	0.02	97.9
Kleine Pathoekeweg, Brugge in 2005:[d] Black-headed Gull	0.03	98.3	0.02	98.0
Kleine Pathoekeweg, Brugge in 2005:[d] Herring Gull + Lesser Black-backed Gull	0.14	93.5	0.08	93.3
Kluizendok, Gent in 2007:[e] Black-headed Gull	0.04	98.0	0.02	98.0
'De Put', Nieuwkapelle in 2006:[f] Black-headed Gull + Common Gull	0.10	94.8	0.06	93.5

Notes: For (b), (c), (d), (e) and (f) this was based on the number of passing birds from 2 hours before sunrise till 4 hours after sunset because a negligible number was found in a spot-check during the night (completely dark period). In fact, most gulls crossed the wind farm in the evening (flight movements to the roost). Based on the calculated number of certain and probable collision fatalities, in relation to the average number of passing birds (surveyed zone for flight movements around the turbines, see footnotes a–f). See also Everaert & Stienen (2007) and Everaert (2008). The micro-avoidance rates were deduced from the collision risks and calculated on the basis of the collision risk model approach of the Scottish Natural Heritage.

[a]Within a 60 m radius around the turbines, with 120 m distance between the turbines in line.
[b]Within a 75 m radius around the turbines, with 150 m distance between the turbines in line.
[c]Within a 100 m radius around the turbines, with 200 m distance between the turbines in line.
[d]Within a 140 m radius around the turbines, with 280 m distance between the turbines in line.
[e]Within a 150 m radius around the turbines, with 300 m distance between the turbines in line.
[f]Within a 100 m radius around the turbines, with 200 m distance between the turbines.

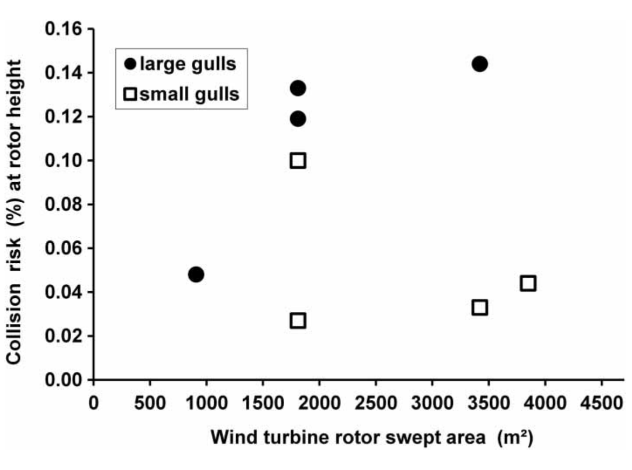

Figure 3. Collision risk (%) of small and large gulls at rotor height (see also information in Table 2), in relation with the rotor swept area of the turbines in the wind farms. Herring Gull and Lesser Black-backed Gull are large gulls, and Black-headed Gull and Common Gull are small gulls. The left group below 3000 m^2 are wind farms with 400–800 kW turbines, and the right group higher than 3000 m^2 are wind farms with 1800–2000 kW turbines.

2008). The highest mortality rates in Flanders, were seen in wind farms close to the coast or important wetlands for birds. In a review by Hötker (2006), it was also found that wind farms near wetlands and mountain ridges had significantly more collision fatalities than in other more common landscapes.

At the studied wind farms in Flanders, the large number of gulls colliding at four locations and terns at one location (Zeebrugge) was striking, despite the fact that these birds are largely diurnally active. As a result of the tern collisions, a significant negative impact (1.4–2.0% additional mortality) on the breeding colony in Zeebrugge has been identified (Everaert & Stienen 2007). Since most terns in Flanders are breeding in Zeebrugge, this was also a significant impact at a regional/national level. Recently, the turbines in Zeebrugge were replaced by larger ones (higher) with more space in between and below. This repowering decreased the number of collision fatalities among the terns but no conclusions can be made yet (the study is still in progress). Evidently, most

Table 3. Average avian mortality rates from collisions at some wind farms in Europe. These studies used correction factors (search area, scavenging removal and/or search efficiency rates) to adjust the number of found fatalities.

Place	Number of turbines	Type of turbines (kW)	Number of birds/ turbine/year	Years of study	Reference
Belgium (Oostdam, Zeebrugge)[a]	25[a]	200–600	19–24, average 21	7	this paper, with more detailed information in the report Everaert (2008)
Belgium (Boudewijnkanaal, Brugge)	14	600	21–35, average 26	5	
Belgium (De Put, Nieuwkapelle)[b]	2	800	min. 1	1	
Belgium (Centrale, Schelle)	3	1500	7–18, average 12	3	
Belgium (Kleine Pathoekeweg, Brugge)	7	1800	41–43, average 42	2	
Belgium (Rodenhuize, Gent)[b]	2	2000	min. 3	1	
Belgium (Kluizendok, Gent)	11	2000	6–8 , average 7	2	
Belgium (Zandvlietsluis, Antwerpen)[b]	2	2000	min. 21	1	
The Nederlands (Zeeland)	5	250	3	1	Musters *et al.* (1996)
The Nederlands (Oosterbierum)[c]	18	300	22–33	1	Winkelman (1995)
The Nederlands (Urk)[c]	25	300	15–18	1	Winkelman (1995)
The Nederlands (Almere)[d]	10	1650	20	1	Krijgsveld *et al.* (2009)
The Nederlands (Waterkaaptocht)[d]	8	1650	27	1	Krijgsveld *et al.* (2009)
The Nederlands (Groettocht)[d]	7	1650	39	1	Krijgsveld *et al.* (2009)
The Nederlands (Westereems)[e]	88	3000	average 10–42	2	Brenninkmeijer (2011)
The Nederlands (Delfzijl-Zuid)[e]	34	2000	average 2–7	5	Brenninkmeijer & van der Weyde (2011)
Germany (Island Fehmarn, West)	23	2300	4	1	BioConsult & ARSU (2010)
Germany (Island Fehmarn, Mitte)	16	2300	6	1	
Germany (Island Fehmarn, Presen)	17	2300	29	1	
Germany (Island Fehmarn, Klingenberg)	11	2300	13	1	
England (Blyth)	9	300	1.3	2	Still *et al.* (1996)
France (Vendée)[f]	8	2400	11–34	3	Dulac (2008)
Spain (Salajones)[g]	33	660	22	1	Lekuona (2001)
Spain (Izco)[g]	75	660	23	1	
Spain (Alaiz)[g]	75	660	4	1	
Spain (Guerinda)[g]	145	660	8	1	
Spain (El Perdón)[g]	40	500–600	63	1	
Spain (Basque Country)	40	650–850	5–7	3	Onrubia *et al.* (2002)
Spain (Tarifa)[h]	190	100–150	0.5	1	SEO-Birdlife (1995)
Spain (Tarifa)[h]	66	150–180	0.1	1	

[a]During the first 3 years there were 23 turbines, during the last 2 years only 24 turbines were operational, and during the last year 3 turbines were not operational during the breeding season.
[b]No small-sized fatalities were found but because of a 14 and 30 days search interval birds may have been missed.
[c]Difference between obvious and probable-obvious, probable and possible collision fatalities. Calculated from numbers in spring and autumn, originally expressed as birds/turbine/day. In reality the rates in spring and autumn were possibly higher, taking the calculated collision risk at night into account, but due to the expected lower rates during the rest of the year, the represented rates here (per year) will be a good estimate (Winkelman, pers. comm.).
[d]These rates were calculated from numbers in October–December, originally expressed as birds per turbine per day.
[e]Difference between obvious – obvious and possible collision fatalities, and an extrapolation and correction was made because not all wind turbines were studied.
[f]Based on the calculated maximum number per year.
[g]Possible underestimation, because only partly corrected for scavenging and search efficiency.
[h]This is only the number of large sized birds. Small sized birds are not included because they were not surveyed.

collisions in Flanders were the result of regular flight movements of local gulls in relation to their roost (highest movement around dusk and dawn) and flight movements of local gulls and terns near a breeding colony (Everaert & Stienen 2007, Everaert 2008). Krijgsveld *et al.* (2009) also found that most collision fatalities with large modern turbines concerned local and diurnally active birds (73%), with comparatively few nocturnally migrating birds (27%). In a review by Hötker *et al.* (2006), similar results were found. At locations without distinct seasonal migration, this is not surprising, because in contrast to migrant birds, local birds generally will pass a wind farm many times per year.

Combined with the mortality rates of several wind farms in the Netherlands (in similar European lowland

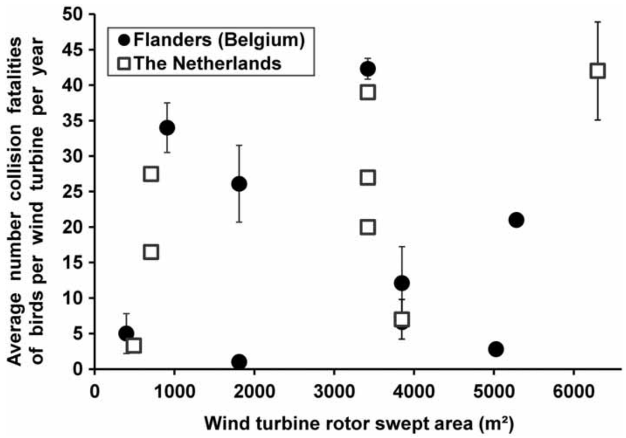

Figure 4. Average number of collision fatalities of birds per wind turbine per year for several lowland wind farms near wetlands or other areas with water in Flanders (this study) and the Netherlands (see list of locations in Table 3) with sd for data from several years, in which all possible collision fatalities were searched, and with the use of correction factors as described in this paper. The left group below 2500 m^2 are wind farms with 250–800 kW turbines, and the right group higher than 2500 m^2 are wind farms with 1500–3000 kW turbines. There was no significant relationship between the mortality rate and the rotor swept area of the turbines (Spearman rank correlation: $\rho = 0.1$, df = 15, $P > 0.05$).

conditions near wetlands or other areas with water), no significant relationship could be found between the number of collision fatalities and the rotor swept area of the turbines (Fig. 4). In contrast to more common landscapes, Hötker (2006) also found no significant relationship between mortality rate and the size of wind turbines near wetlands and mountain ridges.

It seems likely that idiosyncratic local factors (e.g. bird numbers, species composition, behaviour, flight height, proximity of certain bird areas and spatial characteristics of the wind farm) lead to strong variation in mortality rate, so obscuring any possible effects of wind turbine size in wind farms. Further variation can also result from differences and limitations in the correction factors used. Since large wind turbines have more installed capacity (MW), repowering wind farms with larger but fewer wind turbines, might reduce total mortality at certain locations. Only an experimental setup or extensive studies at sites where smaller turbines were replaced by larger ones can give more clarity on this subject.

The actual collision risk at wind turbine height (=from ground level to tip height) for small gulls at small and large turbines in Flanders, was similar with the reported risk of 0.01–0.02% at small turbines in the Netherlands (Winkelman 1992). The actual collision risk of both small and large gulls at rotor height in Flanders, was also within the average of 0.07% and 0.11%, respectively, for Sandwich Tern and Common Tern in the Zeebrugge wind farm (Everaert & Stienen 2007). The calculated collision risks of gulls and terns with small and large turbines in Flanders, together with the results from the Netherlands, confirm the notion that species composition, behaviour and flight height, can be more important factors than wind turbine size in wind farms.

The collision risks for gulls and terns in Flanders are also similar with those reported for other species groups and for all birds together. In a wind farm with large turbines in the Netherlands, Fijn *et al.* (2012) calculated a maximum collision risk of 0.04% for regular day and night flights of Bewick's Swans *Cygnus columbianus bewickii* to their roost. This is similar with the results (0.02–0.04%) for all birds in a wind farm with small turbines (Winkelman 1992). Also in the Netherlands, Krijgsveld *et al.* (2009) found a collision risk of 0.14% on average for all birds that crossed large turbines (1650 kW) at wind turbine height during the night in three wind farms (two lines and one cluster). A similar average of 0.10–0.17% was found with small wind turbines (Winkelman 1992). Krijgsveld *et al.* (2009) also determined that during the night at wind turbine height, there was a clear difference between local mainly diurnally active birds like gulls (0.16%) and migrating birds mainly consisting of small passerines (0.01%).

In the Zeebrugge wind farm, a significant relationship was found between the mortality of gulls and the number of gulls crossing the wind farm (Everaert 2008), and the mortality of terns was significantly related to the number of breeding pairs at the peninsula close to the turbines (Everaert & Stienen 2007). Large-scale distribution and aggregation in Griffon Vultures *Gyps fulvus* has also been positively related to the mortality in wind farms (Carrete *et al.* 2012). However, research in several wind farms in Europe, has shown that certain species groups like gulls, raptors and some passerines, collide more than one would predict from the number of birds present (Drewitt & Langston 2006, Hötker 2006, Hötker *et al.* 2006, Winkelman *et al.* 2008). For example, the mortality of raptors like the Griffon Vulture, was not closely related to the counted number of birds within the wind farms (de Lucas *et al.* 2008). Therefore risk assessment studies often incorrectly assume a linear relationship between frequency of observed birds and fatalities. It is now known that bird mortality in wind farms can be highly related to physical characteristics around individual wind turbines (Ferrer *et al*. 2012). So, this makes the subject very complex to study. Even during the day, some species are vulnerable to collision. Possible reasons for this can be found in the fact that at close distances, rotating wind turbine blades are not seen as dense objects (Hodos 2003). Many bird species also have their eyes placed laterally on the head, through which the viewing angle to the front is rather small. Moreover, the retina of the birds eye has its largest depth of field and distinctive character for colours in the lateral direction. This increases the risk of collisions (Martin 2011).

There are very few studies that have calculated micro-avoidance rates. The available data are from offshore wind farms where micro-avoidance has been calculated as the proportion of birds (crossing the wind farm) that took avoidance action at close distance to the wind turbines. Krijgsveld *et al*. (2011) calculated a micro-avoidance rate of 97.6% for all bird species flying through a wind farm, which is similar to the value for small gulls in Flanders. Desholm & Kahlert (2005) calculated a micro-avoidance rate of 83.7% and 93.5% for migrant sea ducks flying through a wind farm during the day and night, respectively. In both studies, radar was used. However, the results of these studies are difficult to compare with the results presented in this paper, because avoidance of the turbines is not the same as avoidance of the rotor swept area of the turbines. It is recommended that current collision risk models can be further optimized with the use of more and better field study information of collision risk for a diversity of bird species and locations in existing wind farms.

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