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OFFSHORE WIND FARM IMPACTS

# Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms

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**Abstract** Bird collision assessments are generally made at the scale of a single wind farm. While especially in offshore situations such assessments already hold several assumptions, even bigger challenges exist on estimating the cumulative impact of multiple wind farms and the impacts at population level. In this paper, the number of collision victims at Belgian offshore wind farms was estimated with a (theoretical) collision risk model based on technical turbine specifications, bird-related parameters and bird density data of both local seabirds and passerine migrants. Bird density data were gathered by visual censuses and radar registrations. The outcome of the model was extrapolated to future development scenarios in the Belgian part of the North Sea and in the entire North Sea, and then further used for a preliminary assessment of the impact at population level for the species at risk. The results indicate that the cumulative impact of a realistic scenario of 10,000 turbines in the North Sea might have a significant negative effect at population level for lesser and great black-backed gull. We further show that during a single night of intense songbird migration, the number of collision victims among passerine migrants might be in the order of magnitude of several thousands in the entire North Sea. We argue that it is of great importance to further develop methods to quantify the uncertainties and to minimise the assumptions, in order to assure more reliable cumulative impact assessments.

**Keywords** Offshore wind farms · Bird collisions · Seabirds · Bird migration · Collision risk modelling · Impact assessment

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## Introduction

The European Union aims at an offshore wind farm (OWF) capacity of 43 GW in the near future, which is equivalent to more than 14,000 3 MW turbines. With an offshore capacity of 6.6 GW present at the beginning of 2014 (EWEA, 2014), the number of offshore turbines still to be installed is thus enormous. Their distribution will no longer be limited to the near shore areas, illustrated by the fact that at the Doggerbank in the central part of the North Sea plans were licensed to build a 9 GW wind farm. At the Belgian part of the North Sea (BPNS), the Belgian government reserved a zone of 238 $km^2$ for offshore wind farms. At this point, three wind farms are operational in Belgian waters. By 2020, eight wind farms and thus over 500 wind turbines are expected to be operational (Table 1).

The major part of the planned OWF developments in European waters are located in the North Sea (EWEA, 2011). On the other hand, internationally highly important numbers of seabirds breed along the North Sea coasts, totalling more than 4 million individuals—all of these making intensive use of the North Sea for feeding during at least part of the year (Tasker et al., 1987; Mitchell et al., 2000). During autumn and spring, an estimated number of 1.0–1.3 million seabirds annually migrate through the 'migration bottleneck' of the Southern North Sea (Seys, 2002; Stienen et al., 2007). Large numbers of non-seabirds are also known to migrate at sea (Bourne, 1980; Buurma, 1987; Alerstam, 1990; Lensink et al., 2002). Estimates of the number of non-seabirds travelling through the Southern North Sea each migration season vary from 85 million (Lensink et al., 2002) up to several hundred millions (estimates of Helgoland mentioned in Hüppop et al., 2006; Krijgsveld et al., 2011). All of this results in concern about how the planned OWF developments might affect both local seabird communities as well as migrating birds.

Offshore wind farms are known to have several direct and indirect effects on birds, among which increased mortality through collision (Langston & Pullan, 2003; Fox et al., 2006; Drewitt & Langston, 2006; Furness et al., 2013). Importantly, as seabirds are long-lived species with a delayed maturity and small clutch size, even the smallest change in adult survival may have a substantial impact at a population level (Croxall & Rothery, 1991; Sæther & Bakke, 2000; Stienen et al., 2007).

Assessments of bird collisions are generally made at the scale of a single wind farm. While these assessments already hold several assumptions, even bigger challenges exist on estimating the cumulative impact of multiple wind farms. But considering the future large-scale exploitation, there is an urgent need to extrapolate local estimates of the number of collision victims and frame them into an international context. Therefore, this study aims at making a preliminary quantification of the cumulative number of collision victims in the Belgian wind farm zone and the entire North Sea, and at assessing the potential impact at population level of the species at risk.

## Materials and methods

### Research strategy

Collisions of birds with fixed and rotating structures of wind turbines have been recorded in numerous wind farms on land (e.g. Barclay et al., 2007; Everaert & Stienen, 2007). For obvious reasons, it is more difficult to assess the number of collision victims at OWFs, and

**Table 1** Overview of wind farms in the Belgian part of the North Sea—operational turbines are marked in bold (situation on November 24th, 2014), while an asterisk indicates that the exact number of turbines and/or total capacity is still to be confirmed

| Project | Number of turbines | Capacity (MW) | Total capacity (MW) |
|---|---|---|---|
| C-Power | | | 325 |
| phase 1 | **6** | 5 | |
| phase 2&3 | **48** | 6.15 | |
| Belwind | | | 336 |
| phase 1 | **55** | 3 | |
| phase 2 | 55 | 3 | |
| demo | **1** | 6 | |
| Northwind | **72** | 3 | 216 |
| Norther | 47–100* | 3–10* | 258–470* |
| Rentel | 47–78* | 4–10* | 289–468* |
| Seastar | 41 | 4–10* | 252–540* |
| Mermaid | 24–80* | 3–10* | 228–304* |
| Northwester 2 | 22–28* | 3–10* | 220* |

at this point, actual data on offshore collision rates are lacking. Band, (2012), however, developed a (theoretical) collision risk model (CRM) to estimate bird collision risks based on technical turbine specifications, bird-related parameters and bird densities.

To collect data on bird densities inside OWFs, a twofold strategy was followed (Fig. 1):

- Visual censuses from research vessels aimed at estimating local seabird densities and species-specific flight altitudes. This method provides a high taxonomic resolution, but is restricted to daylight and good weather conditions only.
- Radar research complemented the visual census data with continuous observations of the flux of

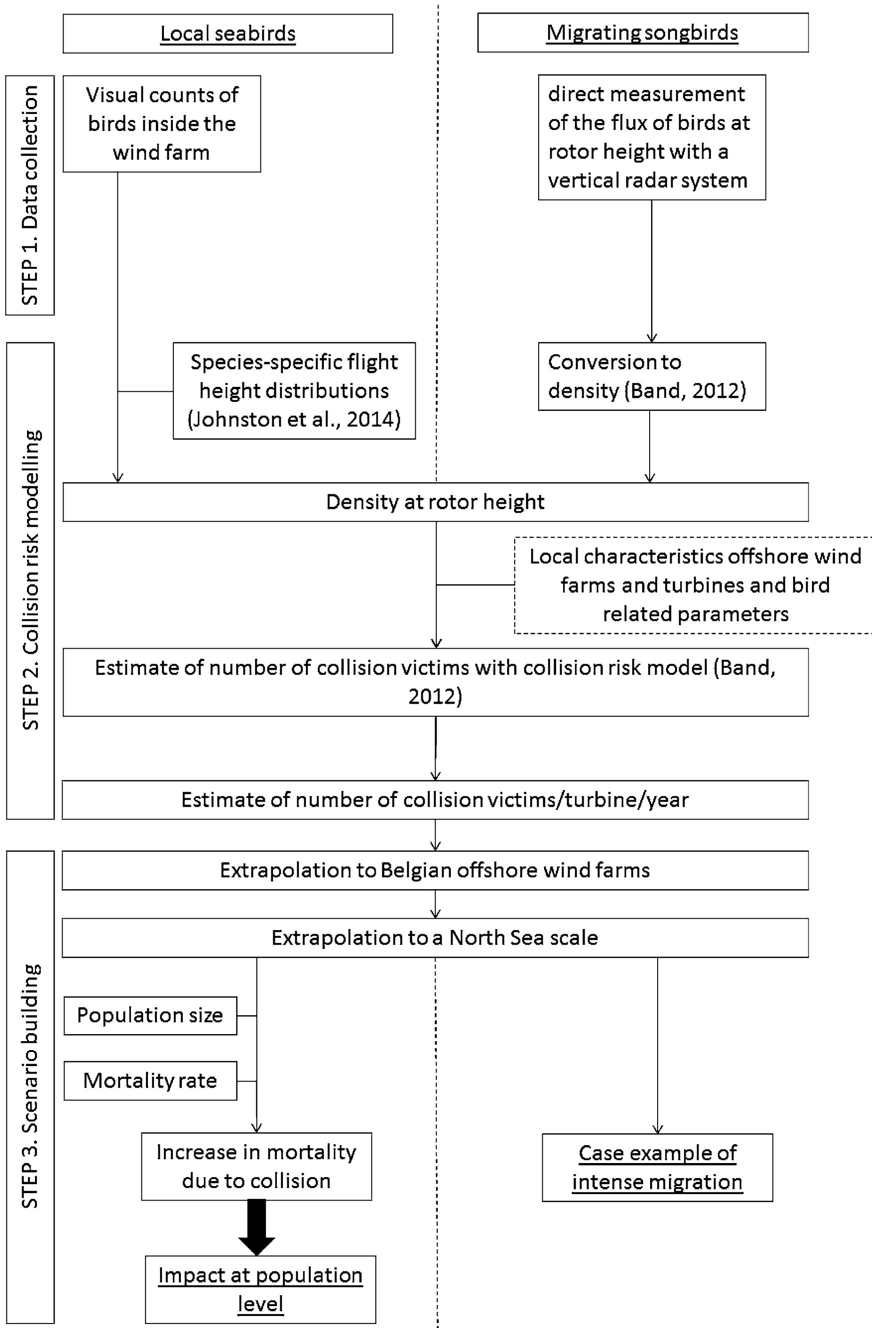


**Fig. 1** Schematic presentation of the analytical concept

birds, however, with a significantly lower taxonomic resolution.

The visual census data were used to estimate the number of collisions among local seabirds. For an approximation of the number of migrating songbirds expected to collide with the turbines, we used radar data of passerine migration in the area. Unfortunately, as persistent technical problems hampered continuous radar data collection, we only used one night of radar data, which was chosen specifically as an example of particularly heavy songbird migration, occurring only a few nights per year.

Finally, the outcome of the CRM was extrapolated to the future development scenario for the Belgian wind farm zone and to a scenario of 10,000 wind turbines in the entire North Sea, allowing for a careful estimation of the impact at population level.

## Research techniques

### *Data collection (step 1)*

This study presents two cases: long-term visual observations of seabirds and a case example of radar observation of intense bird migration at night.

*Visual counts* We used the results of the monthly seabird surveys through the Bligh Bank OWF, conducted as part of a before–after control–impact study to assess changes in local seabird densities (Vanermen et al., 2014), and following the internationally applied European Seabirds At Sea (ESAS) method (Tasker et al., 1984). The focus is on a 300 m wide transect along one side of the ship's track. The density of flying birds was assessed through so-called 'snapshot counts': right at the start of each minute, the number of birds flying within a quadrant of 300 by 300 m inside the transect is counted. The flight altitude of all observed seabirds was categorised as 'within', 'below' or 'above' the rotor swept zone.

In this study, we only used the visual observations collected in the wind farm at the Bligh Bank (five rows of 11 turbines), since the wind farm at the Thorntonbank consisted only of a single row of six turbines at the time of the surveys.

*Radar observations* The Merlin radar system that was used to assess bird flight intensity (DeTect Inc., Florida, USA), consists of two identical solid state S-band radar antennas, one scanning in the horizontal pane and one in the vertical. By rotating in the vertical pane, the vertical radar (VSR) creates a 'radar screen' that registers all targets moving through that screen. Every registration by the VSR can be seen as one (or a group of) target(s) passing through that area. This way of data collection allows to derive the flux of birds through the area, and it also provides information on flight altitudes.

For logistical reasons, the radar system was installed on the transformer platform on the Thorntonbank, inside the C-Power wind farm at about 25 km from the coast. The radar antennas were located on the top deck, 36 m above the sea-surface, on the south-western side of the platform. The vertical radar was oriented along the east–west axis and was operated at a range of 1.8 km.

Obviously not only birds were recorded by the radar; this but also happened for rain, waves, boats, wind turbines and etc. These unwanted echoes are being referred to as 'clutter'. To effectively remove this clutter from the vertical radar data, we used the following filtering rules:

– we selected data of a night without precipitation (October 21st and 22nd 2012);
– only the data in an area of 500 m wide without turbines were retained;
– following Krijgsveld et al., (2011), we removed all tracks with a track length less than three echoes.

Applying these filtering rules allowed for determining the flux of birds at rotor height. As the radar does not differentiate between individual birds, the flux is expressed as the number of (groups of) birds/h/km.

The massive nocturnal bird movement that was registered by the radar during the night of 21–22 October 2012 can without doubt be assigned to passerine migration, most likely thrushes, which are known to migrate at sea in large numbers (Lensink et al., 2002; Hartman et al., 2012). This was confirmed by visual observations of large numbers of thrushes migrating at sea during a seabird survey in the morning of October 22nd. The flux of this night-time fall migration was used as a case example of high bird flight intensity during migration.

### *Collision modelling (step 2)*

The CRM estimates the bird collision risk based on technical turbine specifications, the number of turbines and bird-related parameters. Input data on body length, wingspan, flying speed and nocturnal activity of birds are presented in Table 2. Technical data on the turbines and OWFs (e.g. rotation speed, pitch and turbine dimensions; Table 3) were obtained from the wind farm concession holders. We further assumed that the turbines were operational 100% of the time.

The CRM also includes a micro-avoidance rate, accounting for last-minute avoidance actions of birds. This factor is hard to assess, but is considered to be very high and is generally set to at least 95% (Chamberlain et al., 2006; Krijgsveld et al., 2011; Everaert, 2014). The number of estimated victims is proportional to the percentage of birds that does not perform avoidance actions (=1—% micro-avoidance). A seemingly small difference in avoidance rate between 95 and 99.5% therefore results in a factor 10 difference in terms of estimated collision victims. Most probably, this rate is species-specific and may also depend on weather conditions. However, as species-specific avoidance rates are not available, we applied the micro-avoidance value of 97.6% as found by Krijgsveld et al., (2011) based on their extensive radar research in a comparable offshore environment.

*Visual counts* The 'snapshot counts' as performed during the seabird surveys allowed to estimate densities of flying birds within the Bligh Bank wind farm, which were used as input for the CRM. Following the strategy applied by Vanermen et al., (2014), seabird count data collected within the OWF boundaries were aggregated per monitoring day. The resulting count data were assumed to follow a negative binomial distribution, and the expected seasonal densities and resulting 95% confidence intervals (CIs) were modelled making use of the R package MASS (Venables & Ripley, 2002).

Six seabird species occurring in the Bligh Bank OWF were considered to be at risk of colliding with the turbines, because of their presence inside the wind farm area on the one hand and a relatively high species-specific percentage of individuals flying at rotor height on the other hand (Furness et al., 2013; Vanermen et al., 2013; Johnston et al., 2014). Collision rates were then calculated by combining the seasonal densities of flying individuals inside the OWF with species-specific flight height distributions (including 95% CIs) as modelled by Johnston et al., (2014), thus applying the extended CRM (option 3—Band, 2012). A range of uncertainty around the collision rate estimate was obtained by additionally calculating collision rates using the lower 95% CI limits of species-specific flying heights and densities on the one hand and the upper 95% CI limits on the other hand.

*Radar observations* The registered flux of nightly migrating birds at rotor height in the wind farm at the Thorntonbank was transformed to density values using the equation:

$$D_A = (\pi/2)\,FL/v \;\;(\text{Band, 2012})$$

- $D_A$ bird density (birds/km$^2$),
- *FL* bird flux (birds/km/h),
- *v* flight speed (km/h).

**Table 2** Bird-related input data for the Band (2012) collision risk model

| | Bird length (m) | Wingspan (m) | Speed (m/s) | Nocturnal activity | Flight type |
|---|---|---|---|---|---|
| Northern gannet *Morus bassanus* | 0.94[a] | 172.5[b] | 14.9[c] | 2[d] | Flapping |
| Common gull *Larus canus* | 0.41[a] | 1.11[b] | 13.4[b] | 3[d] | Flapping |
| Lesser black-backed gull *Larus fuscus* | 0.58[a] | 1.34[b] | 13.1[b] | 3[d] | Flapping |
| Herring gull *Larus argentatus* | 0.6[a] | 1.34[b] | 12.8[b] | 3[d] | Flapping |
| Great black-backed gull *Larus marinus* | 0.71[a] | 1.67[b] | 13.7[b] | 3[d] | Flapping |
| Black-legged kittiwake *Rissa tridactyla* | 0.39[a] | 0.96[b] | 13.1[b] | 3[d] | Flapping |
| thrushes *Turdus sp.* | 0.24[a] | 0.36[a] | 12.4[b] | 5 | Flapping |

[a] Cramp, (1977–1985)

[b] Alerstam et al., (2007)

[c] Pennycuick, (1997)

[d] Garthe & Hüppop, (2004)

**Table 3** Wind farm- and turbine-related input data for the Band (2012) collision risk model for the two cases

| | Local seabirds | Case example of night-time migration |
|---|---|---|
| Name of wind farm | Belwind | C-Power |
| Latitude | 51.67°N | 51.55°N |
| Tidal offset | 2 m | 2 m |
| Number of turbines | 55 | 54 |
| Hub height (MSL) | 72 m | 95 m |
| Rotor diameter | 88 m | 126 m |
| Pitch | 15° | −1°[a] |
| Maximum blade width | 3.5 m | 5 m |
| Rotation speed | 16.4 rpm | 7.4 rpm[a] |

[a] values during the period of data collection

*Extrapolation and impact on population level (step 3)*

For extrapolations, the CRM results obtained for the Bligh Bank OWF were recalculated to a number of collisions per turbine per year and multiplied by the number of turbines that are expected to be constructed. Current prospects are that a maximum of 564 turbines will be constructed in the BPNS by 2020. Based on the goals set by the European Union, we considered a realistic scenario of 10,000 wind turbines for the extrapolation to a North Sea scale. In these extrapolations, we consistently used the turbine input data from the Vestas V90 turbines, the turbine type built on the Bligh Bank.

As a final step, we estimated the additional mortality resulting from collision mortality and based on the extrapolated CRM results, the known population size of the species at risk and their yearly adult mortality rate.

## Results

### Bird densities

The densities of six seabird species that were regularly observed flying at rotor height in the Bligh Bank OWF were used to estimate the number of collision victims (Table 4).

Isolating the radar recordings obtained during the night of 21–22 October 2012 (8 pm until 6 am), we observed an average flux at rotor height of 237 (groups of) birds/km/h. The flux rose to a maximum of 570 (groups of) birds/h/km (at rotor height) around midnight (Fig. 2). This corresponds with approximately 83,000 (groups of) thrushes flying through the wind farm area in the BPNS (which is 35 km wide) at rotor height during 10 h of nocturnal migration.

### CRM results

Based on the densities of flying seabirds assessed during our ship-based surveys in the Bligh Bank wind farm and the corresponding CRM results, we expect up to 102 [22; 704] casualties per year for the six selected seabird species at this specific location, corresponding with 1.9 [0.4; 12.8] victims per turbine per year (Table 5). Respectively, 48.0 and 32.5% of the victims are expected to be lesser and great black-backed gulls. The remaining four species accounted for less than 16% of all victims.

Applying the CRM on the night-time flux of passerines, as observed by the vertical radar, results in an estimated number of 28 collision victims during that specific night at the Thorntonbank wind farm.

### Extrapolating to the BPNS and the North Sea

Extrapolating the CRM results to the level of the BNPS leads to an estimated 297 thrushes to collide with offshore turbines at the BPNS during a single night with migration intensity comparable to that of 21–22 October 2012. Further extrapolating the results to a scenario of 10,000 turbines leads to an estimated number of about 5,257 thrushes colliding during a single night of heavy migration in the entire North Sea.

Based on the daytime visual observations and the species-specific flying altitudes, each year up to 1,046 [226; 7,219] seabirds are expected to collide with the turbines in the BPNS. The major part of the victims will be gulls (1,025 [226; 7,024]) and to a lesser extent

**Table 4** Modelled values for the expected densities (and indication of the lower and upper 95% CI limits) of flying individuals of six seabird species in the Bligh Bank OWF in winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November)

| | Northern gannet | Common gull | Lesser black-backed gull | Herring gull | Great black-backed gull | Black-legged kittiwake |
|---|---|---|---|---|---|---|
| Winter | | 0.05 [0.01; 0.19] | 0.02 [0.00; 0.17] | 0.06 [0.00; 0.78] | 0.02 [0.00; 0.17] | 0.65 [0.30; 1.38] |
| Spring | 0.06 [0.02; 0.18] | 0.02 [0.00; 0.14] | 0.31 [0.13; 0.72] | 0.02 [0.00; 0.14] | 0.02 [0.00; 0.14] | 0.18 [0.04; 0.73] |
| Summer | | | 0.18 [0.07; 0.43] | | 0.04 [0.00; 0.25] | |
| Autumn | 0.03 [0.00; 0.24] | | 0.03 [0.00; 0.24] | | 0.23 [0.10; 0.57] | 0.13 [0.05; 0.36] |

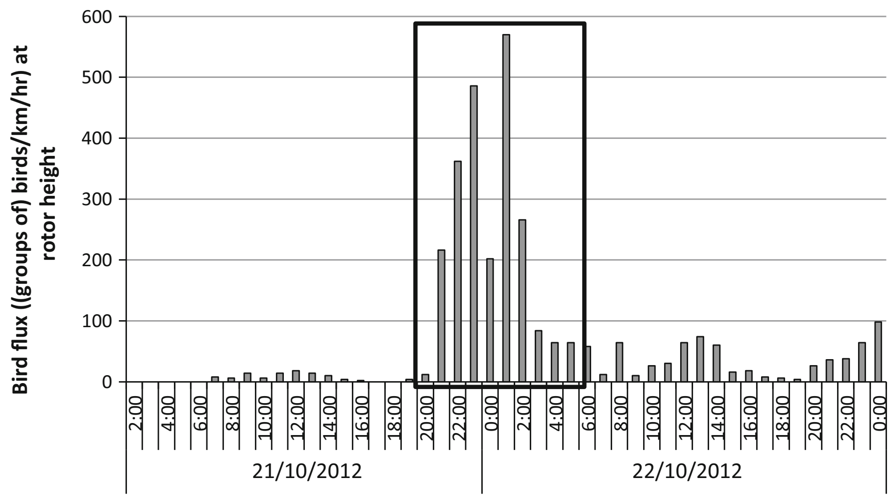


**Fig. 2** Bird flux (groups of birds/h/km) at rotor height for 21–22 October 2012. The data that were used in this analysis are indicated by the rectangle

**Table 5** Estimated number of collision victims including a range of uncertainty based on observed densities of flying birds inside the Bligh Bank wind farm, using the CRM option 3 (Band, 2012)

| | N/year | N/(turbine × year) |
|---|---|---|
| Northern gannet | 2 [0; 19] | 0.0 [0.0; 0.3] |
| Common gull | 2 [0; 23] | 0.0 [0.0; 0.4] |
| Lesser black-backed gull | 42 [9; 266] | 0.8 [0.2; 4.8] |
| Herring gull | 7 [0; 130] | 0.1 [0.0; 2.4] |
| Great black-backed gull | 33 [9; 208] | 0.6 [0.2; 3.8] |
| Black-legged kittiwake | 16 [4; 58] | 0.3 [0.1; 1.1] |
| Total | 102 [22; 704] | 1.9 [0.4; 12.8] |

northern gannets (21 [0; 195]). The additional mortality, based on the extrapolated CRM results to a scenario of 10,000 turbines, ranges from 0.2% [0%; 1.8%] for common gull to 9.4% [2.0%; 59.8%] for lesser black-backed gull (Table 6).

## Discussion

Based on 3 years of visual census data in the OWF at the Blighbank, we expect 102 [22; 704] casualties per year at this specific site for the six selected seabird species. With 1.8 [0.4; 12.5] casualties per turbine per year, the major part of the victims (98%) are expected to be gulls. This is less than a third of the number calculated by Poot et al., (2011), reporting an estimated 6.8 gull victims per turbine per year at the Egmond aan Zee offshore wind farm (OWEZ) in the Netherlands. This substantial difference in estimated collision rate can be explained by the more offshore location of the Bligh Bank compared to OWEZ, located respectively 46 versus 10 km from the coast, which is inevitably reflected in lower background densities of gulls. Importantly, the CRM results presented by both studies already account for (potentially site-specific) attraction or avoidance effects, as all data were gathered after construction.

In their research on wind farm-induced mortality in German waters, Dierschke et al., (2003) regard an increase of the existing mortality rate by less than 5% as acceptable. For Flanders, Everaert (2013) also sets the acceptable level at 5%, but with a more stringent threshold of 1% for vulnerable species and species facing population decline. It is important to note that these threshold values are indicative, set to function as an 'early warning signal', and the true critical threshold will depend on species-specific population dynamics (Dierschke et al., 2003; Furness et al., 2013). Nevertheless, the results presented here show that the cumulative impact of large-scale wind farm development might potentially cause significant increases in bird mortality levels, putting specific seabird populations under pressure. For lesser and great black-backed gull, the calculated additional mortality for a scenario of 10,000 turbines is 9.4 [2.0; 59.8] and 8.7 [2.4; 54.6]%, respectively. This corresponds with the findings of Furness et al., (2013), identifying both species as being most vulnerable to collision mortality impacts. Black-legged kittiwake too might show a relevant increase of the existing adult mortality by 0.7 [0.2; 2.7]%. Knowing that its population is already declining (Frederiksen et al., 2004; OSPAR, 2009), added mortality due to collision fatalities might put further pressure on the species.

In the ten nocturnal hours of thrush migration that were considered in this study, the vertical radar registered 2,372 bird groups at rotor height in an area of 1 km wide, resulting a CRM estimate of 28 collision victims at the Thorntonbank OWF during that specific night. It is important to keep in mind that the observed flux is expressed as a number of groups of birds/km/h. Each radar registration potentially consisted of more than one bird, so the outcome of the CRM is likely to underestimate the actual number of collisions. This was clearly a night with intense migration, considering that Krijgsveld et al., (2011) report that per autumn season, a mean of 103,115 bird groups travelled through a 1 km stretch at OWEZ at rotor height. As thrushes are known to migrate along wide fronts (Buurma, 1987; Lensink et al., 2002), the flux that was registered by the radar can be expected to be representative for the entire wind farm zone in the BPNS and possibly even a much wider part of North Sea. This would mean that during that specific night approximately 83,000 (groups of) thrushes passed the Belgian wind farm zone at rotor height. Further extrapolating the CRM result to a scenario of 10,000 turbines leads to an estimated number of about 5,257 thrushes colliding during a single night of heavy migration in the entire North Sea.

The CRM results of this one night of thrush migration should, however, be handled with care. The goal of this case example was to demonstrate that during spring and fall migration large numbers of (song) birds fly through the area at night. The uncertainty of the CRM results and the fact that we do not exactly know which species were registered by the radar does not allow to assess whether or not the number of migrating songbirds colliding with wind turbines at sea could have a significant effect at population level. At least the result of the extrapolations give an idea of the order of magnitude of the expected number of collisions.

**Table 6** Estimation of the additional mortality per 10,000 offshore turbines and a micro-avoidance of 97.6%, based on an extrapolation of the CRM results obtained at the Bligh Bank OWF

| Species | Biogeographical population | Population level[a] | Yearly mortality (%) | Number of collisions per year | Additional mortality per year (%) |
|---|---|---|---|---|---|
| Northern gannet | NE Atlantic | 915,000[a] | 8.1[c] | 364 [0; 3,455] | 0.5 [0.0; 4.7] |
| Common gull | NW and C Europe | 1,640,000[b] | 14.0[c] | 364 [0; 4,182] | 0.2 [0.0; 1.8] |
| Lesser black-backed gull | ssp. *graellsii* + *intermedius* | 930,000[b] | 8.7[c] | 7,636 [1,636; 48,364] | 9.4 [2.0; 59.8] |
| Herring gull | ssp. *argenteus* + *argentatus* | 3,030,000[b] | 12.0[c] | 1,273 [0; 23,636] | 0.4 [0.0; 6.5] |
| Great black-backed gull | N and W Europe | 420,000[b] | 16.5[d] | 6,000 [1,636; 37,818] | 8.7 [2.4; 54.6] |
| Black-legged kittiwake | NE Atlantic | 6,600,000[b] | 5.9[c] | 2,909 [727; 10,545] | 0.7 [0.2; 2.7] |

[a] Birdlife international, (2004)

[b] Wetlands International, (2013)

[c] BTO, (2013)

[d] Poot et al., (2011)

To estimate the number of collision victims of an offshore wind farm using the CRM (Band, 2012) and to extrapolate these results to a wider context, we had to make several assumptions which are listed in the following paragraphs. These assumptions result in uncertainties on top of the uncertainty ranges already provided in this study, and which were based on the 95% CIs for the density estimates and the species-specific flying height profiles as published by Johnston et al., (2014).

Assumptions made in the CRM calculations

(1) The outcome of the CRM is largely affected by the avoidance rate used in the calculations (Chamberlain et al., 2006). As we do not dispose of species-specific avoidance rates, we decided to use the same value for all species, i.e. the micro-avoidance rate of 97.6% as determined by Krijgsveld et al., (2011) during an extensive radar study at the nearby OWEZ. Because of the large uncertainty concerning avoidance rates, Cook et al., (2012) recommend collision estimates to be presented for a range of avoidance rates (e.g. 95, 98, 99 and 99.5%). In order to guarantee a clear overview of the results, however, this was not done here, but it should be noted that avoidance rates relate to CRM results in a linear manner and the results can thus easily be transformed accordingly.

(2) According to Band, (2012), the simplifications of the CRM regarding bird shape, bird flying speed and turbine blade shape cause an additive 20% of uncertainty on the results.

Assumptions in extrapolations and cumulative impact assessments

(1) By extrapolating the CRM results from the Bligh Bank (visual census of seabirds) and the Thorntonbank (radar observation of night-time thrush migration) to the entire wind farm zone in the BPNS and the entire North Sea, we assumed an equal distribution of birds, while in fact seabird distribution across the North Sea is far from homogenous (e.g. Stone et al., 1995). Especially in gulls which are most vulnerable for collision (this study, Furness et al., 2013) there is a strong inshore-offshore gradient in density, leading to a large difference in expected gull mortality between our study and the more inshore OWEZ wind farm (Poot et al., 2011). Also for passerines, it is highly unlikely that they migrate in equal densities over the entire North Sea, although thrushes are known to migrate along wide fronts (Lack, 1963; Bourne, 1980; Buurma, 1987; Lensink et al., 2002), Hence, we are well aware of the fact that the numbers of estimated collision victims obtained for local OWFs are highly site-specific, largely reflecting the local seabird community. The main goal of extrapolating, however, is not to present actual figures on cumulative impacts, but rather to frame these locally expected collision numbers in a wider and international context.

(2) For the hypothetic scenario of 10,000 wind turbines, we used the technical specifications of the turbines which were installed on the Bligh Bank. As Johnston et al., (2014) showed that a lower hub height results in more collision victims, applying the turbines characteristics of the relatively small 3 MW Vestas V90 type can be considered as a worst case scenario.

(3) We assumed the OWFs to be operational 100% of the time. Again, this can be regarded as a worst case scenario, as we did not account for the time when the wind is below cut-in wind speed, when the rotors may be stationary, nor for the time when the rotors are stopped and feathered in very high wind speeds or for operations and maintenance (Band, 2012).

(4) To calculate the potential additional mortality due to turbine collisions we used adult mortality values. As the yearly mortality of young birds tends to be higher than the adult mortality, actual additional mortality resulting from a certain number of collision fatalities will be smaller than the figures presented here. Since additional mortality of immatures has a less critical effect upon population size, ideally, cumulative impact assessments should be based on species- and population-specific demographic data combined with age-specific mortality levels (Masden et al., 2010; WWT, 2012).

Future research

It is clear that the outcome of the CRM, and thus of the assessment of the impact at population level, could be largely improved if less assumptions would be needed.

There is a clear need for species-specific micro-avoidance rates, ideally taking account of different bird behaviour under a range of conditions. To assess species-specific avoidance rates, radar, operated at close range, should be combined with simultaneous visual observations as much as possible. Combining radar and visual observations could prove to be invaluable for an integrated assessment of bird mortality. It should be stressed that the CRM remains a theoretical model. To be able to directly and accurately quantify the actual number of collisions, devices that measure collisions of birds with turbines should be used in wind farms across the North Sea, meanwhile allowing calibration of the CRM. Several of these devices already exist and are described in a review by Collier et al., (2012).

The extrapolation of the results to a North Sea scale could be largely improved if more site-specific data on post-construction bird densities, OWFs and turbines would be available. This would allow CRM results obtained at OWFs in various parts of the North Sea to be combined, which would result in a much improved estimate of the cumulative number of collisions and the impact at population level. In order to tackle this specific issue, there is an urgent need for international collaboration.

Lastly, there is a strong need for the development of species-specific population models, using demographic data and age-specific mortality values (Poot et al., 2011; WWT, 2012), which would allow to assess which additional mortality levels would cause populations to decline. Special attention should be addressed to vulnerable species and species facing population decline.

## Conclusions

The results presented here are subject to large uncertainties and the extrapolations made are based on several assumptions. The outcome, however, is valuable and indicates that the cumulative impact of a realistic scenario of OWF development in the North Sea might have significant negative effect at population level for lesser and great black-backed gull. The radar data of song bird migration are exemplary and do not allow to make an assessment at population level but they indicate that during nights with intense songbird migration, the number of collisions in the entire North Sea can be in the order of magnitude of several thousands. Therefore it is of great importance to further develop methods in order to minimise the assumptions made and to further quantify the uncertainties.

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