Update on the current state of knowledge on the impacts of offshore wind farms on birds in the OSPAR Region: 2019-2022

J.J. Leemans
M.P. Collier

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Authors: J.J. Leemans *MSc*., M.P. Collier *MSc*.

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Bureau Waardenburg
Ecology & Landscape

Bureau Waardenburg, Varkensmarkt 9, 4101 CK Culemborg, the Netherlands
0031 (0) 345 512 710, info@buwa.nl, www.buwa.nl

Preface

The Dutch ministry of Agriculture, Nature and Food Quality has commissioned Bureau Waardenburg to update a literature review on the effects of offshore wind on birds. This review follows up on an earlier review and covers peer-reviewed literature since the end of 2019 up until mid-2022 and the most relevant grey literature for the topics dealt with.

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1 Introduction

1.1 Background

In May 2022, the OSPAR Intersessional Correspondence Group Offshore Renewable Energy Development (ICG-ORED) decided to collaborate on a regional approach regarding the effects of development of renewable energy on the marine environment. The main goal of the ICG-ORED is to develop common principles and by 2024 develop guidance to promote and facilitate sustainable development and scaling up of offshore renewable energy in a way that cumulative environmental impacts are minimised gain an overview of the cumulative effects of offshore wind farm development on species in the OSPAR region. Priority in this will be given to birds

In the Netherlands, the cumulative effects of wind farm developments in the southern North Sea on protected species are already being assessed on a regular basis in a series of consecutive model calculations within the Framework for Assessing Ecological and Cumulative Effects (in short ‘KEC’; cf. the Dutch abbreviation). Additionally, in order to facilitate knowledge development, the Dutch government launched, already in 2016, a longitudinal study on the ecological effects of offshore wind farms, the so-called offshore wind ecological program (‘WOZEP’). However, the regional focus of these studies is still limited to the southern and central North Sea. Considering that the ecological effects of offshore wind farm developments are transboundary and dynamic, a regional focus in cumulative assessments is desirable.

The largest cumulative effects of offshore wind developments for birds are currently predicted to be collision risk and habitat loss. A pilot study of these effects on birds will be launched. The first step in the development of the bird pilot is to carry out a literature review on the current state of knowledge on the impacts of offshore wind farms on birds in the OSPAR Region.

1.2 Scope of this report

This report provides an update of earlier reports on the state of knowledge on the impacts of offshore wind farms, which are summarized by Zoutenbier *et al.* (2020). We assumed that these earlier reports cover the relevant literature up to the end of September 2019. Therefore, this report will merely include literature from October 2019 onwards and up to the end of July 2022. Furthermore, the current literature review is limited to the effects on birds in the OSPAR Region, thus literature focusing on other species groups or other regions is not included. Furthermore, our review limits itself to literature directly related to offshore wind farm developments. Hence, we acknowledge that many publications that are relevant for impact assessments but were merely conducted as ecological studies, such as for instance offshore distributions of seabirds, their biology or the availability of their food sources and coherent carrying capacity of offshore areas are not covered by our work. In addition, we focussed on scientific studies generating new knowledge, and less on reviews that often relied on literature from the period before 2019.

The primary focus of this literature review is on scientific, peer-reviewed papers. However, substantial amounts of knowledge on the impacts of offshore wind farms may additionally be collected in impact assessment frameworks (referred to as ‘grey literature’) and generally only few of these are eventually published (Marques *et al*. 2021). This report will therefore also include some grey literature that fills important knowledge gaps that are not covered by scientific literature, even if it involves work carried out before the above-mentioned cut-off date. As this substantially increases the number of potential sources, we only include relevant grey literature covering the following knowledge gaps:

- Collision risk per species.
- Species-specific avoidance rates.
- Barrier effects.
- Displacement/habitat loss per species.
- Disturbance distances per species.
- Use of corridors in wind farms.

The description of the effects of offshore wind developments follows Drewitt & Langston (2006) and each is covered in a separate paragraph. This deviates from Zoutenbier *et al.* (2020) but follows the definitions in wider use. The effects are introduced by a brief description based on assumed knowledge from before the end of September 2019, followed by the current state of knowledge on the effects based on the most recent literature. Relevant grey literature is described under separate headings.

2 Offshore wind farm effects on birds

Drewitt & Langston (2006) outlined the potential effects of wind developments on birds as being: 1) collision mortality; 2) displacement; 3) barrier effects and 4) habitat loss; with the first three widely being identified as particular relevance to offshore wind farms (e.g. Fox *et al.* 2006, Furness *et al.* 2013, Fox & Petersen 2019). With reference to offshore wind farms, habitat loss is often considered analogous to displacement, with the presence of wind turbines resulting in effective habitat loss.

2.1 Collision risk

Birds flying in and around offshore wind farms run the risk to collide with the rotor blades or to a lesser extent with the tower of wind turbines, (illuminated) platforms and transformer stations, or even with vessels associated with the wind farm, resulting in injuries or death of the individual. The turbulent airflow around the rotor blades may also lead to birds losing control over their flight, leading to injuries or even death casualties. Collisions may affect local seabirds at any time of the year, but also land birds during the migratory seasons. Most research on collision risk in offshore wind farms focusses on the factors that either increase or decrease the risk of collisions (King 2019). Collision rates are usually assessed with predictive models as recording collisions at sea remains challenging (Masden & Cook 2016). Predicted collision rates can be greatly affected by avoidance rates. Avoidance can be described as macro-, meso- and micro-avoidance behaviour and refers to flying birds. Macro-avoidance relates to avoidance of the entire wind farm area, meso-avoidance of wind turbines within the wind farm and micro-avoidance action to avoid individual rotors. These three types of avoidance can be combined to overall avoidance rates, which are an important input parameter for collision rate models. A situation where birds are attracted to the wind farm, due to perching opportunities or increased food supply, can be described as attraction or negative avoidance.

Breeding birds

The potential for seasonal- and sex-specific collision risks in northern gannets (*Morus bassanus*) breeding on Bass Rock (Scotland) was assessed by Lane *et al*. (2020). Using GPS data, Lane *et al.* (2020) found that during the during chick-rearing period, both sexes made shorter trips, spent more time within sites proposed for future wind farm developments, and were therefore potentially at greater risk of collision (eight times higher) than compared to the pre-hatching period. Also, females made longer trips than males in both these periods, flew higher and spent a greater proportion of time within the proposed wind farm sites, resulting in a potential collision risk three times higher than for males. The sites in this study concerned mostly proposed, pre-construction wind farm sites and only two small operational wind farms, in which birds were not recorded, so only gives an indication of habitat use rather than effects of wind turbines. Additionally, geolocation loggers revealed that during autumn, adults from this colony migrate through the southern North Sea, whereas juveniles remain in their autumn migration confined to the coast (Lane *et al*. 2021). Therefore, adults breeding on Bass Rock are more likely to encounter offshore wind farms, suggesting a higher collision risk than juveniles (Lane *et al*. 2021). An analysis of ship-based counts (ESAS) showed that most gannets present in the UK part of the southern North Sea during the breeding season were immature birds, while outside the breeding season most birds were adults (Pollock *et al*. 2021).

Another study on northern gannets focused on birds breeding on Helgoland (Peschko *et al.* 2021). They found that most gannets (89%) predominantly avoided offshore wind farms, but 11% frequently entered them when foraging or commuting between the colony and foraging areas. Birds that entered offshore wind farms, used these sites mainly for foraging instead of resting. Furthermore, these birds preferred areas inside the wind farm at 250-450 m distance from the wind turbines. The flight of gannets was significantly higher inside compared to outside offshore wind farms but remained mostly below the rotor-swept zone. Flight heights inside offshore wind farms were close to the rotor-swept zone, particularly in those individuals that predominantly showed avoidance for offshore wind farms.

Van Erp *et al.* (2021) focused on the temporal variation in bird abundance near offshore wind farm Luchterduinen (10 nm west of the Dutch coast) during the breeding season. They used a bird radar located in the wind farm to show that during the breeding season bird abundance near the wind farm peaked a few hours after sunrise before decreasing throughout the day and showed a secondary peak just prior to sunset. Abundances increased through the breeding season up to the end of June. This information can improve the temporal accuracy of collision risk models.

Migrating birds

Several studies report on the offshore movements of migrating birds (mostly passerines but also wildfowl, waders and gulls), which could be used to inform impact assessments of offshore wind farms.

Radar data from a Belgian offshore wind farm indicated that intense bird migration (presumed nocturnal migrants such as thrushes) with crossings of more than 500 birds/km/hour occurred in a total of 14 hours during autumn 2019, and never during the spring migration in 2021 (Brabant *et al.* 2021). Using collision risk modelling (extended SOSS Band model, Band 2012), the authors estimated that around 700 collisions could have been avoided in autumn 2019 if, as a mitigation measure, the wind turbines would have been idled during these intense migration hours when bird flux exceeded 500 birds/km/hour.

Manola *et al*. (2020) used radar data from a Dutch offshore wind farm to examine the weather conditions associated with nocturnal migration intensity over the North Sea. Nights without precipitation and frontal systems, dominated by high pressure systems and tailwinds in spring and sidewinds in autumn, were found to be most suitable for intense migration over the North Sea. Relative humidity, temperature and cloud cover did not differ significantly between intense and low migration nights. A similar study showed that on nights with intense nocturnal migration over the southern North Sea in spring, birds flew mostly from the United Kingdom towards the east, meaning that the prevailing westerly wind direction may support migration flights (Bradarić *et al*. 2020). However, in autumn, birds headed into the direction of the prevailing wind resulting in migration being timed to exploit periods with tailwinds. Information on the circumstances on which nights intense migration occurs may facilitate effective curtailment measures.

A study using automated radiotelemetry (uniquely coded NTQB tags and Motis registration recievers) looking into the migration routes of 10 species of songbirds showed that 25% of migrating individuals used an offshore route through the German Bight area in the south-eastern North Sea during autumn (Brust & Hüppop, 2021). In species with more westerly migratory destinations the proportion of offshore migrating birds was larger. Among birds migrating towards the southwest, thrushes (redwing *Turdus iliacus* and song thrush *Turdus philomelos*) showed the highest proportions of offshore flights. Additionally, of the following species at least one individual likely also took an offshore route: common blackbird (*Turdus merula*), common starling (*Sturnus vulgaris*), blackcap (*Sylvia atricapilla*), common whitethroat (*Sylvia communis*), garden warbler (*Sylvia borin*), and dunnock (*Prunella modularis*). The understanding of inter-specific variation in the tendency of different species of songbirds to fly offshore, implies that some species of songbirds might be more prone than others to the potential impacts of offshore wind farms, such as collision risk.

Other studies focused on specific species that might migrate between the United Kingdom and the mainland of West-Europe. A pilot tracking study of four common shelducks (*Tadorna tadorna*) showed that shelduck may be exposed to offshore wind farms in the southern North Sea on their migration from the United Kingdom to the Dutch or German Wadden Sea (Green *et al*. 2021). All birds took slightly different routes, while one GPS fix was recorded inside an operational wind farm. Most of their flights occurred at collision-risk height.

Furthermore, in a literature-based study initiated within WOZEP, Eurasian curlew (*Numenius arquata*) is suggested to be prone to suffer population impacts by future offshore wind farm developments, as birds may cross the North Sea on their seasonal migration between the United Kingdom and the mainland of Europe (Fijn *et al*. 2021). However, more knowledge is necessary on the number of individuals that may cross the North Sea and the routes they tend to take, in order to be able to make more accurate predictions on the estimated number of collision victims among curlews. For these purposes, GPS tracking data could provide valuable insights. Jiguet *et al.* (2021), for instance, reported a likely non-lethal injury of a tagged curlew by a coastal wind turbine during its migration journey.

Fijn *et al.* (2022) found that among black-headed gulls (*Chroicocephalus ridibundus*) breeding in the Dutch Wadden Sea, five out of eight tracked birds crossed the North Sea on their migration to and/or from the United Kingdom. As far as could be determined, 83% of these crossing occurred at night. The authors argue that these new insights should be considered for re-assessing the potential cumulative effects of offshore wind farm developments on black-headed gull populations.

Collision Rate Models

Actual reports of birds colliding with offshore wind turbines are very scarce, because direct measurements on collision mortality in the marine environment are challenging, as collecting corpses is almost impossible at sea and conducting long-term observations on collision events requires substantial effort and funding. Therefore, Collision Rate (or Risk) Models (CRMs) are often being used to predict the risk posed by offshore wind farms to seabird populations. In order to reduce uncertainty in calculations with these CRMs, a better understanding of bird flight behaviour, such as speed and height, is needed. Studies on such parameters are not necessarily conducted within the frameworks of offshore wind farms but could be relevant for ecological impact assessments. Therefore, we discuss here a number of studies, but the list of publications in this field of subject may be not all-encompassing, as not all studies on flight behaviour of birds are relevant for CRMs.

Brabant & Vanermen (2020) used the stochastic Collision Risk Model to calculate the estimated number of collision victims for six target species in nine Belgian offshore wind farms. They estimated a total of 69.5 ± 53 (SD) victims per year among these species, of which 37.7 (54%) victims among great black-backed gull (*Larus marinus*). For black-legged kittiwake (*Rissa tridactyla*), common gull (*Larus canus*), herring gull (*Larus argentatus*), lesser black-backed gull (*Larus fuscus*) and northern gannet they estimated respectively 5.3, 5.5, 1.7, 18.8, and 0.5 collision victims per year. The authors stress that these absolute numbers come with a large uncertainty, as the outcomes are highly sensitive to the value of certain parameters, especially avoidance rate and flight speed. Nonetheless, these models can be very useful to compare the relative impact of different scenarios of wind farm development. Comparably, Masden *et al*. (2021) found that the stochastic Collision Risk Model was most sensitive to the parameters of bird density, (non-)avoidance rate, percentage of birds at rotor height, and flight speed. The authors suggest that using site specific flight speeds, accounting for variation in relation to wind direction, affects cumulative collision estimates.

The usability of available data for collision risk modelling may also vary depending on how the data is collected or analysed. In that sense, Péron *et al.* (2020) show that incorrectly handling errors in GPS data to calculate the flight height (distributions) of birds may lead to inaccurate collision risk estimates. Consequently, reviews like that of Largey *et al.* (2021) on the methods and technologies that can be used to provide bird flight data to assess the impact of wind energy developments are useful. They found that four empirical measurement methods could improve the estimation of bird flight parameters: radar, telemetry, ornithodolite and LiDAR.

Waggitt *et al.* (2019) developed a method to combine several data sources with which they modelled monthly distribution maps of 12 seabird species in Northeast Atlantic. The bird densities underlying these maps may serve as input for collision risk models.

Grey literature

In a study for the WOZEP-program, Van Bemmelen *et al.* (2022) used GPS-tracking data to model the macro-avoidance rates for Sandwich terns (*Thalasseus sandvicensis*) breeding in the Netherlands and the UK. The study found average macro-avoidance rates of 0.22 and 0.05 respectively, but the authors urge caution with the lower figure. Additionally, the study found that 87% of all birds were flying at altitudes below 20 m.

Potiek *et al.* (2022) and follow-up studies (Collier *et al.* 2022, Soudijn *et al.* 2022a) used the stochastic Collision Risk Model to calculate the estimated number of collision victims in all operational, planned, and proposed wind farms in the southern North Sea up to 2030 for the species of seabirds (10 species) and migrants (8 species) that are most vulnerable to suffer population impacts due to collision mortality. Among the 10 seabirds, the estimated number of collision victims was highest for northern gannet and lowest for arctic skua (*Stercorarius parasiticus*), while among the migratory species collisions were highest for common starling and lowest for Bewick's swan (*Cygnus (columbianus) bewickii*) (Table 1). The cumulative effects of these collisions were assessed at the population level for different scenarios of wind farm development. Collision victims among northern gannet and herring gull exceeded acceptable levels of population impact in all scenarios (see Chapter 2.6), while for black-legged kittiwake and great black-backed gull these thresholds were violated in one scenario. For all other species, thresholds were not exceeded.

Table 1 *Numbers of estimated annual collision victims (± SD) per species in all operational, planned, and proposed wind farms in the southern North Sea up to 2030. Adapted from Potiek et al. (2022).*

Species	**Collisions**
Lesser black-backed gull	441 ± 10
Herring gull	655 ± 27
Little gull	143 ± 2
Great black-backed gull	2,174 ± 73
Black-legged kittiwake	1,268 ± 55
Northern gannet	7,001 ± 126
Arctic skua	2 ± 0.03
Great skua	29 ± 1.7
Common tern	99 ± 2
Sandwich tern	65 ± 0.9
Bewick's swan	10 ± 0.04
Brent goose	104 ± 0.13
Common shelduck	473 ± 5
Eurasian curlew	670 ± 5
Black tern	33 ± 0.2
Common starling	22,411 ± 41
Red knot	1,245 ± 0.7
Bar-tailed godwit	729 ± 3

Welcker & Vilela (2018, 2019) and Welcker (2019) wrote several reports on nocturnal bird migration in the German North Sea and Baltic Sea. Using radars, they found that nocturnal bird migration through these areas peaked in April and October. Migration intensities strongly increased after sunset, peaked before midnight, and subsequently decreased through the night. Higher bird flux rates were related to increasing tailwinds, and to a lesser extent, with seaward crosswinds. Additionally, weather conditions with low humidity and high barometric pressure, moderate winds and no precipitation were generally preferred by nocturnal migrants. In spring, migration intensity was positively correlated with higher ambient temperatures, while migration intensity increased with lower temperatures in autumn. The intensity of migration in the German North Sea declined with increasing distance to shore. Within the vertical range of the radars up to 1 km, 35% of all flights were recorded below 200 m. In the North Sea sites, the mean flight height was about 100 m higher in spring than in autumn, which is suggested to be due to seasonal differences in the prevailing wind direction in the area. Probably for the same reason, in autumn, flight height decreased with increasing distance to shore. Flight heights were positively correlated with migration intensity. At the end of the night, birds generally flew at lower altitudes, which suggests that an increasing proportion of birds prepares to land. This pattern likely explains the increase of the rate of flight calls in the course of the night, with highest rates usually being reached just before dawn. Migration intensity as measured by the radar was positively correlated with the number of recorded flight calls of nocturnal migrants, especially in October and November when migration of the most vocal species (e.g. thrushes) peaked. In both seasons, the highest flight call rates were recorded in conditions with completely overcast skies, while in autumn the flight call rate was also higher with clear skies. In overcast conditions, birds might decrease their flight height and/or increase their call frequency due to decreased visibility, while clear skies in autumn are generally related to increasing migration intensities. In total, flight calls of 127 bird species were recorded in the offshore sites in the German North Sea and Baltic Sea at night.

Avoidance and attraction

With reference to collision assessments, the terms avoidance and attraction are commonly used in scientific literature to refer to flying birds, whereas the term displacement is used for local, foraging or swimming birds (see 2.2).

Johnston *et al.* (2022) estimated an overall degree of attraction of lesser black-backed gull within a 4 km boundary of five wind farms in the Irish Sea. However, when comparing avoidance/attraction behaviour within various distance bands, a weak macro-avoidance response of lesser black-backed gull was found for birds between 3-4 km distance from the wind farms. Inside the wind farms at distances of 1-2 km from the edge, the birds appeared to be significantly attracted. At a meso-scale, lesser black-backed gull showed vertical avoidance at distances of <70 m to the wind turbines, meaning that at rotor height avoidance increased at distances closer to the turbines, while below rotor height attraction increased at distances closer to the turbines. This suggests that birds actively avoided flying at rotor height by decreasing their flight height.

Grey literature

Using GPS data, Vanermen *et al.* (2022) found no meso-scale response of flying lesser black-backed gull inside Borssele wind farm, which suggests that these flying birds have no significant preference to use turbine corridors.

Skov *et al.* (2018) performed visual and radar observations inside Thanet Offshore Wind Farm to determine overall avoidance rates for northern gannet, black-legged kittiwake, herring gull, and great- and lesser black-backed gull. They calculated overall avoidance rates for these species of respectively 0.999, 0.998, 0.999, 0.996, and 0.998. As these rates may not directly be useful as avoidance rates for collision risk models (CRMs), Bowgen & Cook (2018) recommended avoidance rates that may be better suitable for use in the Band model (Band 2012), which was at that time the most commonly used CRM.

The authors differentiated between two variants of the model (option 1 and 3). For northern gannet, they suggested an avoidance rate of 0.995 when using option 1 of the Band model but could not determine a rate for option 3. For black-legged kittiwake, this was 0.99 for option 1 and 0.98 for option 2 of the Band model. For herring gull, great- and lesser black-backed gull, they suggested avoidance rates 0.995 (option 1) and 0.993 (option 3).

Tjørnløv *et al.* (2021) calculated values for use in collision rate models taking avoidance into account. Species- or group-specific micro-avoidance for gulls was estimated and ranged between 0.938 for large gulls to 0.977 for small gulls.

2.2 Displacement and habitat loss

Displacement refers to the reduced density of species in the wind farm area (plus buffer) compared to the pre-construction densities (Marques *et al.* 2021). For offshore wind farms this is likely to relate to disturbance from the presence of the turbines, increased vessel activity and/or changes in prey availability related to OWF presence. In contrast, densities of birds in and around a wind farm may increase due to for example the provision of roosting spots or increase of prey resources or habituation. However, note that attraction not necessarily has a positive effect on birds as it may also increase collision risk (Marques *et al.* 2021). Marques *et al.* (2021) reviewed all available literature on bird displacement, concluding that negative effects of wind farms on bird abundance are often reported, yet other studies frequently found no displacement effects or even attraction effects. This variability suggests that displacement varies between species and within individuals of the same species, depending on the age and life cycle of the individual, in combination with local circumstances, the characteristics of the relevant wind farms and time after construction. Still, differences in the design of studies may also explain variability in the results (Marques *et al.* 2021).

Vanermen *et al.* (2020) identified three major topics for future research on seabird displacement: 1) assessing species-specific displacement rates, meanwhile looking for correlations with wind farm configuration characteristics, 2) large gull movements in and around offshore wind farms, and 3) an empirically informed species-distribution model to support marine spatial planning. A preliminary study regarding the first topic, indicated remarkable large numbers of common guillemot, razorbill (*Alca torda*) and northern gannet inside a Belgian wind farm concession zone, which might indicate habituation of these species to the presence of wind turbines. However, the authors stress that it is much too soon to draw any conclusions from this preliminary study, as these results are merely based on one survey (Vanermen *et al.* 2021).

Digital aerial surveys and satellite telemetry showed that red-throated divers (*Gavia stellata*) were strongly displaced by offshore wind farms in the German Bight (Heinänen *et al*. 2020). Red-throated divers showed a very strong displacement effect up to 5 km from the wind farm, but a significant effect could be detected up to 10-15 km away. Furthermore, the results indicate that displacement distance was shorter with decreasing visibility and larger during the night (potentially as a reaction on the lights coming from the wind farms at night), which both suggest that the birds use visual stimuli to perceive disturbance. Using a ‘before–after’ control impact analysis approach and a long-term data set, Mendel *et al.* (2019) investigated the effects of offshore wind farm construction and ship traffic on loon (*Gavia* spp.) distributions in the German North Sea on a large spatial scale. Loons showed significant shifts in their distribution in the ‘after’ period and subsequently aggregated between two offshore wind farm clusters. The decrease in loon abundance became significant as far as about 16 km from the closest offshore wind farm. Additionally, Vilela *et al.* (2021) found that the distribution of red-throated divers in the German North Sea became more localized in a central area after wind farm development increased, while before then, divers were more widely distributed. Yet, no population decline of red-throated divers was observed in the total area between 2001 and 2018, despite the erection of 20 offshore wind farms. However, it must be noted that the main construction period of offshore wind farms in the German Bight started in 2012 and the most relevant wind farms (closest to the core area of the birds) became operational in 2014/2015. Population level effects may thus not yet have been visible in 2018. Another report (grey literature) found a decrease in the population of red-throated diver from 31,000 to 11,000 in the German North Sea between 2011 and 2017 (Schwemmer *et al.* 2019).

Allen *et al.* (2020) reviewed the development of monitoring and analysis techniques of red-throated diver displacement over the years. The authors conclude that the emergence of digital aerial surveys techniques and advancements in spatial modelling greatly improved our understanding of the impacts of offshore wind farms on these birds. Yet, knowledge gaps remain on the species’ habitat preferences and population dynamics like density-dependent competition, and on our understanding of magnitude of displacement of red-throated divers due to wind farm related vessel activity. Furthermore, understanding on the cumulative effects across the entire life cycle of the birds is also inadequate. Lastly, estimates of diver abundance should come with an empirical, peer-reviewed correction factor to correct for diving birds that may bias at-sea surveys.

After six years of post-construction monitoring at Thornton Bank, Vanermen *et al.* (2019a) showed that the numbers of northern gannet, razorbill and common guillemot have dropped by 98%, 75-80%, and 60-63% respectively. Herring gull and great black-backed gull were found to be attracted to the wind farm with respectively 3.9-4.9 and 5.3-6.6 times increases in densities in the wind farm area. Great cormorants (*Phalacrocorax carbo*) were also strongly attracted, showing an increase in numbers with factors of 40-43, as they were virtually absent in the area before construction. No significant or inconclusive results were found for northern fulmar (*Fulmarus glacialis*), great skua (*Stercorarius skua*), little gull (*Hydrocoloeus minutus*), common gull, lesser black-backed gull, black-legged kittiwake, and Sandwich tern.

Peschko *et al.* (2020a) carried out a Before-After Impact-Control (BACI) analysis to study the displacement of common guillemot and black-legged kittiwake after the construction of four offshore wind farms north of Helgoland. The analysis showed that relative density of kittiwakes inside the wind farms decreased by 45% in the breeding season, and by 10% in spring, this latter effect not being significant. The relative density of guillemot in the wind farms was reduced by 44% in the breeding season, and by 63% in spring. The authors estimated that guillemots showed a response radius to the wind farms of approximately 9 km in spring, whereas for kittiwakes this radius was around 20 km in the breeding season. In another study, guillemots were shown to strongly avoid offshore wind farms close to their colony on Helgoland with a 63% reduction in the resource selection of the offshore wind farm areas compared with the surroundings (Peschko *et al.* 2020b). Furthermore, when turbine blades were rotating, the avoidance of guillemots increased to 75%.

A similar study on northern gannets showed that the birds' resource selection of offshore wind farm areas close to Helgoland was reduced by respectively 21% and 37% compared to the surroundings (up to 15 km from the wind farm borders) during the breeding seasons of 2015 and 2016 (Peschko *et al*. 2021). The authors also found individual variation in the response to operating offshore wind farms of northern gannets breeding on Helgoland. The wind farms were predominantly avoided by 25 individuals (89%), while three birds (11%) frequently entered the wind farms. For the first group of birds, the wind farms resulted in habitat loss and/or barrier effects.

Vanermen *et al*. (2021) used GPS tracking data to compare the numbers of lesser black-backed gull before and after the construction of the Belgian Norther wind farm. They found a decrease in occurrence by 71% compared to the pre-construction period and accounting for the trend in control areas. However, large gulls such as lesser black-backed gulls tend to be attracted to fishing vessels. As such, the authors argue that it is hard to assess whether this distribution is due to disturbance induced by wind turbines, the absence of fishing activities inside the wind farm or a combination of both. Nonetheless, it is suggested that collision mortality is still the main concern for lesser black-backed gull, rather than the impact of habitat loss.

Using GPS tracking data, Vanermen *et al*. (2019b) found an increase in the presence of non-flying lesser black-backed gulls at the edge of offshore wind farm Thornton Bank. These results suggest that lesser black-backed gulls are attracted to the outer wind turbine jacket foundation for resting. On the other hand, significantly fewer birds were present in the middle of the wind farm than in the surroundings of the wind farm.

Grey literature

A review of studies about the displacement of common guillemot and razorbill in relation to offshore wind farms concluded that displacement rates varied from from +112 to -75%, showing variation in the strength of the displacement effects or even attraction (APEM 2022). Furthermore, high displacement rates were correlated with low auk abundance in the study area, and thus are potentially an artefact of low sample size. The authors hence suggest that a displacement rate of -50% for auks would be an appropriate precautionary approach to assume for use in assessments, especially for offshore wind farms with moderate to high densities of auks.

Based on aerial and ship-based surveys, a recent study analysed the effects of all operating offshore wind farms (OWFs) in the German EEZ on six seabird species (Garthe *et al.* 2022, Peschko *et al. in prep.*). A 'before–after control impact' (BACI) analysis was conducted to estimate the possible effects of OWF presence on the species density and to estimate the response range to the OWFs. For **common guillemots**, in autumn and in winter, a strong decline in abundance of respectively 91% and 67% was detected inside OWFs + 1 km buffer and of respectively 80% and 54% inside OWFs + 5 km buffer. Guillemot density was significantly affected up to a distance of 18-21 km in autumn and 15-18 km in winter. For **razorbills**, a decline in abundance of 55% inside OWFs + 1 km buffer and of 47% inside OWFs + 5 km buffer was detected in winter. Razorbill density was significantly affected up to a distance of 0-3 km. For **northern gannets**, in summer and autumn, abundance declined by respectively 75% and 81% inside OWFs + 1 km buffer and by respectively 32% and 43% inside OWFs + 5 km buffer. Northern gannet density was significantly affected in summer and autumn up to a distance of 0-3 km. For **northern fulmars**, in spring and summer, abundance declined by respectively 91% and 64% inside OWFs + 1 km buffer and by respectively 84% and 43% inside OWFs + 5 km buffer. Northern fulmar density was significantly affected up to a distance of 3-6 km in spring and 0-3 km in summer. For **black-legged kittiwakes**, in spring, abundance declined by 35% inside OWFs + 1 km buffer and birds were affected up to a distance 0-3 km. In winter, an abundance increase was detected for black-legged kittiwakes, which was not found to be significant for OWFs + 1 km buffer, while for OWF + 5 km buffer an increase in abundance of 27 % was detected. **For lesser black-backed gulls** in summer an insignificant increase was detected for OWFs + 1 km buffer, while an abundance decline was found of 42% inside OWFs + 5 km buffer. Lesser black-backed gull density was significantly reduced up to a distance of 12-15 km. In autumn an increase in abundance of 70% was detected for OWFs + 1 km buffer.

Soudijn *et al.* (2022b) estimated the number of victims due to habitat loss in all operational, planned, and proposed wind farms in the southern North Sea up to 2030 for the species of seabirds (10 species; see Table 2) that are most vulnerable to suffer population impacts due to displacement. The study was based on densities of birds according to the ESAS- and the Dutch MWTL monitoring database and used the assumption that all birds in wind farm footage areas would be displaced, of which a certain fraction would die as a consequence of this displacement. This fraction was based on Bradbury *et al.* (2014) and Leopold *et al.* (2015). Among the evaluated species, the highest number of victims is estimated for common guillemot (Table 2). For seven species, population modelling allowed to assess the cumulative effects of habitat loss for different scenarios of wind farm development. Mortality due to habitat loss was found not to exceed Acceptable Levels of Impact on the populations of these species (see Chapter 2.6).

Table 2 Numbers of estimated annual victims per species due to habitat loss in all operational, planned, and proposed wind farms in the southern North Sea up to 2030. Adapted from Soudijn et al. (2022b).

Species	**Victims due to habitat loss**
Gavia sp.	267
Northern fulmar	171
Northern gannet	251
Great cormorant	4
Common eider	34
Common scoter	87
Sandwich tern	46
Common guillemot	14,148
Razorbill	2,610
Atlantic puffin	708

2.3 Barrier effects

Barrier effects refer to the deflection of flight paths in response to the wind farms, which may lead to increased energy expenditures. These effects will mainly impact seabirds during the breeding season if these birds have to adjust their flight paths repeatedly as central place foragers (Pollock *et al.* 2021, Green *et al. in prep*.). Barrier effects may result in areas behind wind farms becoming less accessible due to increased energetic requirements. Migrating land birds may also have increased energetic costs, although these are likely to be small for individual wind farms (Masden *et al.* 2009). Compared to collision risk and displacement, fewer studies have been published on barrier effects at offshore wind farms. Consequently, no relevant studies were found for the period considered.

2.4 Disturbance related to offshore wind farms

Also, other effects than the wind turbines themselves but that are associated with offshore wind farms may cause local birds to be temporarily disturbed or may lead to permanent displacement or habitat loss (§2.2). These temporal disturbances entail, for example, noise, light and disturbance by vessels.

The distribution of red-throated divers in the German Bight was found to be affected by ship traffic, including wind farm related ships (Burger *et al.* 2019). Divers were significantly more abundant in areas with low-frequency ship traffic. Ships sailing at high speed were seemed to be more disturbing than slow-speed ships. Also, Mendel *et al.* (2019) found that ship traffic had a significant negative impact on loons (*Gavia* spp.), indicating that offshore wind farms deterred loons through the combined effect of the wind turbines themselves and the associated ship traffic. In addition, ship speed was identified to have a strong effect on divers: after disturbance from high-speed vessels, resettlement of the disturbed area took longer than after disturbance from slow- or medium speed vessels (Dorsch *et al.* 2019). This latter study also indicated that divers kept longer distances to offshore wind farms at night, when wind turbines were illuminated with bright red aviation lights and white navigation lights (Dorsch *et al.* 2019).

When approached by small boats, moulting common eiders (*Somateria mollissima*) off the coast of Norway showed an average flight-initiation distance (“flock-to-boat distance at which an energy-demanding escape occurred”) of 177 m and were on average displaced by 771 m from their original location (Dehnhard *et al*. 2020). Most flocks resumed their normal behaviour within 10 minutes after disturbance. However, flocks may encounter less suitable habitat after disturbance. These results suggest considerable effects of small boats on moulting common eiders.

Hansen *et al.* (2020) experimentally showed that common guillemots (*Uria aalge*) respond to underwater noise, with indications of a greater response with higher sound levels.

Mercker *et al*. (2021) developed a novel statistical approach to integrate and assess the cumulative effects of different human activities on marine-bird habitat quality, including offshore wind farms, by comparing observed distributions with scenarios without human disturbance. Therefore, this tool may be a valuable component of marine assessments.

Grey literature

A recent study of Goodship and Furness (2022) reviewed literature on species-specific disturbance distances to human disturbance by, for example, wind farm vessels. Buffer zones are presented that indicate the potential distance the protect the birds from human disturbance (table 3). However, the authors argue that for more precise disturbance distances, site-specific data should be collected for more accurate assessments. Moreover, the study relies mainly on older literature, with the ones related to offshore wind farm developments since 2019 being limited to one source, proving that more studies on the disturbance effects of offshore wind farms are welcome.

Table 3 Suggestions for disturbance buffer zones (m) for a selection of seabird species during breeding (BR) and non-breeding (NBR) season. Adapted from Goodship and Furness (2022).

Species	Buffer zone (m) suggestions
Common eider	BR = 100-200 m; NBR = 200-500 m
Common scoter	BR = 300-500 m
Red-throated diver	BR = 500-750 m; NBR = ≤1000m
Black-throated diver	BR = 500-750 m; NBR = ≤1000m
Great northern diver	NBR = 100-350m
Little tern	BR = 100-300m
Sandwich tern	BR ≥200m
Common tern	BR = 200-400m
Arctic tern	BR ≥200m
Roseate tern	BR ≥200m

2.5 Indirect effects

Changes in prey resources

Several studies show the effects of offshore wind farms on underwater prey resources in and around the wind farms (*e.g.* Slavik *et al.* 2019, Dannheim *et al.* 2020, Coolen *et al.* 2022). Indirectly, however, changes in prey resources may (partly) be reflected by changes in the distribution of birds (*i.e.* displacement or attraction). Although at present no new literature has emerged on the direct effects of these changes in prey resources on birds, the impact of offshore wind across the marine food chain is the focus of a new study led by the University of Aberdeen.

In addition to the natural developments of prey resources, the co-use of offshore wind farms may also create new circumstances that could affect the ‘attractiveness’ of these areas for seabirds. For example, marine aquaculture is expected to be extending in the areas of offshore wind farms, which could increase collision risks to birds. Benjamins *et al.* (2020) carried out a thought experiment to assess the potential of such risk to bird species. The results showed substantial variation between species, but large gulls (*Larus* sp.) and European shag (*Phalacrocorax aristotelis*) were expected to be at the greatest potential risk. However, the authors stress that the general lack of information on interactions between birds and fish farms has a significant knowledge gap, and greater focus on these interactions is needed to improve future risk assessments.

Grey literature

Besides direct effects that offshore wind farms may have on birds, the large-scale at which these developments are expected to take place may have substantial effects also on local wind patterns, wave generation, tidal amplitudes, stratification of the water column, dynamics of suspended particles and bedload transport of sediment, while also providing extra hard substrate for biota. These developments are yet to occur, but the first modelling studies for the North Sea have been conducted that indicate that in certain areas major changes could take place (Boon *et al.* 2019, Zijl *et al.* 2021).

2.6 Cumulative and population level effects

There is a general agreement that there is a key need for an understanding of the potential cumulative impacts of offshore wind farms on birds (Fox & Petersen 2019, May *et al.* 2019). There have been several attempts to carry out such cumulative assessments, each with different assumptions and without a general consensus on a certain approach (May *et al.* 2019). For instance, Gusatu *et al.* (2021) proposed a holistic cumulative methodology to assess impacts of 18 different offshore wind farm related pressures on seabed habitats, and reference species of fish, seabird and mammal species in the entire North Sea. Based on a literature review that was validated through expert questionnaires, the study identified that barrier effects, habitat loss, and risk of contact with fuel or chemicals would be the pressures to which the investigated bird species (fulmars, razorbills and guillemots) would be the most sensitive. Piet *et al.* (2021) goes further in their unpublished report than the cumulative assessments of offshore wind farms, with the aim to assess the cumulative impacts of all main human activities in the North Sea under various planning scenarios. They used a semi-quantitative risk assessment, including the pressures of the different human activities and the impacted ecosystem components, which was then applied to identify the main threats to the North Sea biodiversity and evaluate the effectiveness of the management measures to mitigate those threats. The study suggests that considerable potential reduction in impact risk can be reached for birds, depending on the design of the wind turbines or their location. This relates respectively to increasing capacity of wind turbines (*cf.* Thaxter *et al*. 2017) and planning offshore wind farms in areas with lower bird densities (*cf.* Leopold *et al.* 2015). In contrast, Soudijn *et al.* (2022) and Potiek *et al.* (2022) modelled in their unpublished works in more detail the cumulative impacts respectively of habitat loss and collisions caused by offshore wind farms in the Southern North Sea on all relevant bird species (the results of the studies are discussed in above chapters). In another report, Searle *et al.* (2022) examined how seabird collisions, displacement and barrier effects could be integrated in one individual-based mechanistic model of seabird movement, behaviour, demographics and OWF interactions (*i.e.* the so-called SeabORD model). They concluded that further research is needed on the quantitative population level effects of displacement and on seabird behaviour outside the breeding period. In chapter 2.1 we also split up published literature to studies on breeding- and migratory birds. However, a cumulative impact assessment would also mean to evaluate effects throughout the whole annual cycle of an individual. For example, Thaxter *et al*. (2019) also demonstrated, using GPS telemetry, that the vulnerability of lesser black-backed gulls to collisions was high near to colonies but was also high at some migration bottlenecks and wintering sites where exposure to turbines was greatest.

These tradeoffs of grasping cumulative impacts of all human activities together (or alternatively all wind farm developments both onshore and offshore) or evaluating all relevant bird species in detail depict the difficulty of the issue of cumulative impact assessments. Nonetheless, as May *et al.* (2019) also concluded, while the current monitoring- and modelling techniques may be unable to describe the whole complexity of wind and wildlife interactions, we need to use the best available methods to describe natural variability of animal populations to support risk-based decision-making. Policies that support the use of adaptive management will promote assessments at the population level.

In addition to the difficulty to quantify the impacts of all relevant human activities that lead to bird mortality, translating these into population level effects has its own challenge. Population viability analyses are now routinely used during the consenting process for offshore wind energy developments to assess potential impacts to seabirds (Miller *et al.* 2019). But how these models are used gives still space for improvement. For instance, Horswill *et al.* (2022) argues based on the example of data collected from 70 colonies of black-legged kittiwakes across the UK and Ireland that including temporal trends in population viability assessments dramatically influences the projected rate of population decline. Therefore, they argue that environmental factors driving current population dynamics need to be incorporated in population viability impact assessments. In another study, Horswill *et al.* (2021) also pointed out the danger of using values from surrogate species or other populations of the same species in population level assessments when no data is available from the target population. Also for this study, they used black-legged kittiwakes breeding in the United Kingdom and Ireland as an example to indicate that using surrogate values to fill in missing parameters have large potential demographic impact, and that resulting biases are driven in unpredictable directions thus precluding assessments from being consistently precautionary.

Furthermore, even if the effects are calculated at the population level, impact assessments need to be able to make statements whether or not these effects will have a significant negative impact on the population. Such evaluations have often been carried out using relatively simple criteria and thresholds like the the Potential Biological Removal (PBR). However, this approach has been challenged as *e.g.* it does not take any environmental variability into account and it implicitly assumes a fixed level of undemonstrated density dependence in population development (O'Brien *et al.* 2017, Miller *et al.* 2019). To solve such problems, the Dutch government has recently initiated the development of a novel method of impact assessment based on the outcome of population models. Within this approach, species-specific thresholds were defined for 21 bird species that consist of two parts:

- A threshold population decline 30 years after the onset of a continuous prolonged impact, as a percentage X of the projected population size without the impact, which is considered acceptable.
- A threshold probability Y that X is below this acceptable level after 30 years, which is considered an acceptable risk.

3 Final remarks and recommendations

Studies published since 2019 mainly describe displacement and figures relating to collisions, often following standard methods and being site-, and development-specific so being less relevant here. In connection with collision risk, several studies show evidence for avoidance. The level and scale at which displacement occurs varies between species and studies, likely to do with species sensitivity, and wind farm and habitat characteristics. As these studies are predominantly described from peer-reviewed literature, there is undoubtedly publication bias towards where effects have been demonstrated.

This review shows that the geographical scope of published studies on offshore wind farm effects in the OSPAR region is concentrated around British, German, Dutch and Belgian waters in the southern North Sea. Few studies address the effects in the Irish Sea and Baltic Sea, while studies of offshore wind farm effects in the Northern Atlantic are lacking. This limited geographical scope may partly be explained by the number of offshore wind farms in these areas, which is generally less than in the southern North Sea. Nonetheless, it shows that knowledge gaps on the effects of offshore wind farms on birds in these regions remain to be addressed by future studies. The geographical scale of the density maps produced by Waggitt *et al.* (2019) show how the coherence of bird occurrence in the whole Northeast Atlantic can be achieved. Such studies on recent bird densities, extended by local age composition, -bird behaviour, and -flight characteristics could certainly help planning and assessment of offshore wind farms (*e.g.* Cleasby *et al.* 2020, Fauchald *et al.* 2021, Fijn *et al.* 2021, Potiek et al. 2019).

This review also shows that no studies address the effect of different configurations of offshore wind farms, or for instance the use of corridors intended for birds, which is therefore another knowledge gap to be filled. Yet, in the coming years we reach the period when the lifetime of the first offshore wind farms is reached, raising the question around the effects of decommissioning of these structures. Currently, knowledge regarding the biological communities that develop on these structures and their ecological role in the North Sea is currently insufficient to inform such decommissioning decisions (Fowler *et al*. 2019).

Recently, concern has also risen about potential ‘knock on’ effects through the food chain that could be caused by OWF-induced ecosystem shifts such as, *e.g.*, changes in seasonal and spatial stratification patterns, hydro-morphological changes and maybe even changes due to increases in benthic production on the foundations of the turbines and adjacent platforms (Zijl *et al.* 2021).

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