

Corridor use by seabirds in an offshore wind farm

Nienke Kwant-Heida*, Elisa L. Bravo Rebolledo, Koen Kuiper, Jacco J. Leemans, Rob S.A. van Bemmelen, Abel Gyimesi

Waardenburg Ecology, Culemborg, The Netherlands

NKH ORCID: 0009-0001-3387-2230; ELBR ORCID: 0000-0002-1234-0251;

JJL ORCID: 0009-0003-1185-2591; RSAVB ORCID: 0000-0002-0688-7058;

AG ORCID: 0009-0005-9782-1271

*Correspondence author: n.kwant-heida@waardenburg.eco

Abstract

Offshore wind farms may have negative effects on birds, for example by forming barriers to and from foraging areas. Corridors have been suggested as a potential mitigation measure to counter barrier effects. In a corridor, the spacing between wind turbines is larger than in the rest of the wind farm. We studied whether birds use the corridor more than the area inside the wind farm in Borssele offshore wind farm in the Netherlands. Using standard European Seabirds At Sea (ESAS) methodology, we mapped the densities of birds from 20 ship-based surveys over a two-year period. No differences in seabird densities were found between the corridor and the wind farm for five species for which sample sizes were sufficient (Razorbill *Alca torda*, Common Guillemot *Uria aalge*, Black-legged Kittiwake *Rissa tridactyla*, Common Gull *Larus canus*, and Lesser Black-backed Gull *L. fuscus*). Our study found no conclusive support for corridor use. However, corridor use might be different when the corridor is wider, oriented differently, or when shipping traffic is absent. Therefore, we cannot exclude that a corridor is a suitable mitigation measure for reducing barrier and/or collision risk, based on this study.

Keywords ship-based survey, barrier effects, North Sea, avoidance, mitigation, renewables

Introduction

The rollout of offshore wind farms is indispensable for the energy transition to achieve the goals of the Paris Climate Agreement (Macquart *et al.* 2023). However, the development of offshore wind energy is also expected to have negative effects on wildlife, in particular birds (Green *et al.* 2022, Watson *et al.* 2024). Potential negative impacts on seabirds arise through habitat loss due to seabirds avoiding wind farms (Dierschke *et al.* 2016, Garthe *et al.* 2023), collisions with wind turbines (Desholm & Kahlert 2005, King 2019), or barrier effects. Barrier effects lead to higher energy expenditure when flying around a wind farm, or even a disruption in the connectivity between important areas, such as breeding grounds and foraging areas (Drewitt & Langston 2006, Fox & Petersen 2019).

Most of the ongoing studies on mitigating the negative effects of offshore wind farms focus on collisions and habitat loss (Gartman *et al.* 2016, Gulka *et al.* 2024). However, with the footprint of current and planned offshore wind farms getting ever larger, concerns of barrier effects are also increasing. A potential mitigation measure that has been suggested is creating a corridor in large offshore wind farms, with larger spacing between wind turbines than in the rest of the wind farm (Krijgsveld 2014, Goodale *et al.* 2019). The spatial configuration of wind farms and turbine spacing have been indicated to potentially counteract barrier effects, with birds showing less avoidance when turbines are placed further apart (Masden *et al.* 2012, Gartman *et al.* 2016, Gulka *et al.* 2024, van Bemmelen *et al.* 2024). Existing knowledge about the effects of turbine configuration in offshore wind farms on seabirds is limited, however some evidence that the distance between turbines influences the use of wind farm areas by birds exists. For example, Vanermen *et al.* (2019) observed more Lesser Black-backed Gulls *Larus fuscus* flying between turbines 1,700 m apart, than between turbines 800-900 m apart. Moreover, a study on Sandwich Terns *Thalasseus sandvicensis* found less avoidance of wind farms where turbines are spaced less densely (van Bemmelen *et al.* 2024).

In this study, the use of a strip in the wind farm where spacing between turbines is wider compared to the rest of the wind farm, that may be used as a corridor by birds (further on referred to as 'corridor'), was investigated. This was done as part of a larger study into the impacts of offshore wind farm Borssele (further on referred to as 'Borssele'), the Netherlands, on birds. To study corridor use of birds, ship-based surveys were carried out to estimate densities inside the wind farm, just outside the wind farm (further on referred to as 'border') and in the corridor. These densities were compared between the wind farm itself and inside the corridor or at the border, to see whether birds used the corridor more than the wind farm. Part

of this corridor is used as a shipping lane, meaning shipping is allowed, as opposed to the rest of the corridor and the wind farm, where only service vessels for the wind farm are allowed. Some species, such as Common Guillemot *Uria aalge*, are known to be sensitive to disturbance by ships (Fliessbach *et al.* 2019). Therefore, we also studied whether there was a difference in bird densities between corridor transects with and without shipping allowed.

Methods

Study area

Data collection took place in offshore wind farm Borssele, which is located in the southern tip of the Dutch Continental Shelf (NCP) against the border with the territorial waters of Belgium. The water depth in the wind farm ranges from 14 m to 36 m. The total area of the wind farm is 344 km² and it is divided into four subplots. The width of the entrances of the corridor ranges from 2 to 2.4 km, while the average distance between turbines along the rest of the edge of Borssele ranges from 0.9 to 1.4 km. In part of the corridor shipping is allowed (transects BC and FG; Figure 1) and another part it is not (transect CD; Figure 1). Wind turbine construction in Borssele started in the last quarter of 2019. The first sections of the wind farm became fully operational in September 2021. The wind farm consists of 173 turbines of 8-9.5 MW each.

Study period

Fieldwork in Borssele was carried out over the course of two years, starting in December 2021 and ending in December 2023. Ship-based surveys were planned once a month, however due to weather circumstances some surveys had to be cancelled. The most important factor determining whether field trips could be realized was wave height. When wave height exceeded 1m, trips were usually cancelled. In total, 20 surveys were conducted (Appendix I). In 2022, no surveys were conducted in February and November. In 2023, several long periods with unfavourable weather conditions led to the cancellation of trips in January, April, October and November.

Data collection

Seabird density data were collected during ship-based surveys from the Rijkswaterstaat (RWS) vessel 'Scheldestroom', following the European Seabirds At Sea (ESAS) protocol (Camphuysen *et al.* 2004). A standard set of transects was sailed each survey, alternating in direction per survey (A>J or J>A; Figure 1). The transects were located either a) inside the wind farm (OWF), b) in the corridor, or c) along the border of the wind farm (border OWF; Figure 1). There were two types of corridor transects, two inside the shipping lane (BC and FG; Figure 1), and one

outside the shipping lane, but where distance between turbines is just as wide as inside the shipping lane (CD; Figure 1). The sailed route was tracked using a GPS and metadata about the weather were noted at the starting point of each transect. Transects at the border of the wind farm were between 0.9 and 2.6 kilometres from the nearest wind turbine at the edge of the wind farm (Figure 1). The ESAS methodology uses a transect with a width of 300 metres perpendicular to the ships heading. A constant sailing speed of around 9.7 knots (17.96 km/h) was kept as much as possible. This resulted in a transect length of 300 metres every minute. Observers were located on top of the ship, at 10 metres above sea level. The 'Full transect method with snapshot' was applied. The 'Full transect' method dictates that birds are recorded both inside and outside the transect. In other words, birds sitting on or otherwise touching the water inside the transect, for example when foraging, are recorded as 'in transect'. All others are recorded as 'outside transect'. 'Snapshot' refers to observations of flying birds, which are recorded each minute mark as 'in transect'. During the rest of the minute, all flying birds are recorded as 'outside transect'. Only observations recorded as 'in transect' were included in density calculations. Observations were carried out by naked eye, while binoculars were only used for species identification. Depending on whether two or three observers were present, one or two sides of the ship were counted, respectively. On three occasions two sides of the ship were counted (Appendix II). For birds sitting on the water, distance to the transect line was noted in distance bands (bands labelled A – E; 0-50 m, 51-100 m, 101-200 m, 201-300 m, 300+ m).

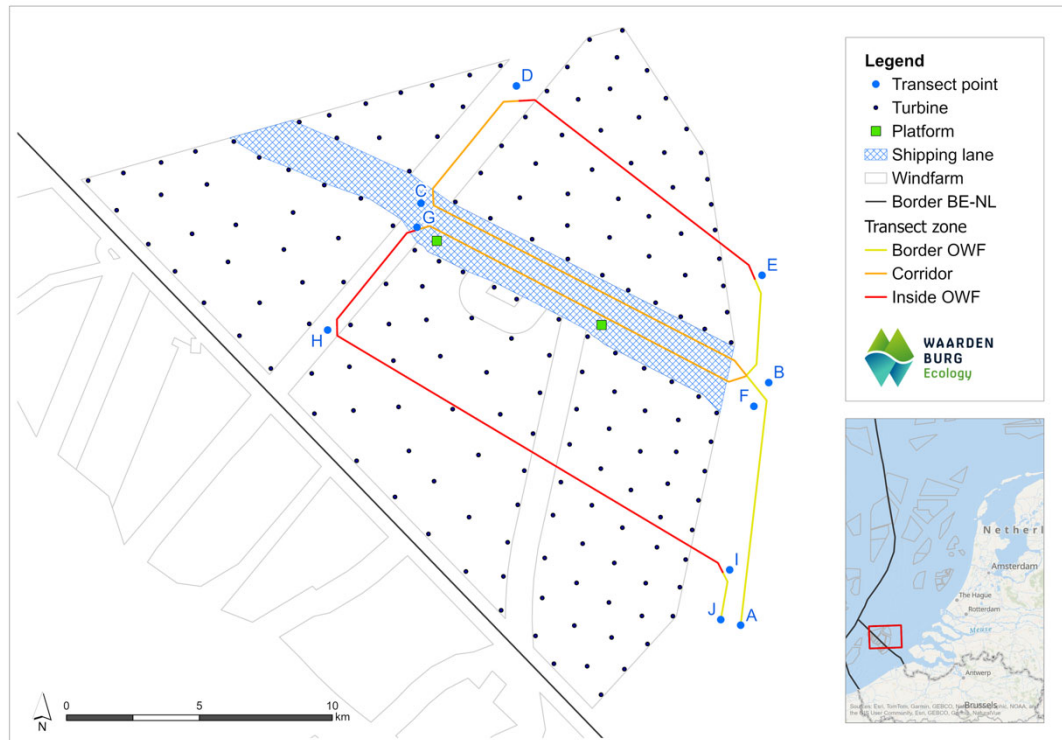


Figure 1. Survey route during ship-based surveys in and around offshore wind farm (OWF) Borssele. Transects were sailed in alternating sequences (A>J or J>A). Highlighted in blue is the shipping lane. The different types of transects are indicated in different colours. Turbine locations and location of the offshore high voltage stations (platform in short) are also given.

Distance analysis

Distance sampling analyses were carried out to correct for imperfect detection of swimming birds at a larger distance from the observer (Buckland *et al.* 2001). This analysis was only carried out for swimming birds, as under the ESAS protocol all flying birds within 300 m are assumed to be detected. Distance models were fitted for each species separately, but only for species with a sufficiently large sample size of swimming birds. A rule of thumb for distance analysis is that 60 observations are needed for a distance analysis, and 60 more for each level of a covariate (Buckland *et al.* 2004). Sample sizes smaller than this can lead to non-robust outcomes of the distance sampling analysis. A detection function describes how the detection probability of birds declines with distance from the transect line. Detection functions consisted of a key function, and either adjustment terms or covariates (Buckland *et al.* 2004). For each species, 8-12 functions were fitted (depending on the number of covariates included), including half-normal and hazard-rate key functions, with cosine and hermite adjustment terms with the half-normal key functions, and simple polynomial adjustment terms with the hazard-rate key function.

Alternatively, sea state, observer team and the natural logarithm of group size were included as covariates with both hazard rate and half normal key functions. The best-fitting model per species was selected based on the lowest Akaike Information Criterion (AIC) value. This ‘best’ model was used to calculate the Effective Strip Width (ESW). The ESW is then used to calculate the density of birds sitting on the water, $D_{swimming}$, per species, assuming perfect detection at the transect line. This was calculated using formula 1, with the ESW and transect length in km.

$$D_{swimming} = \frac{N_{swimming}}{ESW * transect\ length} \quad (1)$$

To calculate the density of flying birds D_{flying} , the entire transect width of 300 m can be used.

$$D_{flying} = \frac{N_{flying}}{width_{transect} * length_{transect}} \quad (2)$$

To be able to use the number of birds as a ‘count’ response in later modelling, assuming a negative binomial in the Generalized Linear Mixed Model (GLMM; see next paragraph), we calculated an ESW weighted for the proportion of birds flying and birds sitting on the water as follows (formula adapted from Leopold *et al.* 2013):

$$Weighted\ ESW = \frac{N_{total}}{\frac{D_{swimming} + D_{flying}}{length_{transect}}} \quad (3)$$

This weighted ESW was then used to calculate the effectively surveyed area (ESA) corresponding to the summed densities of swimming and flying birds. Distance analyses were carried out using the MRDS package in R (Laake *et al.* 2023). Common Guillemot and Razorbill were combined for the distance analysis to arrive at a more robust estimate of the ESW, as these species are similar in shape, colour and size.

Modelling the number of birds

Analyses were carried out in R version 4.2.2 (R Core Team 2023). The BRMS package (Bayesian Regression Models using ‘Stan’; Bürkner 2017) offers an interface for Bayesian computing in Stan (Stan Development Team 2025). Bayesian model outcomes provide no p-value or significance results. Instead, the posterior distribution provides the distribution of potential parameter values given the data and the model. We evaluated the position of 0 in the difference between the posterior distributions of the densities of birds in the OWF and the corridor or the border; we consider the support for differences in densities between the zones as ‘important’ if 0 was outside the (arbitrary) 95% credible interval (van de Schoot *et al.* 2021). Default settings of BRMS were used, including the default non- or weakly informative priors, four chains with 2000 iterations each, of which the first 1000 iterations were regarded as ‘warmup’ iterations,

resulting in 4000 posterior samples. Model convergence was assessed by visually inspecting the mixing of the chains in trace plots, by ensuring that all R-hat values were close to 1 and using posterior predictive checks.

Five bird species were selected for analysis: Common Guillemot, Razorbill *Alca torda*, Black-legged Kittiwake *Rissa tridactyla*, Lesser Black-backed Gull and Common Gull *Larus canus*. These were selected because these species were observed (swimming) at least 60 times during all surveys together. Only ecologically relevant surveys were included in analysis, e.g. during winter season for Common Guillemot and Razorbill (Appendix II).

To investigate differences in bird densities between the zones, the following negative binomial GLMM was fitted for each species (Bürkner 2017). The following model formula was used:

$$N \sim \text{zone} + (1|\text{date}) + \text{offset}(\log_area) \quad (4)$$

with the variables:

N:	Number of birds per transect
zone:	Factor with three levels: inside the wind farm (base level), in the corridor, or at the border of the wind farm.
date:	Date of the survey
log_area	Natural log of the effectively surveyed area (ESA, see above)

Random intercepts were included per survey date and the natural log of the effectively surveyed area was included as an offset, so that numbers of birds are corrected for surveyed area while adjusting for imperfect detection; model outcomes are then numbers of birds per km². The effectively surveyed area was calculated by multiplying the weighted ESW with the length of the transect.

Comparison of the different corridor transect types

To disentangle the effect of shipping and the effect of the corridor itself, posterior distributions were compared for transects in the corridor where shipping was allowed (BC and FG; Figure 1) and the transect in the corridor where shipping is not allowed (CD, Figure 1). If the 95% credible interval of the difference between these posteriors spans zero, it was assumed there is no effect of shipping and both corridor types were analysed together for a larger sample size. If the interval does not span zero, the difference between the two types of corridor transects is

considered ‘important’ and the two types are analysed separately. This was determined separately for each of the species.

Results

Distance analysis

For the selected species, the best fitting models are summarised in Table 1. The ESW of 179 m for Lesser Black-backed Gull was the smallest and for Common Guillemot/Razorbill the largest ESW was calculated; in some surveys the ESW was 300 m. Only for Common Guillemot/Razorbill adding a covariate for observer team resulted in a better model, therefore different ESWs were used for different observers (Table 1, Appendix III for corrected ESWs per survey). Group size had no significant influence on the detection probability of any of the species. Sea state could only be tested as a covariate for Common Guillemot/Razorbill due to sample size constraints but did not influence detectability.

Table 1. Best fitting models per species in the distance analysis, including resulting Estimated Strip Width (ESW).

Species	Function	Adjustment term	Covariates	ESW (m)
Lesser Black-backed Gull	hazard rate	none	none	179.6
Black-legged Kittiwake	half-normal	cosine	none	196.9
Common Guillemot/Razorbill	hazard rate	none	observers	116-300
Common Gull	hazard rate	none	none	286.3

Corridor types - shipping

No support for differences in density were found for any of the species between corridor transects with and without shipping allowed (Table 2). Therefore, the two types of corridor transects were combined into a single factor level in subsequent models, named corridor.

Table 2. Median, and lower and upper boundary of the 95% credible interval, of the difference of the posterior samples between the two types of corridor transects (with or without shipping). Calculated as corridor with shipping – corridor without shipping. A difference in bird densities in

the corridor transects with and without shipping is considered important if 0 falls outside these credible intervals.

Species	Median	Lower boundary	Upper boundary
Lesser Black-backed Gull	0.15	-0.78	0.97
Black-legged Kittiwake	-1.07	-7.79	1.55
Common Guillemot	1.47	-10.47	11.58
Razorbill	-0.89	-5.71	1.20
Common Gull	0.89	-5.31	10.06

Bird densities

For the five studied species (Common Guillemot, Razorbill, Black-legged Kittiwake, Lesser Black-backed Gull and Common Gull), all credible intervals span over 0, meaning no evidence of a difference in bird numbers between the wind farm and the corridor or between the wind farm and the border of the wind farm (Table 3). Indeed, the raw densities as well as the posterior distributions of the different zones also overlap mostly (Figure 2, 3).

Table 3. Model estimate and lower and upper boundary of the 95% credible interval of the model estimates of the GLMM on ship-based count data, Intercept is the estimate for inside the wind farm, and border and corridor are estimates of the difference with the wind farm.

Razorbill			
	estimate	lower	upper
Intercept (OWF)	0.26	-0.65	1.11
Border	0.16	-0.66	0.95
Corridor	0.39	-0.34	1.10
Common Guillemot			
	estimate	lower	upper
Intercept (OWF)	0.50	-0.60	1.48

Seabird use of offshore wind farm corridor

Border	0.63	-0.49	1.80
Corridor	0.83	-0.28	1.93

Black-legged Kittiwake

	estimate	lower	upper
Intercept (OWF)	0.31	-0.47	1.06
Border	0.18	-0.63	0.99
Corridor	0.54	-0.21	1.33

Common Gull

	estimate	lower	upper
Intercept (OWF)	-0.40	-2.26	1.39
Border	0.22	-1.25	1.74
Corridor	0.72	-0.55	2.04

Lesser Black-backed Gull

	estimate	lower	upper
Intercept (OWF)	-0.51	-1.55	0.51
Border	0.78	-0.06	1.60
Corridor	-0.28	-1.05	0.50

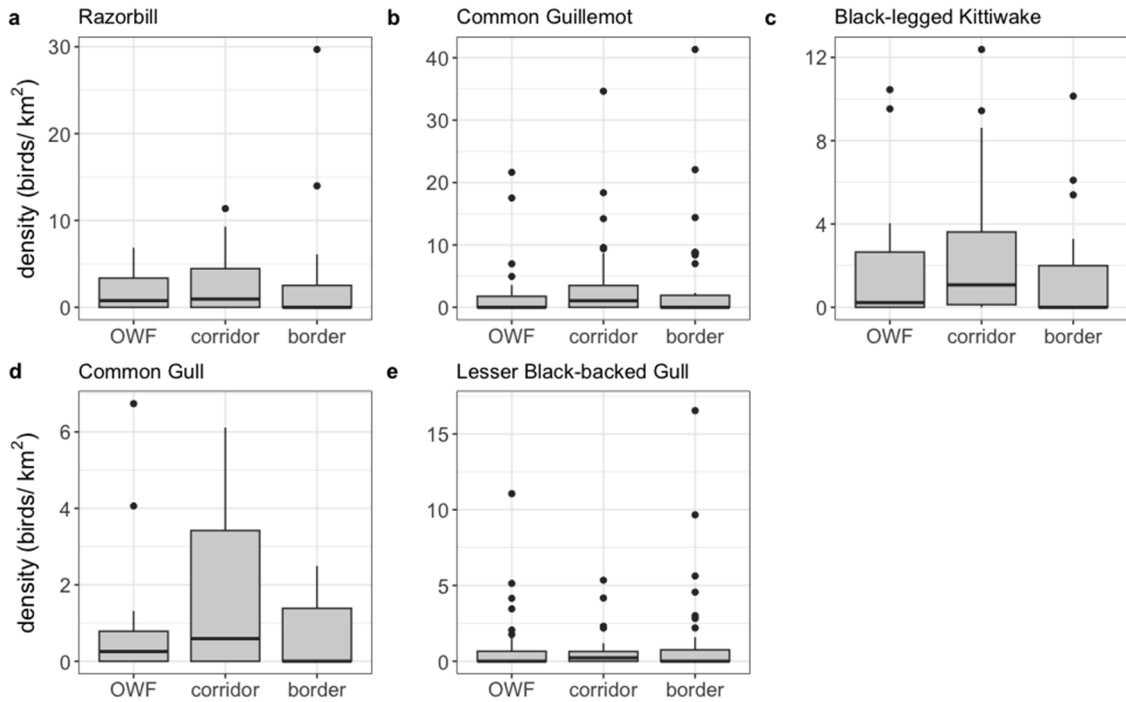


Figure 2. Boxplots of the observed bird density per zone. Thick horizontal lines display the median density and boxes contain the 50% quantile spread around it. All densities are corrected using distance analysis. Note: Scales on the y-axis differ per plot for clarity of details. For Lesser Black-backed gull, one datapoint at 107 birds/km² was left out.

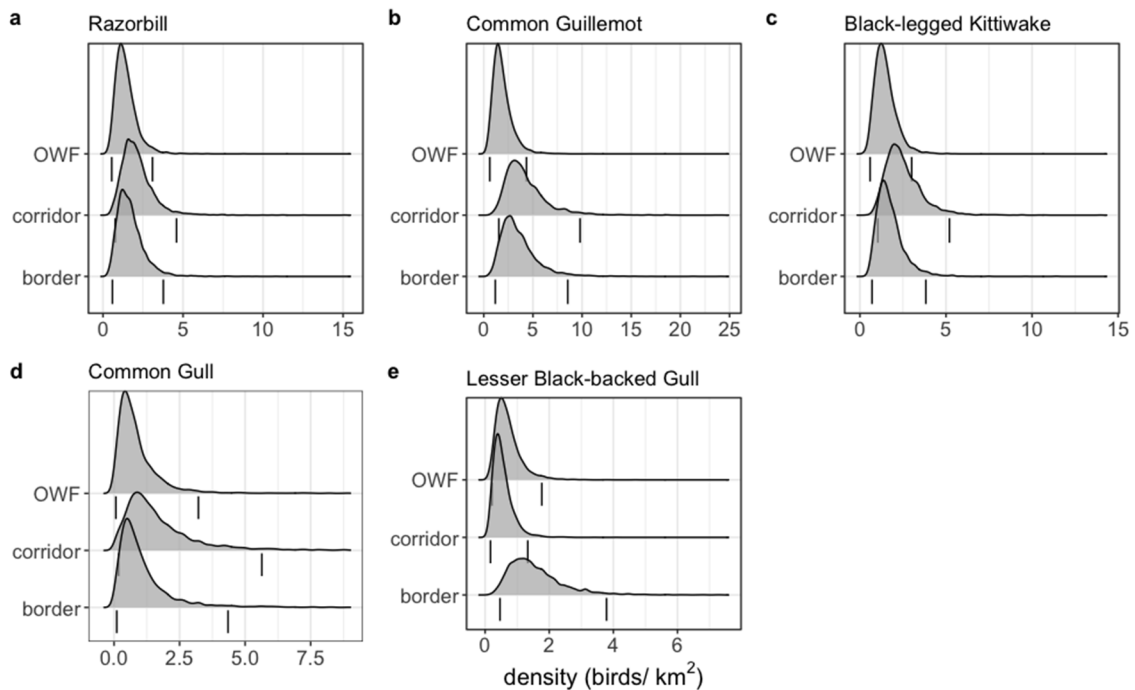


Figure 3. Posterior distributions of the bird densities per zone resulting from the GLMMs. Note: Scales on the x-axis differ per plot for clarity of details. Horizontal lines below the graphs display the 2.5 percentile and 97.5 percentile of the distribution per transect type.

Discussion

In our study in Borssele, we found no support for higher seabird densities in the corridor compared to inside the wind farm. Hence, we cannot conclude that the corridor in Borssele reduced disturbance of a wind farm for species that are generally known to avoid wind farms, such as Common Guillemot and Razorbill (Dierschke *et al.* 2016).

One of the main potential reasons why the study species may not have favoured the corridor in Borssele above other parts of the wind farm is the (perceived) width of the corridor. The width of the entrances of the corridor ranges from 2 to 2.4 km, while the average distance between turbines along the rest of the edge of Borssele ranges from 0.9 to 1.4 km. Hence the difference in spacing between the corridor and the rest of the edge of the wind farm may not be large enough for birds to perceive the width of the corridor as different from the spacing between the turbines. The corridor is also narrower in the western part of the wind farm (Figure 1), meaning the corridor may have a smaller chance of being perceived by birds approaching from the western side of the wind farm. Moreover, a two-kilometre-wide corridor might not be wide enough for species that generally show a larger avoidance distance to offshore wind farms. Common Guillemot have been reported to avoid wind farms starting at a distance of up to 10 to

20 kilometres (Peschko *et al.* 2024, Grundlehner *et al.* 2025), which indicates that a two kilometres wide corridor in wind farms might not be wide enough to substantially reduce the disturbance effect of wind turbines on Common Guillemots, and other seabirds.

Another possible cause for the lack of higher bird densities observed in the corridor could be the presence of vessel activity related to windfarm maintenance. Wind farm vessels will regularly traverse the corridor to visit other parts of the wind farm. Disentangling the effect of such vessels from the isolated effect of an offshore wind farm using observational data is difficult (Mendel *et al.* 2019, Pollock *et al.* 2024). The disturbance effects of these vessels are therefore often not considered in avoidance studies of offshore wind farms (Piet *et al.* 2019, Ferguson *et al.* 2025) and would ideally be studied in an experimental setup. In addition to wind farm maintenance vessels, other ships were allowed to use part of the corridor. However, we failed to find evidence for differences in seabird densities between corridor transects where shipping is and is not allowed. We hardly observed any ships in the corridor during our surveys, which could explain the absence of an effect. Alternatively, we may have been unable to detect an effect due to low effect sizes, inadequate statistical power, or a combination of these. The potential confounding of shipping activity in a corridor on the relative use of the corridor by seabirds will be an important issue in future studies.

We failed to find evidence that implementing a corridor inside an offshore wind farm facilitates seabirds to cross an offshore wind farm, but this does not exclude the possibility that corridors could work elsewhere, with different wind farm and corridor designs, and in different settings. Variation in disturbance distances may depend so much on the location, season, the individuals involved, other disturbance sources and the combination of these factors that uniform answers are difficult to provide (Pollock *et al.* 2024). Therefore, further research is needed to find out whether the width or orientation of a corridor and shipping activity affect the extent to which birds use the corridor. Besides or alternative to ship-based surveys, other techniques could be used to answer these questions such as digital aerial surveys, bird radars, automated camera systems and GPS-tracking. These techniques differ in their impact on bird behaviour, and the spatial and temporal scales of the collected data. A combination of these techniques could thereby allow a detailed study of levels of avoidance and spatially explicit use of offshore wind farms by birds and may show if, and under what conditions, corridors may be beneficial to seabirds.

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Data Availability

Data are available from the Zenodo data repository at <https://doi.org/10.5281/zenodo.19664541> (Bureau Waardenburg BV, 2026).

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