Auks in the German North Sea: Effects of Offshore Wind Farms

A study into Common Guillemot (*Uria aalge*) and Razorbill (*Alca torda*) distribution based on aerial and ship survey data in the German North Sea

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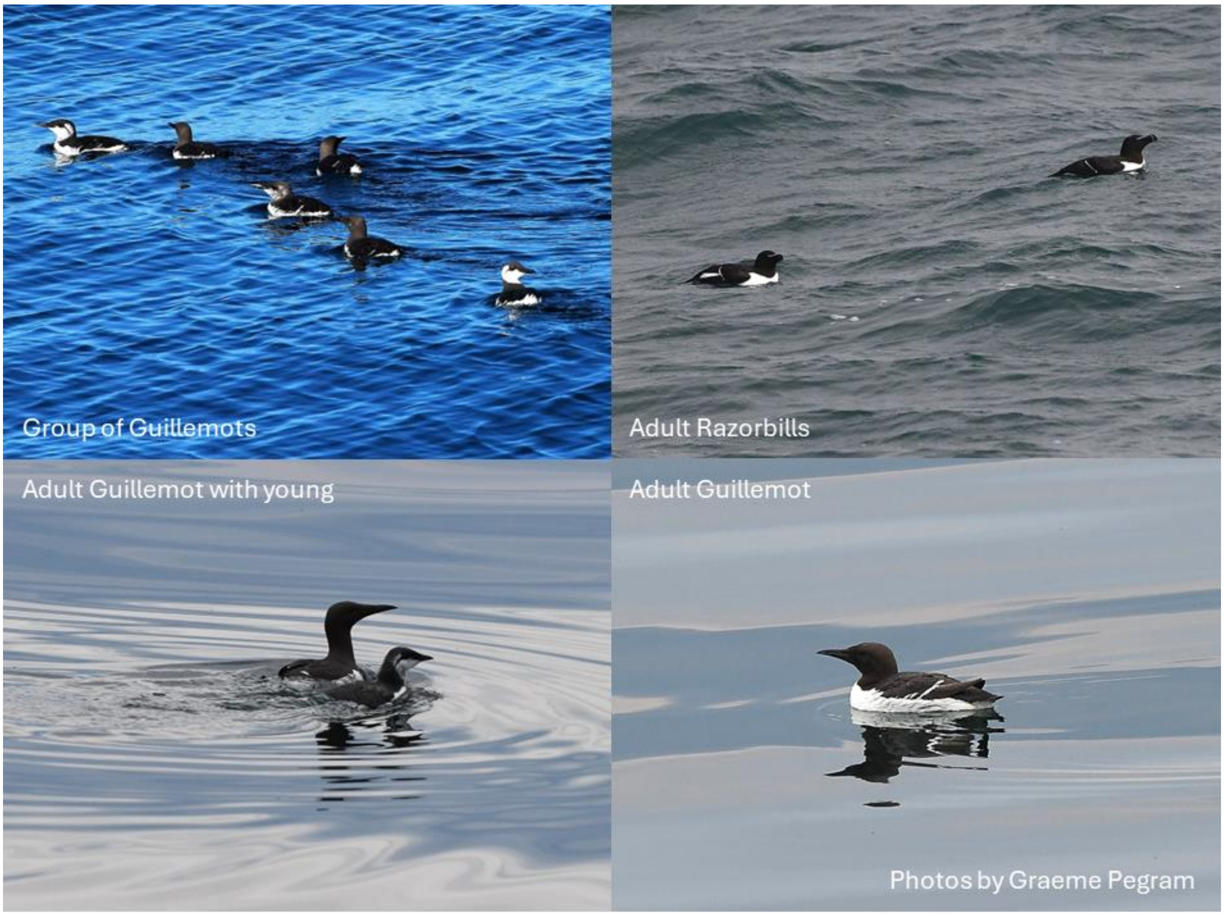

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Auks in the German North Sea: Effects of Offshore Wind Farms

A study into Common Guillemot (*Uria aalge*) and Razorbill (*Alca torda*) distribution based on aerial and ship survey data in the German North Sea

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1 SUMMARY

As part of the energy transition there is an increasing demand for a further expansion of offshore wind energy. However, there are concerns that a rapid expansion of offshore wind farms can have adverse effects on the marine eco-systems and individual species within it. This study aims to assess the reaction of Common Guillemots and Razorbills to the presence of operational offshore wind farms. Seabird behavioural responses to wind farms range from attraction to avoidance. One of the species groups that is potentially affected are auks and among them the Common Guillemot, one of the most abundant offshore seabird species in the German North Sea and the sympatric species, Razorbill. The German North Sea is an important foraging and resting habitat for auks breeding on Helgoland and in the non-breeding season additionally to large numbers from other breeding colonies, mostly in Great Britain.

This study investigated the effects of wind farms on the distribution of Common Guillemots and Razorbills in the German North Sea, with particular focus on differences between autumn and winter, regions and the two species. It is based on a large data set of high-quality data from aerial and ship-based surveys collected over 8 years during post-construction monitoring of all 22 wind farms in operation in the German North Sea by 2021 and during scientific monitoring projects. Data were analysed applying the approach of integrated nested Laplace approximations (INLA) to do approximate Bayesian inference for latent Gaussian models, which yields robust estimates of seabird distributions in space and time. In addition, it does not require pre-construction data and allows model validation.

Common Guillemots and Razorbills showed a very similar spatial distribution in autumn, with areas of higher densities in the northwestern part of the study area and in the southeast, in the vicinity of the breeding colony on the island Helgoland. In winter, overall numbers of auks were substantially higher and the distribution more widespread than in autumn.

Both species showed avoidance effects towards wind farms, although both species regularly occurred within the wind farms as well. We found high variability in the distribution and effect radii between seasons and regions for both species. The calculated effect radius around wind farms was consistently larger in autumn (Common Guillemots: between 6-12 km, Razorbills: 6-11 km) than in winter (Common Guillemots: between 0.4-2 km, Razorbills: no significant avoidance), for the total area analysed. The theoretical habitat loss, a theoretical value assuming a total loss of habitat for all individuals due to avoidance, in autumn was calculated as a radius of 0-4.5 km around the OWF for Guillemots and 0-3 km for Razorbills. In winter, the effect radius was too low to result in a definable habitat loss outside the OWF.

The analysis of the regions separately revealed a similar seasonal pattern for both species. Model results revealed that in both species a large part of the individuals avoided the area inside the wind farms and up to 1 km distance in autumn, with Common Guillemots (reduction of 65-76%) showing a much higher reduction than Razorbills (reduction of 41-56%). Within an area of up to 5 km around the wind farm, densities were still noticeably reduced in Common Guillemots (reduction of 49-66%) and Razorbills (reduction of 31-50 %). In winter, the reductions were much lower and seemed to be confined to the wind farms and up to 1 km distance in both species.

When comparing the different regions, our results hint at a possible increase in effect size with distance from shore and a potential connection with density of turbines within the offshore wind farm, however, more studies are necessary to determine a true connection.

This study provides evidence for a seasonal difference in avoidance of wind farms by Common Guillemots and Razorbills and suggests possible differences between the two species and between different regions.

Definitions:

Effect radius:

The effect radius is defined as the distance from the edge of an offshore wind farm up to which the density is significantly lower than a reference density defined as the overall mean of the dataset used in the specific model (years 2014 – 2021). The displacement effect is a gradient, with lower bird densities close to the OWF and increasing densities until the reference density is reached. To account for the precautionary principle, a range is given for the effect radius.

Theoretical habitat loss:

The theoretical habitat loss is defined as the area corresponding to the habitat of birds that is theoretically no longer available for use and is given as a radius around an OWF. Since the displacement effect is a gradient while the theoretical habitat loss assumes a total loss of the area for auks, the radius of the theoretical habitat loss around an OWF is far lower than the effect radius.

2 ZUSAMMENFASSUNG

Im Zuge der Umstellung auf erneuerbare Energien besteht eine zunehmende Nachfrage nach einem weiteren Ausbau der Offshore-Windenergie. Es wird befürchtet, dass ein schneller Ausbau von Offshore-Windparks negative Auswirkungen auf die Meeresökosysteme und die darin lebenden Arten haben könnte. Die vorliegende Studie untersucht die Reaktion von Trottellummen und Tordalken auf die Präsenz von Offshore-Windparks in ihrer Betriebsphase. Die Verhaltensreaktionen von Seevögeln gegenüber Windparks reichen von Anziehung bis hin zu Vermeidung von Windparks. Zu den potenziell auf Windparks reagierenden Artengruppen gehören Alken, darunter die Trottellumme, eine der häufigsten Hochseevogelarten in der deutschen Nordsee, und der sympatrisch vorkommende Tordalk. Die deutsche Nordsee ist ein wichtiges Nahrungs- und Rastgebiet für die auf Helgoland brütenden Alkenarten und im Winter zusätzlich für große Bestände aus anderen Brutkolonien, v. a. in Großbritannien.

Diese Studie untersuchte die Auswirkungen von Windparks auf die Verbreitung von Trottellummen und Tordalken in der deutschen Nordsee mit besonderem Fokus auf die Unterschiede zwischen Herbst und Winter, Regionen und den beiden Arten. Sie basiert auf einem sehr großen, hochwertigen Datensatz aus flug- und schiffsgestützten Erfassungen, die über einen Zeitraum von acht Jahren an allen 22 Windparks, die bis 2021 in der deutschen Nordsee in Betrieb genommen wurden, sowie im Rahmen von wissenschaftlichen Monitoringprojekten erhoben wurden. Die Daten wurden mithilfe eines Bayes'schen hierarchischen Modells mit Laplace Näherung (INLA) analysiert, das robuste Schätzungen der Seevogelverteilungen in Raum und Zeit liefert. Der räumliche Modellierungsansatz eignet sich insbesondere, um großräumige Verteilungen von Seevogelarten in einem komplexen ökologischen Umfeld zu modellieren. Zudem ist das Modell nicht auf Vorher-Nachher-Daten angewiesen und die Modellgüte lässt sich durch Validierung ableiten.

Die Daten zeigten eine sehr ähnliche räumliche Verteilung bei Trottellummen und Tordalken im Herbst, mit höheren Dichten im nordwestlichen Teil des Untersuchungsgebiets und im Südosten, in der Nähe der Brutkolonie auf der Insel Helgoland. Im Winter war die Gesamtzahl der Alken deutlich höher und großflächiger verbreitet als im Herbst.

Beide Arten zeigten Meidungsverhalten gegenüber Windparks, obwohl Alken auch regelmäßig innerhalb von Windparks nachgewiesen wurden. Der berechnete Meideradius um Windparks war im Herbst durchweg größer (Trottellumme: zwischen 6-12 km, Tordalk: 6-11 km) als im Winter (Trottellumme: 0,4-2 km, Tordalk: keine signifikante Meidung) für die gesamte analysierte Fläche. Der theoretische Habitatverlust, ein rechnerischer Wert, der einen vollständigen Verlust der Fläche für alle Individuen aufgrund von Meidung annimmt, lag im Herbst bei einem Radius um die OWP von 0-4.5 km für die Trottellumme und bei 0-3 km für den Tordalk. Im Winter war der Meideradius so niedrig, dass sich kein Habitatverlust außerhalb der OWP definieren ließ.

In den einzelnen Regionen zeigte sich ein ähnliches saisonales Muster für beide Arten. Beide Arten wiesen eine hohe Variabilität in ihrer Verbreitung und ihren Meideradien auf, sowohl saisonal als auch regional. Die Ergebnisse zeigen, dass bei beiden Arten im Herbst ein großer Anteil der Individuen den Bereich innerhalb der Windparks und bis zu einer Entfernung von 1 km mieden, wobei bei den Trottellummen ein deutlich stärkerer Effekt (Reduktion: 65-76 %) zu verzeichnen war als bei den Tordalken (Reduktion: 41-56 %). Im Umkreis von bis zu 5 km rund um den Windpark waren die Dichten von Trottellummen (Reduktion: 49-66 %) und Tordalken (Reduktion: 31-50 %) ebenfalls klar erkennbar reduziert. Im Winter waren die Effekte wesentlich geringer und schienen sich bei beiden Arten auf die Windparks und eine Entfernung von bis zu 1 km zu beschränken. Im Vergleich der Regionen deuten die Ergebnisse auf eine mögliche Zunahme der Effektgröße mit der Entfernung von der Küste und einen potenziellen Zusammenhang mit der Dichte der Turbinen innerhalb des Offshore-Windparks hin. Es sind jedoch weitere Studien erforderlich, um diesen Zusammenhang tatsächlich zu belegen.

Diese Studie zeigt saisonale Unterschiede der Vermeidung von Windparks durch Trottellummen und Tordalken auf und weist auf Unterschiede zwischen den beiden Arten und in verschiedenen Regionen hin.

Effektradius:

Der Effektradius ist definiert als die Distanz vom Rand eines Offshore Windparks bis zu welcher die Dichte signifikant geringer ist als eine Referenzdichte, welche als der Mittelwert des Datensatzes des genutzten Modells (Jahre 2014-2021) definiert ist. Ein Meideeffekt stellt sich als ein Gradient dar, mit geringeren Individuendichten näher am OWP und ansteigenden Dichten, bis die Referenzdichte erreicht ist. Um dem Vorsorgeprinzip Rechnung zu tragen, wird die Meidung als eine Spanne angegeben.

Theoretischer Habitatverlust:

Der theoretische Habitatverlust ist definiert als die Fläche, die rechnerisch dem Habitat entspricht, welches aufgrund von Meidung nicht mehr nutzbar ist. Der theoretische Habitatverlust wird als Radius um den OWP angegeben. Da der Meideeffekt einen Gradienten darstellt, während der theoretische Habitatverlust eine vollständige Meidung voraussetzt, ist der Radius des theoretischen Habitatverlustes deutlich geringer als der Effektradius.

3 INTRODUCTION

As a result of climate change, energy generation in Germany is to be switched to renewables as fast as possible (EEG 2017, 2014). In order to reduce carbon emissions from electricity generation, there is an increased demand for a rapid expansion of offshore wind energy in the North Sea. According to current plans (BSH 2024) a capacity of 70 GW is to be installed in the German exclusive economic zone (EEZ) until the year 2045 and at least 50 GW by 2035. Therefore, the expansion efforts for offshore wind energy have been significantly increased by the German government in recent years to match these targets.

Although renewable energy is of ecological benefit, there is a risk that a fast expansion can have adverse effects on the ecosystem of the North Sea and individual species within it (Dierschke et al. 2016, Garthe et al. 2023). The construction and operation of offshore wind farms lead to changes in the ecosystem characteristics (e.g. Lindeboom et al. 2011, Vandendriessche et al. 2015). Reactions of species, populations and individuals can range between attraction and avoidance (Welcker & Nehls 2016, Dierschke et al. 2016). Consequences can be collisions, habitat loss of foraging and resting grounds due to avoidance behaviour or, if offshore wind farms (OWFs) represent a barrier, an increased energy expenditure, both with potential effects on population vital rates and demography (Masden et al. 2010, Peschko et al. 2024). One of the potentially affected species groups are auks. Common Guillemots (*Uria aalge*) and Razorbills (*Alca torda*) are the most common representatives of auks within the German North Sea, but Puffins (*Fratercula arctica*), Black Guillemots (*Cepphus grylle*) and Little Auks (*Alle alle*) also occur occasionally.

The Common Guillemot (henceforth Guillemot) is one of the most common offshore bird species in the German North Sea and occurs year-round (Markones et al. 2015). It breeds on the island of Helgoland in increasing numbers, until the recent outbreaks of avian flu: after a total of 4,726 breeding pairs were recorded in 2021, there were 4,435 registered in 2023 (Dierschke et al. 2023). Outside the breeding season, Guillemots occur widespread across offshore areas, especially in areas with water depths between 40 and 50 m (Mendel et al. 2008). In the German North Sea, they reach their highest numbers post-breeding in autumn and in winter, when individuals from other breeding populations, especially from large breeding colonies in Great Britain, migrate into German waters (Bauer et al. 2005, Mendel et al. 2008). In winter, Guillemots and Razorbills are also frequently found closer to the coast (Schwemmer et al. 2014). Razorbills also occur across the entire German North Sea year-round, although they occur in lower numbers than Guillemots. In spring they concentrate in areas far from the coast as well as West of Helgoland, in winter there are concentrations off the East Frisian Islands (Mendel et al. 2008, Markones et al. 2015). Like Guillemots, Razorbills also breed on Helgoland, showing a stable breeding population (84 breeding pairs in 2019 (Walter 2020), 78 in 2020 (Ballstedt et al. 2021), 84 in 2021 (Dierschke et al. 2022) and 74 in 2022 (Dierschke et al. 2023)). The largest part of Razorbills that occur in the German North Sea use breeding areas in the British Islands (Wernham et al. 2002), which is why the highest numbers of Razorbills are found in winter (Mendel et al. 2008). Population size in summer for both species showed a significant increase in the German North Sea between 1990 and 2013 (Markones et al. 2015) or between 1980 and 2016 (Gerlach et al. 2019). Razorbills occur in Germany at numbers of max. 20.000 individuals in winter (Gerlach et al. 2019). At a maximum of 92.000 individuals (autumn), Guillemots in German waters represent ca. 20% of the biogeographical population (Gerlach et al. 2019). However, the winter population of Guillemots in German waters declined substantially by more than 75% between 2003/04 and 2015/16 (Gerlach et al. 2019). This value puts the Guillemot on top of the list of waterbirds with the strongest decreases in the non-breeding period in Germany (Gerlach et al. 2019). However, the breeding population of Guillemots in the UK, where a substantial part of the German wintering population come from, showed stable or increasing numbers between 2000 and 2018 (JNCC 2021a). The reason for the apparent decrease in German waters (Gerlach et al. 2019) is unclear, but since breeding populations seem to be stable, local decreases could be due to a regional re-distribution. For Razorbills the long-term trend for the wintering population numbers in Germany is unknown (Gerlach et al. 2019). The breeding population of Razorbills in the UK, which form a large part of our wintering population, showed a strong increase between 1986 and 2018 (JNCC 2021b).

Both species show clear avoidance behaviour towards offshore wind farms and/or a significantly reduced presence in the vicinity of OWFs in most studies. A study at the first OWF test-site in Germany, "alpha ventus" with 12 turbines, found lower than average densities of auks in distances up to 2.4 km and a linear increase up to 5 km (Mendel et al. 2015). Vanermen et al. (2015) found similar reactions in distances up to 3 km around the Belgian wind farm "Bligh Bank", while Webb et al. (2015) determined avoidance up to 4 km around the British wind farm "Lincs". Grundlehner et al. (2024) found lower densities in up to 10 km distance from the Dutch OWF complex "Gemini" for Guillemots and in up to 2 km distance for Razorbills, supporting avoidance behaviour of auks, but also suggesting species-specific differences. A study on the OWF clusters "Butendiek" and Cluster "Nördlich Helgoland", located off the coast of Schleswig-Holstein (Germany), found significant avoidance during the breeding season and in spring, with densities reduced by 63% and 44%, respectively (Peschko et al. 2020a). The study reports an effect radius of up to 9 km. Another study used telemetry on 12 individual Guillemots in the same study area (breeding colony on Helgoland) during the breeding season and determined that there seems to be stronger avoidance when the rotor blades are in motion (Peschko et al. 2020b). Lindeboom et al. (2011) could not find avoidance behaviour among swimming Guillemots and Razorbills around the Dutch wind farm "Egmond aan Zee", only for flying individuals. Renewed analysis of the data from "Egmond aan Zee" as well as data from the nearby wind farm "Prinses Amalia" found no avoidance behaviour either (Zuur 2018). A study on the Scottish wind farm "Robin Rigg" found no significant avoidance for Guillemots (Vallejo et al. 2017), while another analysis on data from the same site found only weak avoidance behaviour (Zuur 2018). Similarly, no significant avoidance was found around the wind farm "Beatrice" off the Scottish coast, only a slight tendency of avoidance for flying Guillemots, while swimming Guillemots and Razorbills were found in slightly higher densities than expected in the vicinity of "Beatrice" (Trinder et al. 2024).

At the annual Marine Environment Symposium in 2022, which was organized by the German Federal Maritime and Hydrographic Agency (BSH) in cooperation with the German Federal Environment Agency (UBA) and the German Federal Agency for Nature Conservation (BfN), Garthe et al. presented results of a study on avoidance rates towards OWF of several species, including Guillemots and Razorbills, in the German EEZ (Garthe et al. 2022) based on a similar dataset as this study. The analysis utilised Before-After Control-Impact (BACI) methodology and a Generalised Additive Model (GAM). In the presentation, Guillemots were identified as a species of concern, due to apparently very high avoidance distances and significant habitat loss. An effect radius of 15-18 km in winter and 18-21 km in autumn was reported as well as a reduction in habitat use of 67% (up to 1 km distance to OWF) in winter and 91% in autumn. Recently these results for Guillemots were published by Peschko et al. (2024). For Razorbills they identified low avoidance distances (0-

3 km) in winter but still a high habitat loss, with an apparent reduction of 55% in the OWF and up to 1 km distance (Garthe et al. 2022).

While most studies seem to indicate medium to strong avoidance behaviour for auks, comparisons between studies suggest there might be differences due to site, season and species. Therefore, Guillemots and Razorbills are species of particular interest when it comes to the continued expansion of offshore wind energy infrastructure. Due to the high mobility of auks and their highly variable occurrence in space and time, the displacement effect is difficult to determine. Auks can temporarily occur highly aggregated in some areas and in low densities in others. Their distribution depends on multiple factors, such as their highly mobile prey, and varies with season. Our study adds a comprehensive analysis using post-construction data and a Bayesian spatio-temporal hierarchical model on multiple OWF in a large area with varying habitat conditions over several years and we estimated avoidance separately for autumn and winter, and sub-regions in the two species.

For this study, the focus was on the following questions:

1. To what distance from existing OWF do Guillemots and Razorbills show avoidance behaviour?
2. Are there differences between seasons (autumn/winter) and regions when it comes to avoidance behaviour? And if so, can differences be identified between four sub-regions in the German North Sea, that differ in oceanographic features and OWF design/characteristics?
3. What is the reduction in density in the OWF area after construction?
4. How high is the theoretical habitat loss?

4 METHODS

4.1 Survey area

The study area covered a large part of the German North Sea, including coastal waters as well as the Exclusive Economic Zone (EEZ). An overview of the study area, protected areas and the location of offshore wind farms is given in Figure 4-1. For information on wind farm cluster names and the wind farms they contain see appendix (A.1). Data from 22 different wind farm projects between 2014 and 2021 were included in the analyses. These represented the totality of operating wind farms in 2021 in the German North Sea. For each wind farm, the complete autumn or winter period (all surveys) for the post-construction phase was included in the analysis.

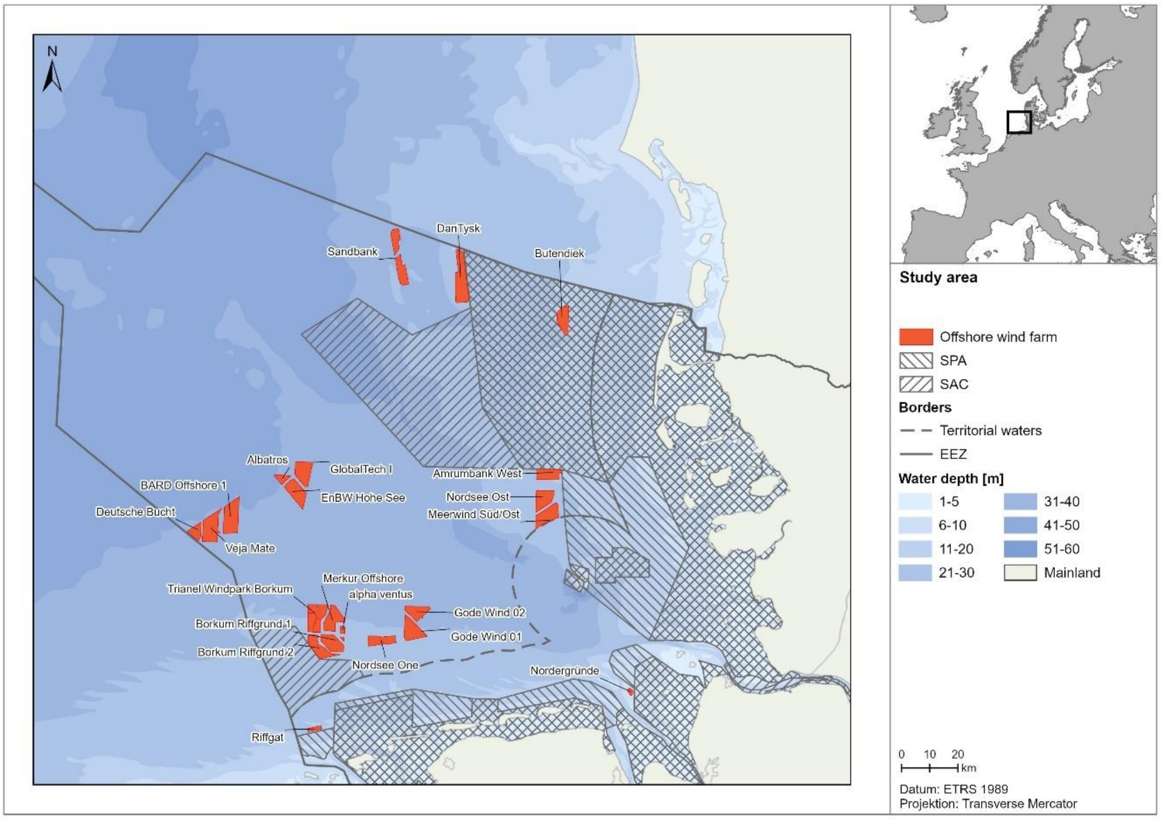

Figure 4-1 Overview of the study area, with EEZ and protected areas, SPA „Eastern German Bight".

4.2 Survey methods

The study includes data from two different survey methods, digital aerial and ship-based surveys. Both methods are expected to give a correct estimate of the number of individuals and their distribution in the area (BSH 2013). However, each method comes with advantages and disadvantages (for details see the following chapters). Analysing data from both methods and comparing results can therefore lead to a more robust result and might reduce bias.

4.2.1 Ship-based surveys

Ship-based surveys were conducted following the methods of the European Seabird-at-Sea-Programme (ESAS; Garthe & Hüppop 1996, 2000) and according to the guidelines of the German Federal Maritime and Hydrographic Agency (BSH) StUK4 (BSH 2013). Surveys were done along transect lines that were spaced ca. 3-4 km apart in speeds of ca. 8-12 knots. Expert observers recorded all activity in a strip of 300 m to the side and 300 m ahead of the ship along those transect lines. Due to the relatively slow-moving vessel and the short distances from the observed subjects, it was almost always possible to determine the auks to species level.

All survey areas were monitored by ship-based observations.

4.2.1.1 Detection correction

Since swimming birds are more easily missed the further away they are from the observer, we used a correction factor to adjust the recorded individuals for this detection bias (Stone et al. 1995, Buckland et al. 2001, Garthe 2003, Garthe et al. 2007). These correction factors are species-specific, since the detectability at distance depends strongly on size, colouration and contrast and for auks on their diving behaviour (Stone et al. 1995). Only swimming and diving birds were corrected in this way (Garthe 2003, Garthe et al. 2007), while numbers of flying birds were taken as is. For Guillemots and Razorbills the correction factor of 1.5 was used (Stone et al. 1995, Garthe 2003, Garthe et al. 2007).

4.2.2 Digital aerial surveys

The digital aerial surveys were conducted according to the standards set by the German Federal Maritime and Hydrographic Agency (BSH 2013) using three different techniques: “APEM”, “DAISI” and “HiDef”. Generally, the survey method stayed consistent per survey area, however in some areas, i. e. “DanTysk/Sandbank” (Cluster “Westlich Sylt”) and Cluster “Östlich Austerngrund”, more than one method was used. All aerial monitoring was based on digital image recordings (pictures or film) collected in the survey area, which were examined later. Unlike in the ship based-surveys, species identification was done based on recorded images, not live in the field. The recorded footage was evaluated by professionals qualified in species identification, with a separate step for random sample quality control. Flight height in digital surveys was high enough that survey aircraft could fly over the wind turbines and disturbance to birds was minimised. In all digital surveys, a twin-engine airplane was used. Precise geographical positions of each observation were recorded using GPS technology. While survey flights were generally only conducted during favourable weather conditions, parameters such as sea state, glare, cloud cover, air and water turbidity were recorded and pictures of insufficient quality were excluded from analysis.

Since Auk species resemble each other strongly and the resolution of the aerial digital survey data is relatively low, sometimes auks cannot be distinguished on the species level with high confidence during aerial surveys. Therefore, the dataset contains a subset of birds identified as either Guillemot or Razorbill, but not on species level. Since these birds increase the dataset by a large margin, we repeated all analyses that were done for Guillemots and Razorbills separately for the group containing all Guillemots, Razorbills and those individuals identified as either one of those species but not to species level. Results for the combined group can be found in the appendix (A.2).

4.2.2.1 APEM

The APEM[1] technique (APEM Ltd.; Busch 2015) is based on still image recordings along transect lines in the survey area. Four cameras took images simultaneously and constantly. The four frames were then merged into one image with an increasing resolution of ca. 3 cm (2014-2016), 2 cm (2017-2020) and 1,5 cm (since 2020) on the sea surface. Flight height was approximately 400 m (1,300 ft) at a speed of 120-130 knots. This method included narrow transect lines (ca. 1.6 km spacing), which were close enough to allow the forming of a grid. This is one of the main differences to the other two survey methods described below.

Cluster 6 was surveyed exclusively by the company APEM Ltd. The area “DanTysk/Sandbank” was also surveyed by APEM in March and April 2014. Here, the transect lines of the survey area were used rather than a grid.

4.2.2.2 DAISI

The surveying technique DAISI[2] (“Digital Aerial Imagery System”) was developed by and belongs to IfAÖ GmbH. Like APEM, it uses a photo technique to record objects along transect lines. DAISI consists of two medium-format cameras with a resolution of 2 cm on the sea surface. Photos were taken at a minimal interval of 1.5 s, which leads to an overlap of ca. 48% between frames. At a flight height of ca. 426 m (1,400 ft) and a flight speed of 100-120 knots, the camera system covered an area of at least 407 m at sea surface level. Transect lines were 3-4 km apart.

The survey areas “DanTysk/Sandbank” and Cluster “Östlich Austerngrund” were monitored using DAISI. “Dan-Tysk/Sandbank” was surveyed by APEM for two months in spring 2014, and Cluster Östlich Austerngrund was surveyed by HiDef in selected months.

4.2.2.3 HiDef

The HiDef[3] technique uses a high-resolution video camera system consisting of four independent cameras with a resolution of 2 cm on the sea surface. The position of the cameras can be adjusted to avoid glare on the sea surface. On each side, the cameras covered an area of 143 m and 129 m with a distance of ca. 20 m in between. Thus, a total coverage of 544 m along a 604 m strip at sea surface level was achieved. Flight height was approximately 549 m (1,800 ft) and flight speed around 220 km/h (120 knots) on transect lines that were ca. 3-4 km apart. Depending on the survey area, species identification and quality control was done by BioConsult SH, IfAÖ, or IBL Umweltplanung.

[1] https://www.apemltd.co.uk/ (zugegriffen am 10.11.2023)

[2] https://www.ifaoe.de/daisi (zugegriffen am 10.11.2023)

[3] https://hidef.bioconsult-sh.de/ (zugegriffen am 10.11.2023)

The survey areas “Butendiek”, Cluster “Nördlich Helgoland”, “Nordergründe”, Cluster “Nördlich Borkum” were exclusively covered using HiDef video systems. Cluster “Östlich Austerngrund” was partly surveyed by DAISI and HiDef. Digital survey data made available to the project via the Federal Agency for Nature Conservation (BfN) is also based on the HiDef method.

4.3 Study period and data set

Data from digital aerial surveys and ship-based surveys in the German North Sea between 2014 and 2021 were available for the analysis, providing comprehensive coverage of the post-construction phase for each wind farm. The data set was reduced to cover only the species-specific seasons of autumn (01.07.-30.09.) and winter (01.10.-29.02.) (species-specific seasons, i.e. functionally specific temporal units in the annual cycle, according to Garthe et al. (2007)). The aerial and ship-based surveys were conducted at different dates, depending on weather and other factors, so the number of surveys per season might differ between years. A total of 277 digital aerial surveys and 297 ship-based surveys were carried out (Table 4-1). The effort per season and year is shown in Figure 4-2. A total of 155 aerial and 104 ship-based post-construction surveys were conducted during the autumn season, while 122 aerial surveys and 193 ship-based post-construction surveys were carried out in the winter season (Table 4-1). Species identification rates were higher during ship surveys due to shorter observation distance. For aerial data the rate of identification to species level for auks was variable between the techniques. For most areas, the identification rate was around 85% (range: 72-100%), however for some areas the identification rate was lower: for Cluster “Östlich Austerngrund” around 53%, for DanTysk/Sandbank around 42% and for Cluster 6 around 41%. For ship-based data, identification to species level was high in all areas, on average 96% (range: 90-100%). However, all birds included in the dataset were either Guillemots or Razorbills.

The data were collected for different projects, mostly the mandatory monitoring around wind farm projects as well as scientific monitoring projects (Natura2000 Monitoring (BfN)).

The details about specific projects can be found in the appendix (A.2).

During these surveys a total of 147,401 Guillemots and Razorbills were recorded (Table 4-2). Among those individuals, 80,238 were identified as Guillemots and 24,658 as Razorbills and 42,505 could not be identified to species level but were classified as either Guillemot or Razorbill.

Table 4-1 Number of surveys by season, OWF cluster and survey type.

Season	Region	OWF Cluster	Digital Aerial	Ship
Autumn	Region 1	Cluster 6	29	22
		Östlich Austerngrund	34	22
	Region 2	Nördlich Borkum	20	22
		Riffgat	9*	0
	Region 3	Nördlich Helgoland	19	26
		Nordergründe	10	7
	Region 4	Westlich Sylt	15	0
		Butendiek	19	5
		Autumn total	**146**	**104**
Winter	Region 1	Cluster 6	21	37
		Östlich Austerngrund	21	35
	Region 2	Nördlich Borkum	14	36
		Riffgat	7*	0
	Region 3	Nördlich Helgoland	14	61
		Nordergründe	19	13
	Region 4	Westlich Sylt	12	0
		Butendiek	14	11
		Winter total	**115**	**193**

*covered only by flight surveys for Cluster "Nördlich Borkum"

Table 4-2 Total number of individuals observed during post-construction. The number of surveys per season was variable.

Season	Species	Individuals
Autumn (01.07.-30.09.)	Guillemot	42,598
	Razorbill	724
	Unidentified Guillemot/Razorbill	9,057
Winter (01.10.-29.02.)	Guillemot	37,640
	Razorbill	23,934
	Unidentified Guillemot/Razorbill	33,448
Total		**147,401**

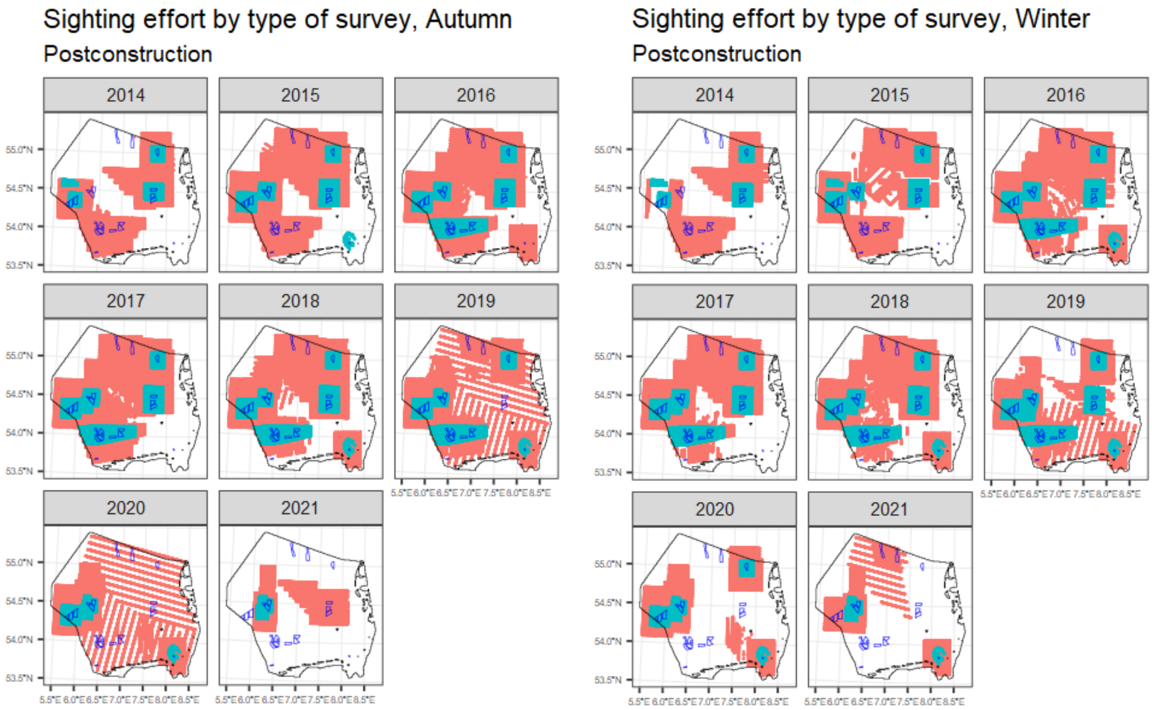

Figure 4-2 Survey effort by season and survey method between 2014 and 2021. Red areas show aerial surveys, blue areas ship-based surveys.

4.4 Statistical analysis

In this study, we used Gaussian Markov Random Fields (GMRF) in Integrated Nested Laplace Approximation (INLA) to analyse the wind farm displacement effect on two auk species, Guillemots and Razorbills, during different seasons (Bakka et al. 2018).

For species identification, given the challenge of differentiating Guillemots and Razorbills from a distance, we analysed separately sightings for both clearly identified individuals and combined sightings for all observed individuals. Seasonal variation was assessed by splitting datasets into the species-specific seasons (Garthe et al. 2007) autumn (1st July-30th September) and winter (1st October-28th February).

To capture the general population trend and for computational convenience, a constrained refined Delaunay triangulation spatial mesh was constructed for the entire survey area using a maximum distance between nodes of 5 km (Figure 4-3). Enough space was added around the prediction area to avoid undesired boundary effects (Lindgren et al. 2011). Seasonal survey data were integrated on the mesh nodes (by species group), preserving information regarding data collection method, sighting counts and observed area.

This setup facilitated an explicit spatial Bayesian hierarchical model that incorporated spatial dependencies as Gaussian Random Markov Fields (GRMF) (Rue & Held 2005), using a Gaussian Field (GF) with a Matérn covariance for the spatial effect. The INLA approach (Rue et al. 2009) was used for inference and prediction, linking GMRF and GF via a Stochastic Partial Differential Equation (SPDE) (Lindgren et al. 2011).

Data was fitted using a Poisson family distribution with a log link, where the intensity of the observed process is the main driver of the posterior probability. Penalized Complexity priors (PC-priors, Fuglstad et al. 2019) described prior knowledge of hyperparameters defining the spatial random effect. The prior probability of the spatial range being smaller than 10 km was set at NA, allowing the INLA framework to automatically select an appropriate value based on the model's specifications and the data. Meanwhile, the probability of the spatial variance being larger than 0.1 was set at 0.1. These priors are robust, in the sense that they do not have an impact on outcomes and, in addition, have an ecological interpretation (Simpson et al. 2017).

Two models, both utilizing the INLA approach for Bayesian inference and SPDE for spatial correlation, were developed for each species group and season as well as for both species combined including individuals not identified to species level per season. All surveys with sighting effort inside the minimum convex polygon around each OWF (cluster) were included.

1. The first model, a spatial GRF with two-dimensional Matérn covariance, visualized species distribution during the post-construction phase and included data collection method as categorical covariate. The observed density is based on the full set of surveys around the OWF (clusters) per season and species or the species combined. The predicted density was calculated up to 20 km around OWFs.

2. The second model was a "distance- only" spatial GRF with one-dimensional Matérn covariance, which also included data collection method as categorical covariate. This model estimated the impact of wind farms on bird displacement, providing 95% Confidence Intervals, and calculated mean densities in 500 m bands from the wind farms up to 30 km (total area) or 25 km (regions) for effect radius and habitat loss assessments. The distances were chosen to be as large as possible while still providing sufficient coverage of the areas surrounding the OWF by the survey areas. For the regions the distances were shortened to minimize overlap.

These two approaches combined provide a detailed understanding of distribution and displacement of Guillemots and Razorbills near wind farms. The calculations were performed using the R statistical software and the inlabru package (R Core Team 2019, Bachl et al. 2019).

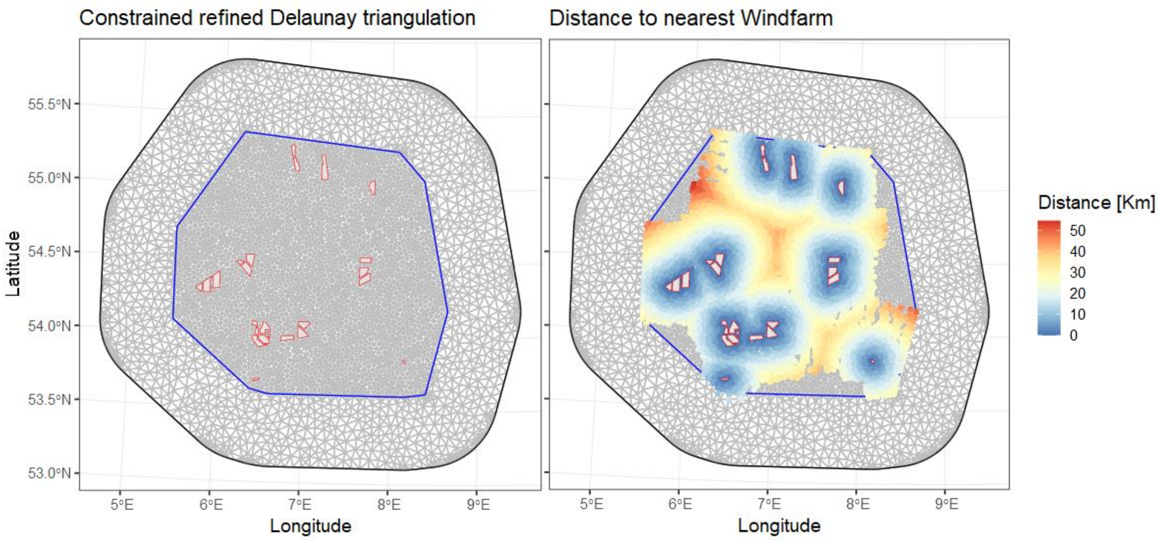

Figure 4-3 *Constrained refined Delaunay triangulation spatial mesh over the study area (left) and the same mesh with overlayed distance to nearest OWF (right).*

4.4.1 Effect radius

The effect radius or displacement distance is defined as the distance from the edge of an OWF up to which auk density is significantly lower than a reference density defined as the overall mean of the dataset (years 2014-2021) used in the specific model. The displacement effect is a gradient, with lower bird densities close to the OWF and increasing densities until the reference density is reached.

In a Bayesian framework, the equivalent of a confidence interval is called a *credible interval*. It provides a range of values within which an unknown parameter falls, with a certain probability, based on the posterior distribution. For example, a 95% credible interval (CI) means there is a 95% probability that the parameter lies within this interval, given the observed data and the prior beliefs. In contrast, the frequentist *confidence interval* is interpreted as a range that would contain the parameter in a certain percentage of repeated samples from the population.

Therefore, the intersection of the upper credible interval (0.05 CI) with the reference value (in this case the overall mean) can be interpreted as the distance until which there is evidence of wind farm impact with a 95% CI. In the following, we refer to this as a significant impact. In order to set a "worst case" upper limit, we used the intersection of the main model curve with the overall mean.

4.4.2 Proportion of reduction

The reduction in density inside an OWF and the surrounding area was calculated based on the modelled densities (both upper CI and mean density). The calculations were done for a square model OWF (8 km by 8 km). Depending on the size and shape of the OWF, the calculated proportions of reduction values vary slightly, but not significantly (compare Garthe et al. 2018). The reduction in density was calculated for the area within a radius of 0 km (inside OWP) to 1 km from the OWF and for 0-5 km distance.

4.4.3 Theoretical habitat loss

Since the displacement effect occurs as a gradient, only a certain percentage of birds are displaced within the effect radius. The aim of calculating the theoretical habitat loss is, to estimate the total number of birds that are displaced and subsequently calculate the area that these birds would need in an undisturbed environment. This area is determined as a radius around a (theoretical) OWF. As the theoretical habitat loss assumes total habitat loss, which does not occur in Guillemots and Razorbills, the calculated radius is smaller than the actual effect radius.

The calculation assumes that the density at the calculated effect radius represents 100% (Figure 4-4).

The final theoretical habitat loss is determined using the formula:

$$A = \frac{N_{Ref} - N_{Loss}}{D_{Ref}}$$

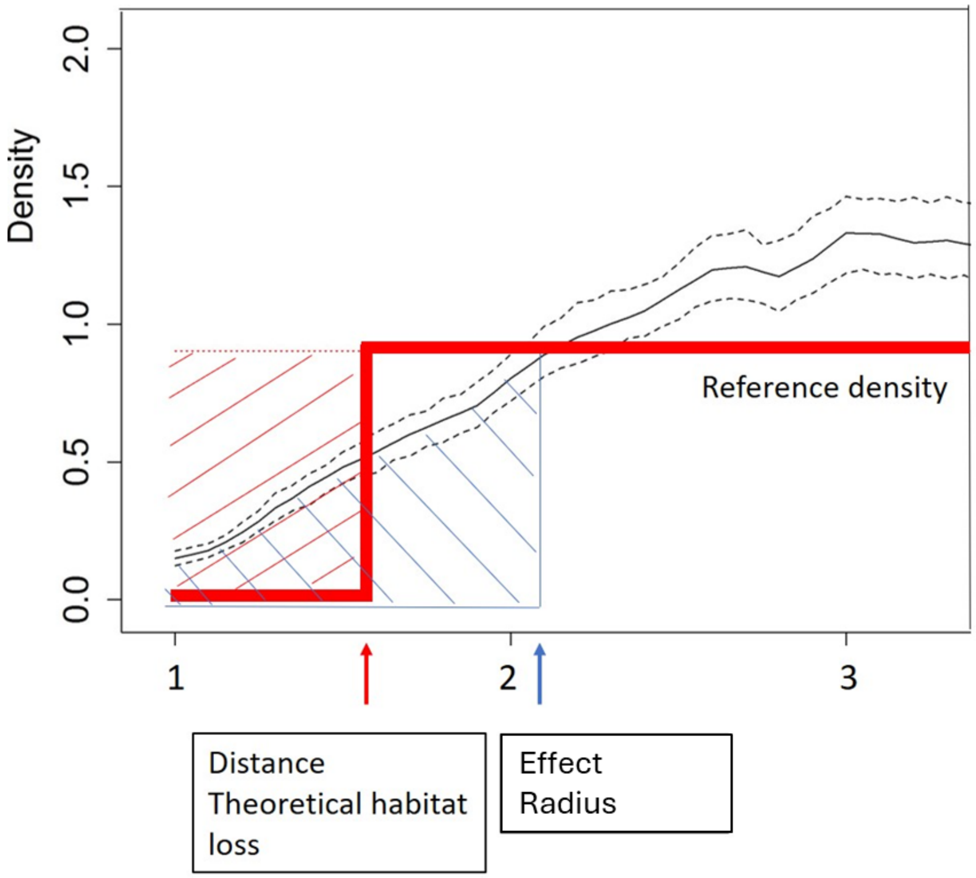

Figure 4-4 Example of calculation of displacement distance and theoretical habitat loss. The reduced bird density up to the displacement distance is used to calculate the area of theoretical habitat loss given the reference density. The result is given as the effect radius around a model OWF.

4.4.4 Total area and regional analysis

Using the above models, the distribution and effect radius was calculated for the entire study area. In a second step, the data was subdivided into four regions, since local conditions and structural differences could affect the effect radius, and the above analysis was repeated. The four regions are shown in Figure 4-5. All flight or ship surveys that crossed each of the regions at any point were included in the respective analysis. The regions were chosen as roughly West (region 1), South (region 2), East (region 3) and North (region 4).

Region 1: Cluster "Östlich Austerngrund" and Cluster 6

Region 2: Cluster "Nördlich Borkum" and Riffgat

Region 3: Cluster "Nördlich Helgoland" and Nordergründe

Region 4: Cluster "Westlich Sylt" and Butendiek

For information on OWFs included in the clusters see Table A 1.

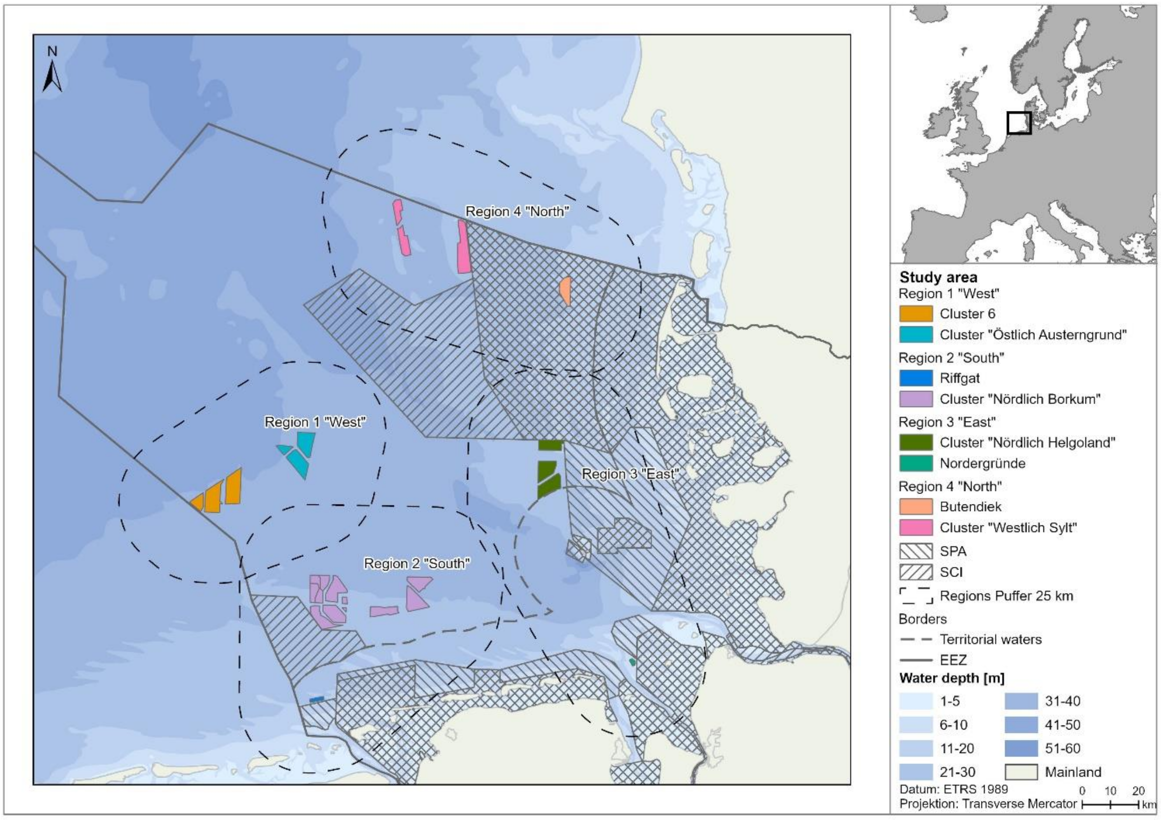

Figure 4-5 Four data subsets to determine potential regional differences.

Due to small sample size for razorbills in autumn, their distribution in autumn and winter is presented in the regional analysis, but the model analysis on the effect radius is only carried out for winter.

5 RESULTS

5.1 Model validation

In order to assess whether the model we used was appropriate for our dataset, we performed a model validation using a subset of our raw data. We performed 20 random runs using 90% of the data for training and 10% of the data for validation each time. The validation scores indicate the alignment between the predicted and observed data. Note, that in ecological studies like this one, a certain variation between predicted and observed data is to be expected due to natural variation. The results showed high scores for Guillemots in both seasons (0.80 for autumn and 0.69 for winter), while the validation scores for Razorbills were comparatively lower (0.33 for autumn and 0.42 for winter; see Figure 5-1). The scores support the high predictive capacity of the models, especially for the models on Guillemots. The validation score is influenced by data availability (sample size per analysis see Table 4-2) and additionally by the species' high mobility and clustered distribution. Removing 10% of the data from the training dataset in a patchy spatial pattern distribution, such as razorbills in autumn with birds concentrated in two small hotspots, might lead to lower-than-expected cross validation scores. Consequently, the scores for the models on razorbills are lower, reinforcing the need for careful interpretation of the results for razorbills.

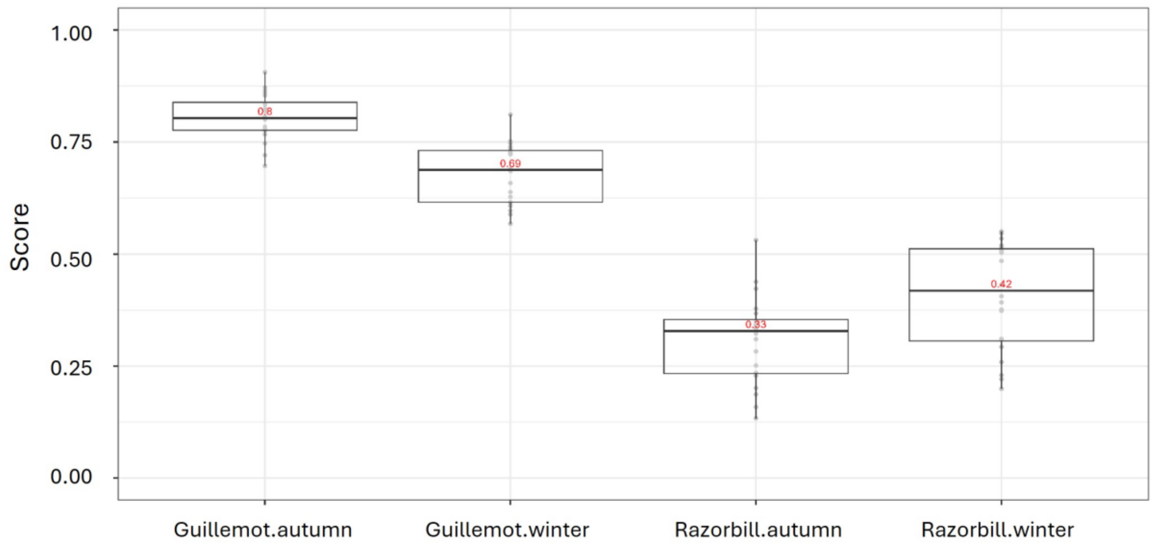

Figure 5-1 Model validation results: The figure presents cross-validation scores from 20 random model runs, each using a 90%-10% validation split. The scores reflect the predictive capacity of the models, with higher scores indicating better alignment between predicted and observed data.

5.2 Total area

Spatial distribution and effect radius for the total area were analysed for Guillemots and Razorbills separately (see the following chapters), and for the species combined (see appendix A.2.1). Note that species identification rates differ between aerial survey techniques, so some areas ("Cluster 6", "Sandbank"/"Dan Tysk", "Östlich Austerngrund") are less well covered by species-specific data. This does not affect the analysis of the effect radius (as species identification is unrelated to distance from OWF) but can be seen in the distribution graphs. A more even coverage was achieved in the dataset when species were combined (see A.2.1).

5.2.1 Distribution

5.2.1.1 Guillemot

In autumn Guillemots showed two distinct areas of concentration within the study area (Figure 5-2 A). There was a concentration of high densities in the North of the German EEZ and a more diffuse concentration of elevated densities in the general northwestern part of the study area. In the Southeast there were very high densities around the island of Helgoland, where the only German breeding colony for Guillemots and Razorbills is located.

In winter (Figure 5-2 B) the distribution appeared more widespread, with high densities around the Cluster ”Nördlich Borkum“ in the Southwest of the survey area as well as high densities around the OWF Cluster “Nördlich Helgoland“ and further north from there in the nature conservation area “Sylter Außenriff-Östliche Deutsche Bucht”.

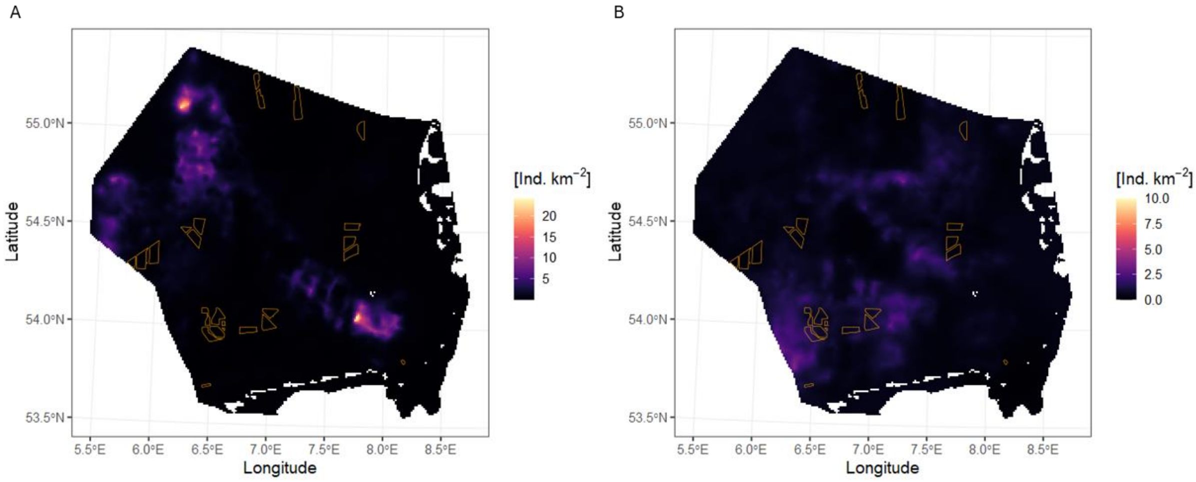

Figure 5-2 Distribution of Guillemots during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

5.2.1.2 Razorbill

Razorbills in autumn were present in far lower densities than Guillemots. Nevertheless, a very similar distribution with high densities in the Northwest and Southeast (close to the breeding colony on Helgoland) was clearly visible (Figure 5-3 A).

In winter (Figure 5-3 B) the distribution was also similar to Guillemots, with the highest densities in the Southwest of the survey area around the Cluster “Nördlich Borkum”. Elevated densities were also found to the Northeast of the area “Fläche N-8” (“Global Tech”/”Hohe See”/”Albatros”), on the edge of the nature conservation area “Sylter Außenriff-Östliche Deutsche Bucht”. Unlike in Guillemots, however, there were no elevated densities around the Cluster “Nördlich Helgoland”.

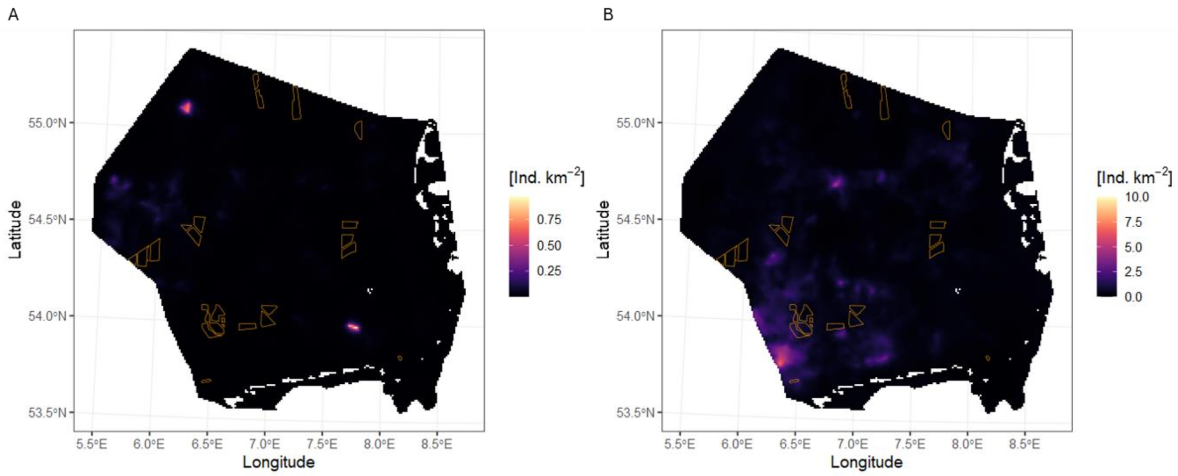

Figure 5-3 Distribution of Razorbills during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

5.2.2 Effect radius

Effect radius was calculated for Guillemots and Razorbills separately and also for a group that included all Guillemots and Razorbills as well as individuals identified only as either Guillemot or Razorbill but not to species level. The results for Guillemots are found in chapter 5.2.2.1 and for Razorbills in chapter 5.2.2.2. The results for the group including Guillemots, Razorbills and unidentified Guillemots/Razorbills are found in the appendix (A.2.1.1).

5.2.2.1 Guillemot

The graphs (Figure 5-4) show the relative density of Guillemots (density relative to the mean) in relation to the distance to the nearest OWF up to a distance of 30 km. Depicted in yellow is the model curve, the black dotted lines show the 95% confidence intervals (CI). The red dashed line is the mean density across the survey area. The effect radius was defined as the intersection of the upper CI (upper dashed black line) and the mean (red).

The graph for Guillemots in autumn (Figure 5-4 A) shows the relative density is below the mean density at the border of the OWF (distance of 0 km) and rises with increasing distance to the OWF. The model curve intersects the y-axis above 0 and below the mean, which indicates that there are fewer Guillemots than average inside the OWF area, but a certain proportion of Guillemots remain present inside the OWF. The relative density increases steadily with increasing distance to the nearest OWF. The upper CI intersects the mean at 5.75 km, indicating a significant effect up to that distance. The model curve intersects the mean at a distance of 11.83 km. The relatively high CI indicates that there is a high degree of variation within the data, which leads to some uncertainty as to the course of the main curve. Given these numbers, the effect radius can be interpreted as between 6-12 km.

In winter the model curve is noticeably flatter than in autumn. The intersection with the y-axis for the upper CI is only marginally below the average, indicating a significant effect for the inside of the OWF at least (Figure 5-4 B). The upper CI intersects the mean at 0.37 km which indicates a minimum for the effect radius. The main curve intersects the mean at 1.84 km, which would put the effect radius at around 0.4-2 km. The comparatively level model curve shows a relatively even distribution of Guillemots at all distances from the OWF.

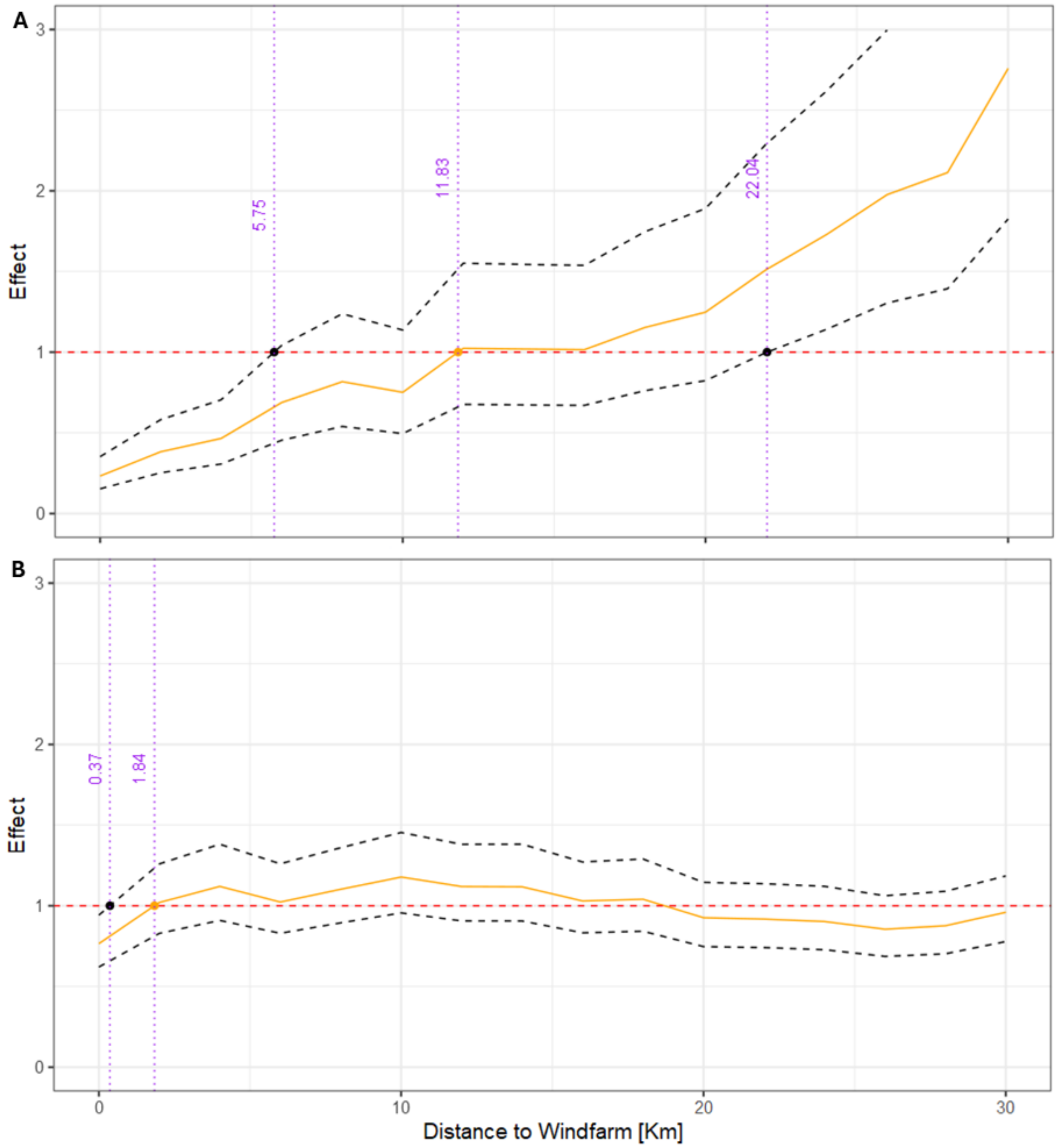

Figure 5-4 *Effect of Distance to OWF on Relative Density of Guillemot in (A) autumn and (B) winter. Yellow = model curve, black dotted lines = 95% confidence intervals (CI), red dashed line = mean density across the survey area, intersection of the upper CI (upper dashed black line) and the mean (red) defined as the effect radius.*

5.2.2.2 Razorbill

The graph for the Razorbill in autumn (Figure 5-5 A) shows the relative density is below the mean at the border of the OWF (distance of 0 km) and rises with increasing distance to the OWF. The upper CI intersects the y-axis below the mean, indicating a significant effect up to 6.29 km, where it intersects with the mean. The main curve intersects the mean at 10.71 km. We can infer an effect radius of ca. 6-11 km. The course of the relative density curve is very shallow, which indicates a relatively even distribution of Razorbills at distances greater than the effect radius.

Razorbills in winter show a relative density that fluctuates around the mean over all distances from the nearest OWF (up to 25 km; Figure 5-5 B). The upper CI intersects the y-axis above the mean, which indicates that there is no significant effect in this case.

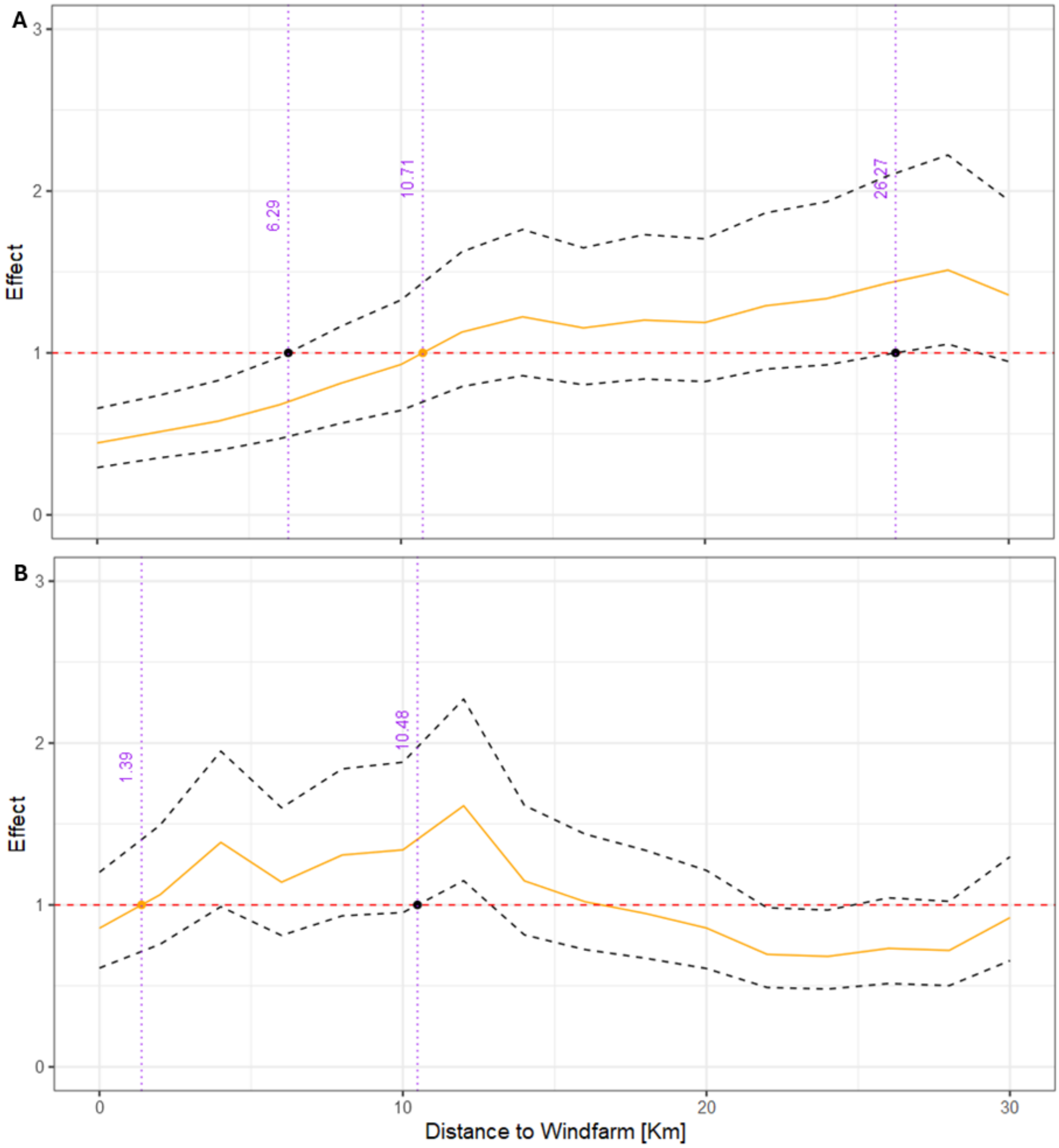

Figure 5-5 Effect of Distance to OWF on Relative Density of Razorbill in (A) autumn and (B) winter. Yellow = model curve, black dotted lines = 95% confidence intervals (CI), red dashed line = mean density across the survey area, intersection of the upper CI (upper dashed black line) and the mean (red) defined as the effect radius.

5.2.2.3 Summary of effect radii

Table 5-1 shows a summary of the effect radii estimated for Guillemots and Razorbills over the whole study area.

Table 5-1 Overview of effect radii (km) for Guillemots and Razorbills in the entire study area; n=number of individuals, n.s.= not significant (i.e. no significant effect of OWF was detected).

	Guillemot		**Razorbill**	
	Effect radius (km) based on: Intersection upper CI; Intersection mean; (n)		Effect radius (km) based on: Intersection upper CI; Intersection mean; (n)	
Season	Autumn	Winter	Autumn	Winter
Total area	5.75; 11.83; (42,598)	0.37; 1.84; (37,640)	6.29; 10.71; (724)	n.s.; (23,934)

5.2.3 Proportion of reduction

The reduction in density inside an OWF (based on the entire study area) was higher in autumn than in winter (Table 5-2). For Guillemots a reduction of 65-76% was calculated inside the OWF and in distances up to 1 km for autumn. For Razorbills a reduction of 41-56% compared to the expected value (if there was no avoidance) was calculated in distances up to 1 km. At distances of 0-5 km Guillemots showed reductions of ca. 49-66%, Razorbills of 31-50%.

In winter, far lower reductions were found (Table 5-2). At a distance of 0-1 km we calculated a reduction of 5-36% for Guillemots, for Razorbills there was no significant effect. At distances of 0-5 km, we found a reduction of ca. 0-8 % for Guillemots, while for Razorbills no reduction was apparent.

Table 5-2 Reduction in density inside and around OWF for Guillemot and Razorbill based on the entire study area. n.s.= not significant.

Species	Season	Effect radius (km) based on upper CI (a) or mean (b)		% Reduction up to 1 km	% Reduction 0-5 km
Guillemot	Autumn	(a)	5.8	65	49
		(b)	11.8	76	66
	Winter	(a)	0.4	5	0
		(b)	1.8	36	8
Razorbill	Autumn	(a)	6.3	41	31
		(b)	10.7	56	50
	Winter		n.s.	n.s.	n.s.

5.2.4 Theoretical habitat loss

In autumn the distance radius for the habitat loss for Guillemots was calculated as 0-1 km based on the lower end of the effect radius and 4-4.5 km based on the higher end. For Razorbill the range was either inside the OWP or at 2.5-3 km (Table 5-3). In winter, the effect radius was very low for both species, so the theoretical habitat loss would lie inside the OWF or there is no detectable habitat loss.

Table 5-3 Theoretical habitat loss around a model OWF for Guillemot and Razorbill. n.s. = not significant.

Species	Season	Effect radius (km) based on upper CI (a) or mean (b)		Theoretical habitat loss radius around OWF (km)
Guillemot	Autumn	(a)	5.8	0-1
		(b)	11.8	4-4.5
	Winter	(a)	0.4	0
		(b)	1.8	0
Razorbill	Autumn	(a)	6.3	0
		(b)	10.7	2.5-3
	Winter		n.s.	0

5.3 Regional subsets

For the regional subareas, spatial distribution and effect radius was also calculated for Guillemots and Razorbills combined and for Guillemots and Razorbills separately. As species identification rates differ strongly within region 4 and was generally lower in region 1, we present the results for Guillemots and Razorbills combined (including unidentified Guillemots and Razorbills) in the following chapters. The results for Guillemots and Razorbills separately are found in the appendix (A.2.2).

5.3.1 Region 1: West

Region 1 is located in the western part of the German EEZ and lies relatively far offshore at water depths of between 31-50 m (Figure 4-5). The data set includes surveys for Cluster 6 and Cluster "Östlich Austerngrund" which consist of 6 wind farms with a total of 345 turbines. The turbines vary in sizes of hub heights: 90 m-134 m, rotor diameter: 116 m-164 m, output: 5 MW-8.8 MW.

5.3.1.1 Spatial distribution for Guillemots and Razorbills combined

In autumn the highest concentrations of Guillemots and Razorbills were found in the west of region 1, where the German and Dutch EEZ meet (Figure 5-6 A). Additionally, they were concentrated in medium density in the northeast of region 1 and then scattered in low to medium densities throughout the study area, with the exception of the OWF areas themselves.

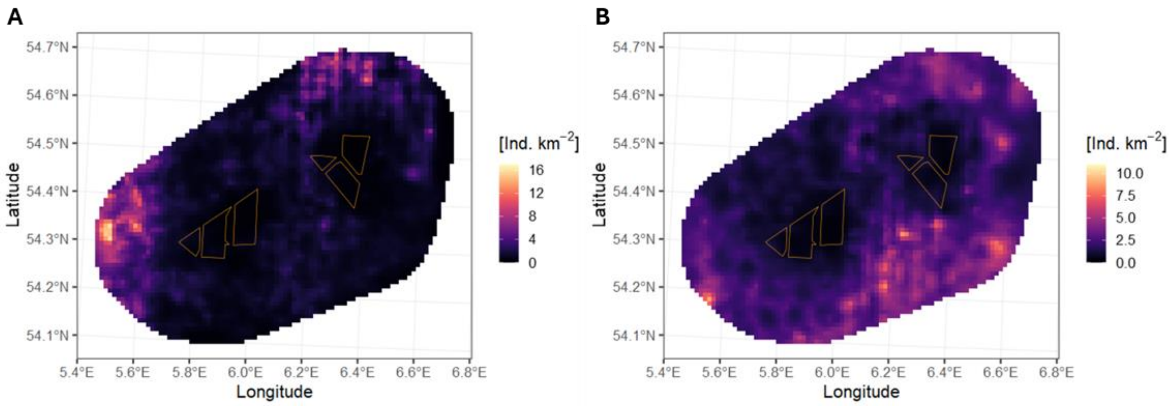

Figure 5-6 Distribution of Guillemots and Razorbills (entire dataset) in region 1 during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

In winter, the densities of Guillemots and Razorbills in region 1 were higher overall (Figure 5-6 B). The highest densities were found in the central southern part in direction of the SPA "Borkum Riffgrund". Auks were scattered in medium to high densities throughout region 1, with the exception of the OWF areas themselves.

5.3.1.2 Effect radius for Guillemots and Razorbills combined

In autumn, a significant effect was detected in region 1 for Guillemots and Razorbills combined up to at least 2.64 km from the OWF, where the upper CI crossed the mean (Figure 5-7 A). The main curve crossed the mean at a distance of 9.53 km. In winter, the effect was also significant with an effect radius of at least 1 km (Figure 5-7 B). The upper CI intersected the mean at a distance of 1.93 km and the main curve at 8.83 km.

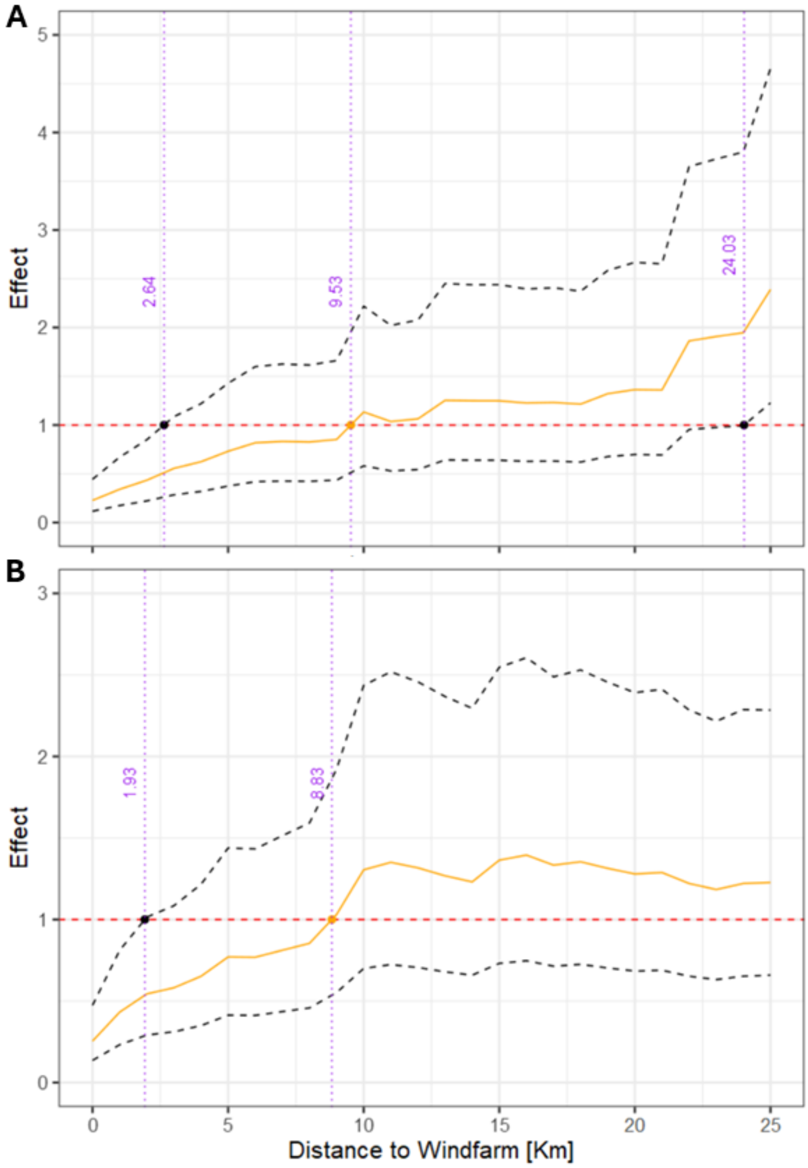

Figure 5-7 Effect of distance to the OWF on relative density of Guillemots and Razorbills (entire dataset) in the region 1 in (A) autumn and (B) winter. Yellow = model curve, black dotted lines = 95% confidence intervals (CI), red dashed line = mean density across the survey area, intersection of the upper CI (upper dashed black line) and the mean (red) defined as the effect radius. Note the different scales in the figures A and B.

5.3.2 Region 2: South

Region 2 lies in the southern part of the German EEZ off the East Friesian Islands at water depths of between 20-40 m (Figure 4-5). The data set includes surveys for Cluster "Nördlich Borkum", which is a large cluster roughly 30 km from the closest island including 9 active wind farms with 435 turbines (in 2021). Some of the aerial surveys for Cluster "Nördlich Borkum" also covered the area around "Riffgat", a wind farm with 30 turbines less than 15 km from the closest island. The turbines vary in sizes of hub heights: 88 m-134 m, rotor diameter: 116 m-164 m, output: 3.6 MW-9.5 MW.

5.3.2.1 Spatial distribution for Guillemots and Razorbills combined

In autumn, auks concentrated in the west of the OWF cluster "Nördlich Borkum" in the SPA "Borkum-Riffgrund" and in the (north)eastern part of region 2, between the OWF cluster "Nördlich Borkum" and the island Helgoland (Figure 5-8 A). During winter, the numbers of auks were much higher and the distribution more widespread, with high densities in the western part of region 2 as well as several patches of high concentrations in the northern part (Figure 5-8 B). The central and southeastern part of the region was less populated, except for one patch of higher concentration.

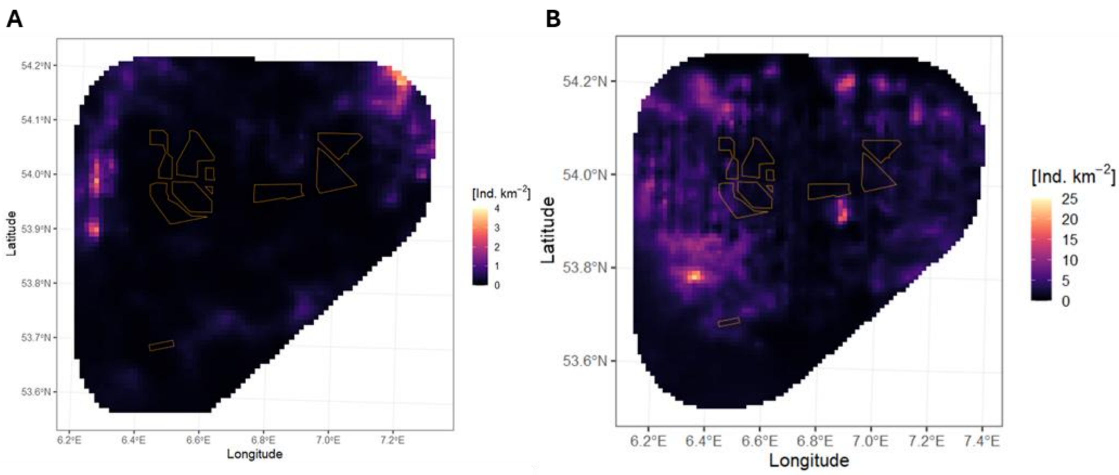

Figure 5-8 Distribution of Guillemots and Razorbills (entire dataset) in region 2 during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

5.3.2.2 Effect radius for Guillemots and Razorbills combined

In autumn, a significant effect up to at least 3 km was apparent for Guillemots and Razorbills combined in region 2 (Figure 5-9 A). The upper CI intersected with the mean at 3.09 km and the main curve at 7.77 km. In winter, no significant effect radius was found (Figure 5-9 B). The density of auks hovers around the mean at all distances.

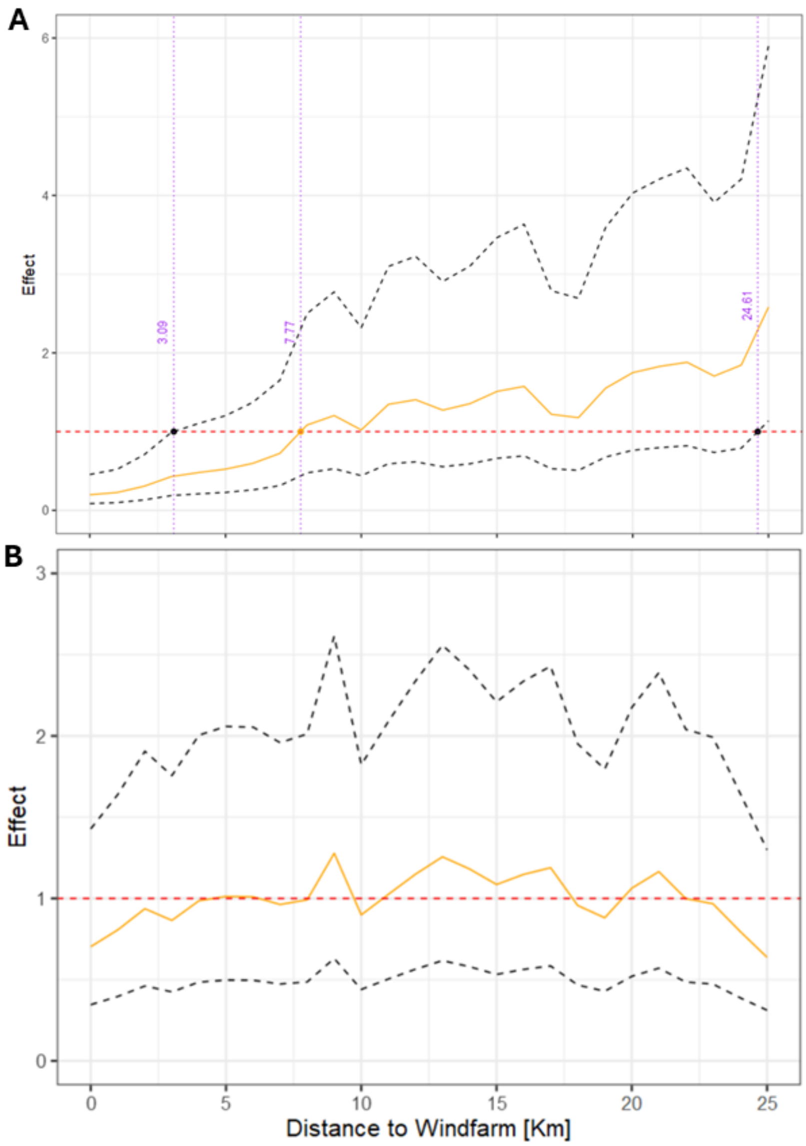

Figure 5-9 Effect of distance to the OWF on relative density of Guillemots and Razorbills (entire dataset) in region 2 in (A) autumn and (B) winter. Yellow = model curve, black dotted lines = 95% confidence intervals (CI), red dashed line = mean density across the survey area, intersection of the upper CI (upper dashed black line) and the mean (red) defined as the effect radius. Note the different scales in the figures A and B.

5.3.3 Region 3: East

Region 3 lies in the eastern part of the German EEZ with Cluster "Nördlich Helgoland" (3 wind farms and 208 turbines in 2021) at a distance of roughly 20 km from Helgoland and around 30 km off the closest Friesian Island at water depths of between 25-35 m as well as the wind farm Nordergründe, which consists of 18 turbines at a distance of roughly 10 km from the closest island and which sits in the intertidal zone (depth 1-10 m; Figure 4-5). The turbines vary in sizes of hub heights: 88 m - 95 m, rotor diameter: 120 m-126 m, output: 3.6 MW-6.15 MW.

5.3.3.1 Spatial distribution of Guillemots and Razorbills combined

In autumn, auks were found almost exclusively in the central part of region 3 (Figure 5-10 A), south-west of the island Helgoland (Figure 4-5), which is home to breeding colonies of Guillemots and Razorbills. In winter, the highest densities of auks were found further north around the OWF cluster "Nördlich Helgoland", especially in a broad distribution south of the OWF cluster or north of Helgoland (Figure 5-10 B). Lower densities occurred in the southern part of region 3 between Helgoland and the OWF "Nordergründe".

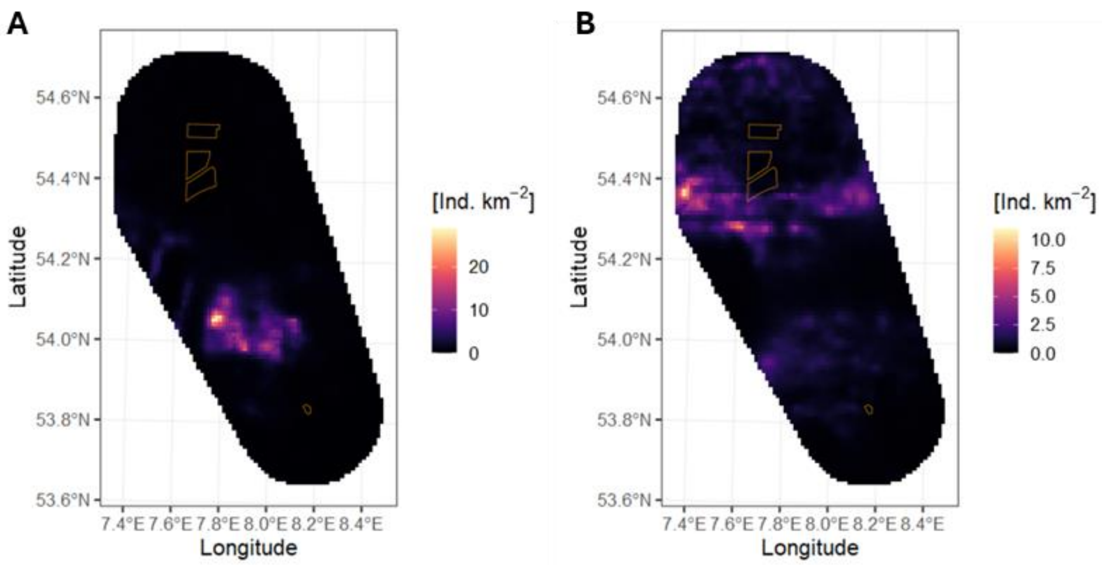

Figure 5-10 Distribution of Guillemots and Razorbills (entire dataset) in region 3 during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

5.3.3.2 Effect radius for Guillemots and Razorbills combined

In autumn in region 3, a significant effect was observed for Guillemots and Razorbills combined. The upper CI intersected the mean at a distance of 6.97 km and the main curve at 10.94 km (Figure 5-11 A). In winter, the density of auks hovers around the mean at all distances (Figure 5-11 B). The upper CI never crossed the mean, indicating no significant effect in winter.

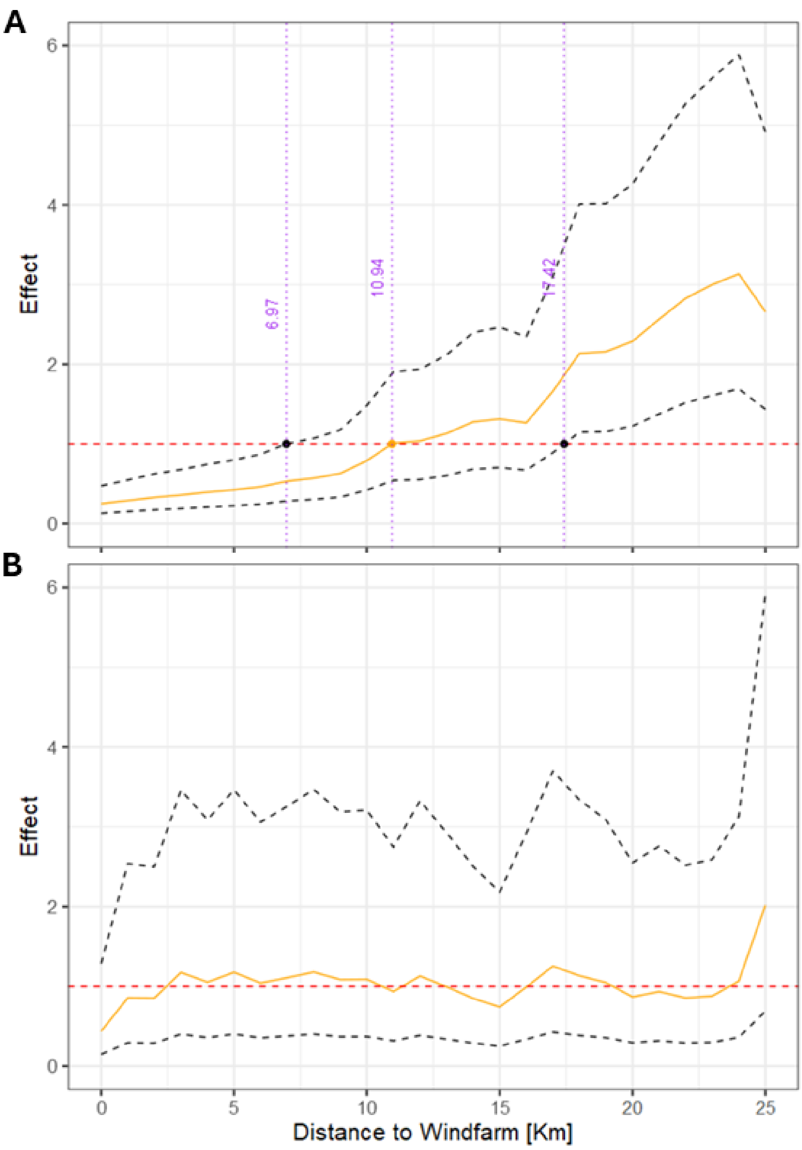

Figure 5-11 Effect of distance to the OWF on relative density of Guillemots and Razorbills (entire dataset) in region 3 in (A) autumn and (B) winter. Yellow = model curve, black dotted lines = 95% confidence intervals (CI), red dashed line = mean density across the survey area, intersection of the upper CI (upper dashed black line) and the mean (red) defined as the effect radius.

5.3.4 Region 4: North

Region 4 lies in the northern part of the German EEZ and includes 3 wind farms, “Sandbank” at roughly 80 km off Sylt or Blåvand as well as “Dan Tysk” at water depths between 21-50 m and “Butendiek”, which lies roughly 30 km from Sylt at water depths of 17-22 m (Figure 4-5). The three wind farms consist of a total of 232 turbines. The turbines vary in sizes of hub heights: 88 m-89.5 m, rotor diameter: 120 m-130 m, output: 3.6 MW and 4 MW.

5.3.4.1 Spatial distribution for Guillemots and Razorbills combined

In autumn, the highest concentration of auks was recorded in a distinct area in the west of the OWF cluster “Westlich Sylt” (Figure 5-12 A). A lower and more diffuse concentration was found in the eastern part of region 4 around the OWF "Butendiek". In winter, the distribution was diffuse and widespread in the entire region 4, with exception of the OWF areas (Figure 5-12 B). A hotspot of auks was recorded in the southern central part of region 4, south of the OWF "Dan Tysk" (OWF cluster "Westlich Sylt").

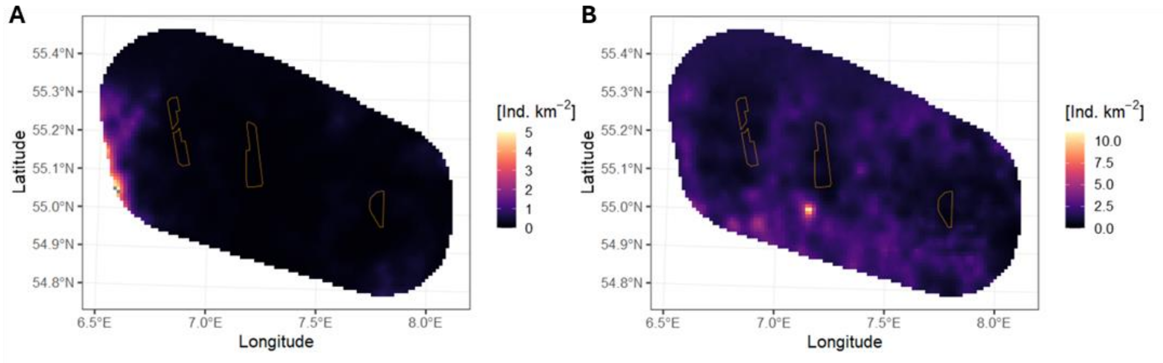

Figure 5-12 Distribution of Guillemots and Razorbills (entire dataset) in region 4 during (A) autumn and (B) winter between 2014-2021 (only post-construction data included).

5.3.4.2 Effect radius for Guillemots and Razorbills combined

The effect radius calculated for Guillemots and Razorbills combined was significant in region 4 in autumn and in winter. In autumn the upper CI intersected with the mean at 6.84 km and the main curve at 14.91 km (Figure 5-13 A). This means a significant effect up to a distance of ca. 7 km. In winter, the upper CI crossed the mean at 1.11 km and the main curve at 8.87 km, indicating a significant effect up to at least 1 km and a lower-than-average density of auks up to 9 km (Figure 5-13 B).

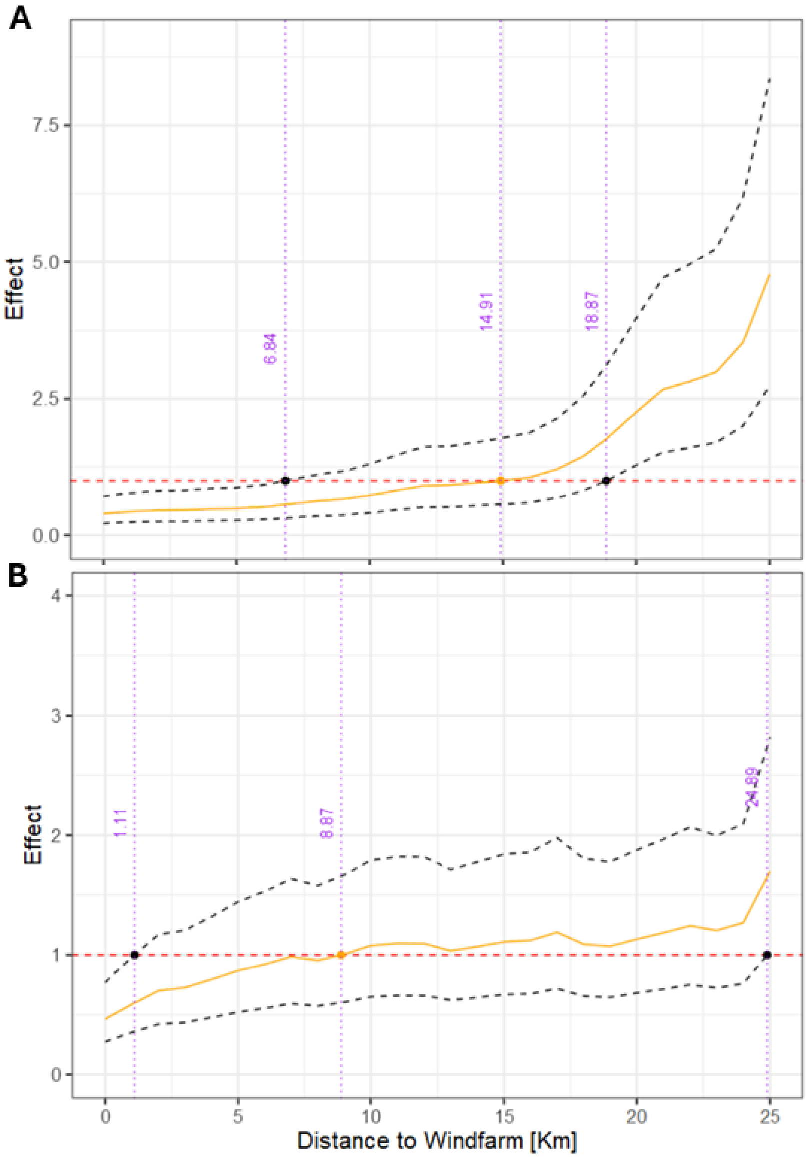

Figure 5-13 Effect of distance to the OWF on relative density of Guillemots and Razorbills (entire dataset) in region 4 in (A) autumn and (B) winter. Yellow = model curve, black dotted lines = 95% confidence intervals (CI), red dashed line = mean density across the survey area, intersection of the upper CI (upper dashed black line) and the mean (red) defined as the effect radius.

5.3.5 Summary of effect radii by regions

Table 5-4 shows a summary of all the effect radii for each region estimated for Guillemots and Razorbills as well as the group containing all Guillemots, Razorbills as well as individuals identified as either, but not to species level.

Table 5-4 Overview of effect radii (km) on Guillemots, Razorbills and all combined in the regions 1-4 separately; n=number of individuals, n.s.= not significant (i.e. no significant effect of OWF was detected). "Low power" = results are of limited power due to low sample size.

	Guillemot		**Razorbill**		**Guillemot & Razorbill**	
	Effect radius (km) based on: Intersection upper CI; Intersection mean; (n)		Effect radius (km) based on: Intersection upper CI; Intersection mean; (n)		Effect radius (km) based on: Intersection upper CI; Intersection mean; (n)	
Season	Autumn	Winter	Autumn	Winter	Autumn	Winter
Region 1	2.45; 9.51; (26,587)	0.80; 6.37; (6,182)	Low power	n.s.; (3,413)	2.64; 9.53; (33,590)	1.93; 8.83; (25,412)
Region 2	3.37; 7.68; (2,869)	n.s.; (10,872)	Low power	n.s.; (8,628)	4.27; 7.78; (3,197)	n.s.; (24,214)
Region 3*	6.86; 11.08; (5,662)	n.s.; (6,046)	Low power	n.s.; (2,005)	6.97; 10.94; (6,181)	n.s.; (10,895)
Region 4	Low power	Low power	Low power	Low power	6.84; 14.91; (4,888)	1.11; 8.87; (15,971)

* includes breeding colony on Helgoland

6 DISCUSSION

6.1 Model quality

Here we compare our statistical approach (Gaussian Random Markov Fields (GMRF) in Integrated Nested Laplace Approximation (INLA)) with the BACI (Before-After Control-Impact) approach, which is widely used in environmental impact assessments to evaluate the effects of interventions on natural systems (e.g. Petersen et al. 2014, Mendel et al. 2019, Peschko et al. 2024).

The BACI method relies on several assumptions and pre-requisites: availability of pre- and post-intervention data, no impact on control areas, the intervention's impact is isolated from other factors, and homogeneity between impacted and control areas. These assumptions are often violated due to limited population distributions and complex spatial-temporal dynamics (Rassweiler et al. 2021), and biases can arise from spatial changes in natural species distributions during study periods, potentially reduced by extending these periods (Mendel et al. 2019, Vilela et al. 2021). Furthermore, variability of factors, like daily environmental conditions, prey distribution and ship traffic, lead to a patchy distribution of seabirds such as auks, which might respond inconsistently to habitat quality around wind farms (Dorsch et al. 2019, Heinänen et al. 2020). The BACI approach, coupled with classical frequentist statistical methods, relies on environmental predictors to assess the effects of wind farms on species distributions and is based on comparing pre- and post-impact conditions within both the impacted and control areas.

In contrast, our study adopts a post-construction model that uses the Log-Gaussian Cox Process (LGCP) with Stochastic Partial Differential Equations (SPDE) for spatial inference (Lindgren et al. 2011). This method is particularly suitable for analysing point-pattern data. In addition, the spatial modelling approach utilized is agnostic regarding environmental predictors and the presence of the wind farms, allowing more freedom to the model to adapt to the actual spatial structure of the species distribution, allowing us to more accurately model the spatial distribution of species after wind farm construction.

Using environmental parameters with different spatial and temporal scales can introduce significant uncertainty into models. In deterministic regression approaches like GLM or GAM, which rely on predefined predictors, this often results in low explained variance due to the complexity of ecological systems. In our analysis, the use of latent Gaussian fields helps to mitigate spatial autocorrelation effects, avoiding overfitting that can occur with simpler models when irrelevant predictors are included (Burnham & Anderson 2002). INLA is also more flexible and robust, reducing the risk of misinterpretation due to incomplete information. In ecological studies, Bayesian hierarchical models have proven superior for modelling large-scale species distributions with complex environmental interactions (Blangiardo & Cameletti 2015). This method includes multilevel spatial random effects that account for all spatially explicit processes influencing species distributions, thus handling multiple sources of uncertainty more effectively (Beguin et al. 2012, Blangiardo & Cameletti 2015, Pennino et al. 2017). Specifically, the LGCP-SPDE approach is designed to handle point-like data, achieving higher predictive accuracy and better confidence interval estimates. This method excels in modelling the underlying intensity of points over space and can provide improved predictive accuracy and confidence intervals due to its ability to model complex spatial structures inherently present in ecological data (Blangiardo & Cameletti 2015). The approach is particularly advantageous for datasets where traditional regression models might fail to capture spatial dependencies adequately (Illian et al. 2012). This framework, by encompassing broader area and time scales, alleviates the need for a control area, captures context-specific species behaviour, and integrates drivers of species variability, thereby generating high-resolution predictions of ecological changes. In addition, our statistical approach allows assessing the quality of the model by calculating a cross-validation score from multiple runs of training and validation data, each based on differing subsets of the data set (see chapter 5.1). Thus, based on the achieved validation scores in this study, we can be confident about the model results.

In the current study, one challenge was to select appropriate areas around OWFs for modelling the effect radius. This is crucial, as the mean density of that area is used as the reference value by which the effect radius is determined. These areas need to be larger than the expected effect radius, but not so large as to potentially include spurious effects unrelated to the OWF. Here, for the total area a distance of 30 km from OWF was used, which appeared as a good compromise between including a large enough area and avoiding including far-away areas that might be affected by factors other than OWF, while still providing sufficient coverage by the survey areas. For the regions the distance from OWF was reduced to 25 km in order to reduce overlap and potential interference between regions.

Additionally, we had to account for possible differences between survey methods, as these could bias the results to some extent. For example, differences in identification rates of auk species resulted in the need to combine data for a meaningful analysis. In this study, survey method (ship or aerial survey) was accounted for in the model.

6.2 Spatial distribution

Our dataset covers all 22 wind farms in operation in the German North Sea in 2021 and contains survey data from 2014 to 2021 (8 years) in autumn and winter, when Guillemot and Razorbill numbers are highest in German waters. This extensive dataset covers a substantial part of the German EEZ during the time of the major wind farm developments in the German North Sea to date.

The autumn and winter distribution of the sympatrically breeding species was similar, which is expected, as Guillemots and Razorbills have similar habitat and preferences in prey species and often spend time in mixed groups (Camphuysen & Webb 1999, Dunn et al. 2019). Since Guillemots and Razorbills mostly hunt at different water depths and for differently sized prey (Ouwehand et al. 2004, Dunn et al. 2019), they are not in food competition with each other.

The number of Razorbills was threefold in winter compared to autumn. As razorbills reach German waters from their British breeding grounds (Wernham et al. 2002) in the course of the autumn and only a small fraction breeds in Germany, autumn numbers were very low and their spatial distribution very patchy. Since Guillemots are far more numerous, both in autumn and in winter, their distribution was more widespread, but the areas of highest density matched strongly between the species. Especially in autumn, two areas of highest densities within the total study area were recorded, that were apparent in both species (Figure 5-2 A, Figure 5-3 A) and supported by the analysis of the larger dataset with the species combined (Guillemots, Razorbills and unidentified

Guillemots/Razorbills; Figure A 1 A). One of these hotspots in autumn is located close to the only breeding colony of Guillemots and Razorbills on Helgoland in the German North Sea. In autumn, both species were comparatively abundant in the south-west of Helgoland, whereas in winter this area was no longer an area of high concentration. The high concentrations especially of Guillemots close to Helgoland post-breeding in autumn may be explained by the fact that the precocial young leave the nest sites prematurely and flightless and are accompanied at sea by an adult for several weeks until fledging (Camphuysen 2002). In addition, during that time the adult birds moult and are also flightless and less mobile (Camphuysen 2002). The other hotspot further north in the study area could be due to the influx of auks into the German Bight from British breeding colonies, that occurs in autumn and is highly dependent on currents. Other potential causes could be good prey availability in the area which would attract large numbers of auks.

The spatial distribution of seabirds (or auks) is generally highly heterogeneous and temporally variable (Fauchald et al. 2011, Maclean et al. 2013). It is heavily dependent on multiple factors, such as prey distribution, weather conditions, water depth, water temperature, and currents. Often these factors are also intercorrelated. Both Guillemots and Razorbills spend most of their time swimming on the water surface, so they are often passively drifted along by the currents (Garthe & Hüppop 2004, Furness et al. 2013). Razorbills tend to be found closer to the coast than Guillemots and their distribution seems to be influenced by the topography of the seafloor, with aggregations being found at slopes with changes in water depths (Mendel et al. 2008). Their spatial distribution is also influenced by season. Breeding birds are restricted to a foraging area in the vicinity of their breeding colony (Dierschke et al. 2004, Peschko et al. 2020b). Post-breeding in autumn the birds move between the breeding colony and their wintering grounds. During that time, the young are accompanied at sea by an adult until independence. During the same period of time, adult birds moult and are flightless for a few weeks (Camphuysen 2002). All of these factors can contribute to a heterogeneous distribution in autumn alongside the species' reaction to OWF.

Razorbills have been described as occurring closer to the coastal regions than Guillemots (Mendel et al. 2008). Our analysis showed strongly overlapping distributions for both species in both seasons. However, Razorbills in winter did seem to show a higher density in more southerly areas (Figure 5-3 B), such as the special protection area (SPA) "Borkum-Riffgrund", whereas Guillemots showed a more widespread distribution (Figure 5-2 B). Overall, the distribution of Guillemots, Razorbills and unidentified Guillemots/Razorbills was widespread, and the total area was occupied by far higher densities of auks in winter (Figure A 1 B).

Garthe et al. (2022) and Peschko et al. (2024) showed a pre- and post-construction distribution for Guillemots in autumn based on the BACI approach and Garthe et al. (2022) additionally showed a pre- and post-construction distribution for Razorbills in winter, based on a dataset of 2003-2020 covering the same area of the German North Sea. We compared the post-construction distribution described there with our findings.

For Guillemots, the spatial distribution in autumn in our dataset appears very similar to the depictions of the post-construction distribution in Garthe et al. (2022) and Peschko et al. (2024) (Figure 6-1). We found similar hotspots in the northwest of the EEZ (northwest of the OWF "Sandbank") and in the southeast around the breeding colony on Helgoland in autumn. In winter the distribution appeared to differ, as Garthe et al. (2022) and Peschko et al. (2024) showed very high densities in the northwest of the EEZ again, which we did not find in our analysis (Figure 6-1).

However, relatively high densities around the Cluster “Nördlich Borkum”, southwest of the Cluster “Nördlich Helgoland” and in the central region of the EEZ (Figure 6-1) were visible in our dataset as well as in Garthe et al. (2022) and Peschko et al. (2024). The datasets in Garthe et al. (2022) and Peschko et al. (2024) and this study were similar but not identical. We defined the seasons following Garthe et al. (2007), while Peschko et al. (2024) (and presumably also Garthe et al. (2022)) reduced the autumn season by two weeks. Each survey provides a snapshot of the distribution of seabirds or auks at a specific day in the covered area. Generally, since Guillemots show high mobility and variability in distribution as well as a strong seasonality, including a high number of surveys in the analysis will help reduce randomness. Since variability in the data was high, these differences in methods (see chapter 6.1) and dataset could explain the differing distributions, despite the large datasets involved in both analyses.

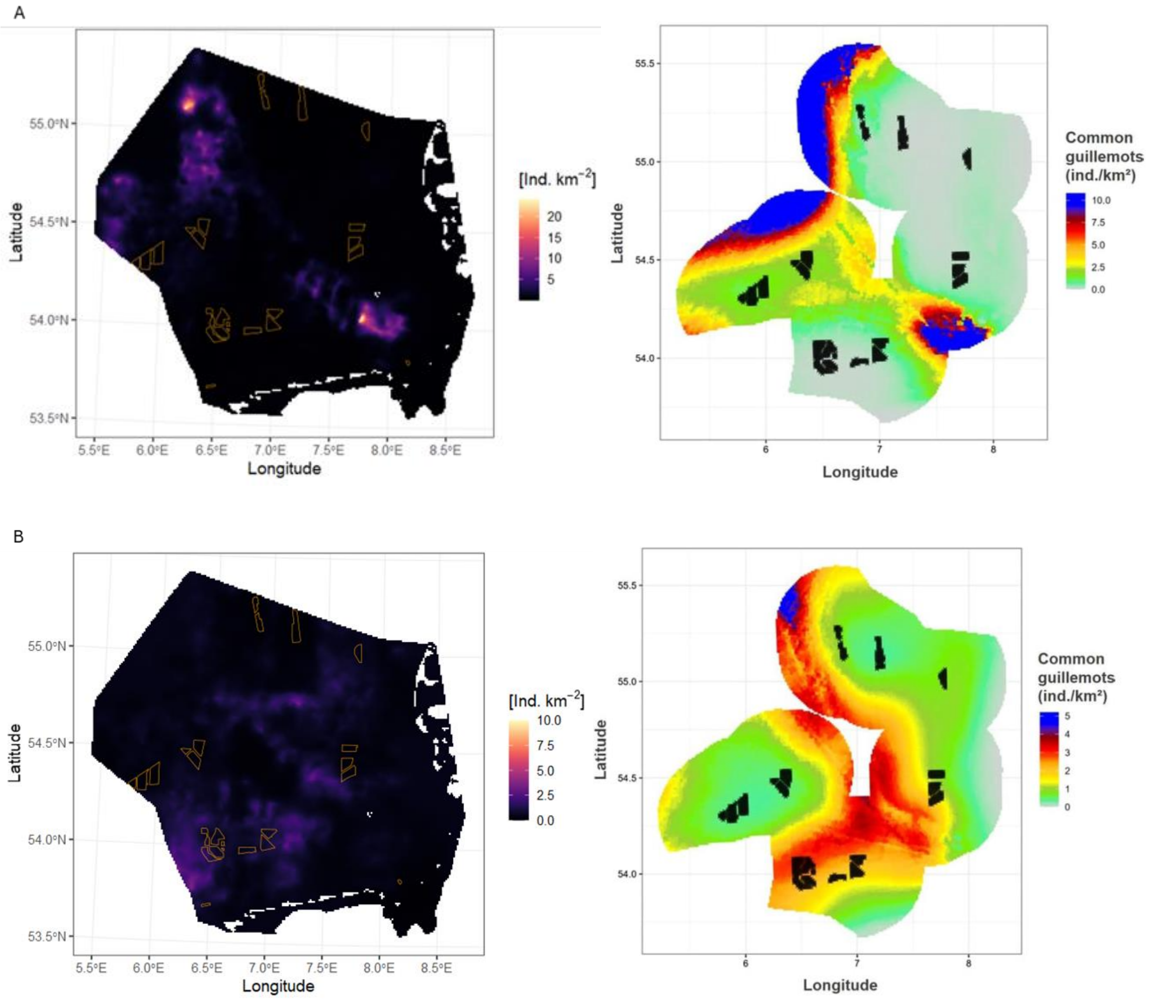

Figure 6-1 *Spatial distribution of Guillemots in this study (left) and according to Peschko et al. (2024) (right) in (A) autumn and (B) winter. Note the different scales.*

The post-construction distribution of Razorbills in winter in Garthe et al. (2022) showed a similar high density in the northwest as was seen in Guillemots. In contrast, we found very low densities in that area for Razorbills. Since a large part of the dataset of both studies was the same, differing statistical approaches between the studies might be a reason for differing distributions, depending on how strongly the model affects the results as opposed to the input data. The high densities we found in the central region of the EEZ could be seen only vaguely in Garthe et al. (2022). However, the high densities we found around cluster “Nördlich Borkum”, particularly around the SPA “Borkum-Riffgrund”, were also visible in Garthe et al. (2022).

6.3 Effect radius

The most striking result in this study with regards to the effect radius is the very strong disparity between autumn and winter. For both Guillemots and Razorbills there seemed to be a much stronger effect of the OWF in autumn than in winter (Table 5-1). This finding was confirmed in the analysis of regions, where Guillemots consistently showed a larger effect radius in autumn than in winter. The sample sizes for razorbills in autumn were too low for a meaningful analysis of the effect radius when subdivided into regions. The effect radii found for Razorbills in winter, however, were comparable to effects (or a lack thereof) in Guillemots.

There are several possible explanations for a larger effect radius in autumn than in winter. Sample sizes for Razorbills were considerably lower in autumn than in winter. With a lower sample size in autumn, the model prediction becomes less reliable and random occurrences could influence the results more than in the model with a larger sample size in winter. This was not true for the Guillemot, however, and since they showed a similar pattern, this factor is unlikely to be of strong impact. Differences in avoidance behaviour towards OWF could be due to the life stage at which the effect was measured. In autumn after the breeding season adult Guillemots and Razorbills are often accompanied by their young for several weeks until they become independent (Camphuysen 2002). This period coincides with the adult birds’ moult, during which they are flightless and less mobile for several weeks (Camphuysen 2002), possibly up to 50 days (Mendel et al. 2008). It is possible that during that time the birds are more wary of disturbances such as OWF. Young Guillemots fledge after approximately 10 weeks (Mendel et al. 2008), and the autumn season (as defined by Garthe et al. 2007) is 3 months long. It is therefore possible that a behavioural difference on account of the unfledged young and the moult is sufficient as an explanation for the strong differences found in avoidance behaviour during autumn. It is also possible that young, inexperienced but independent auks show higher avoidance behaviour towards OWF than adults, which could contribute to the larger effect radius in autumn. Lower effect radii in winter could also arise from a density effect, due to higher overall numbers of auks in winter. Additionally, limited prey availability outside OWF areas may lead to reduced avoidance behaviour towards OWF in winter. During winter, a potentially tighter energy budget and higher daily energy expenditure than in autumn, as shown for Guillemots by Dunn et al. (2020), might contribute to a lower avoidance of OWF. Energy constraints might limit their flexibility and choice of foraging habitat and lead to behavioural adjustments in the form of lower avoidance of OWF.

We calculated significant effect radii between 6 and 12 km in autumn and between no significant avoidance up to 2 km in winter. There was a high amount of variation within the data, but overall, these values are within the range of results from previous studies, which showed a wide range of estimated effect radii for Guillemots and Razorbills (compare Table 6-1), with estimates of avoidance distances ranging between 2-18 km. The strong variation might be due to the fact that previous studies usually did not take into account the season when data were collected, which might strongly affect estimates. Since seasonal variation in avoidance behaviour seems to be very strong in this group, the high variability of results between studies could be at least partially due to the timing of data collection or in which season auks are most likely to occur in the studied area. Studies such as Vallejo et al. (2017), where Guillemot abundance was highest for the breeding season, found no effects of the OWF in a year-round study. Perhaps this is due to the foraging pressure during the breeding season being higher. In our data, the differences between Guillemots and Razorbills in winter (as well as in autumn) were comparatively small, when comparing results from the overall area as well as from the different regions. In contrast, Grundlehner et al. (2024) found a stronger avoidance for Guillemots than for Razorbills in winter, suggesting species-specific differences. We did, however, find a higher theoretical habitat loss in Guillemots in autumn (chapter 5.2.4).

The somewhat large variation in effect radii within seasons and regions may also be explained by individual variability. While some species of seabirds seem to show a relatively consistent reaction to OWF (for example divers; Garthe et al. 2018, Vilela et al. 2020), other species show a more variable reaction, with some individuals never entering wind farms and some entering frequently. These behaviours can only be differentiated if individual birds are tracked, so these studies are generally done for comparatively small sample sizes. However, individual variability in wind farm avoidance has been shown in Northern Gannets, where most individuals avoided the wind farm, but a small proportion (11%) entered the wind farm frequently (Peschko et al. 2021). Studies on Lesser black-backed gulls also showed individual variation in OWF-use (Thaxter et al. 2015, Vanermen et al. 2019). For Guillemots, a similar study also found indications that some individuals might be more likely to enter wind farms than others, but the sample size was small (Peschko et al. 2020b). Variability in avoidance behaviour could also occur depending on the activity the individuals are engaged in. One study found that Sandwich Terns seemed to avoid wind farms while commuting, but were more likely to enter them while foraging (Thaxter et al. 2024). It is likely that both, among- and within-individual variability contributed to the variation in the range of effect radii in this study.

The effect radii calculated for Guillemots and Razorbills by Garthe et al. (2022) in comparison with our own results can be found in Table 6-2. Overall, the estimates in Garthe et al. (2022) are far higher than those we estimated. If we compare the methods with those presented in Peschko et al. (2024) one possible reason for the difference is the definition of the “expected abundance” (in our study, we used the overall mean, Peschko et al. (2024) used before-values), but also the high densities found for Guillemots in the northwest of the EEZ in winter, which we did not find.

The apparent effect radius could be influenced by biotic and abiotic factors other than OWFs. As described in chapters 5.2.1.1 and 5.2.1.2, there are two distinct concentration areas of high densities of Guillemots and Razorbills in the total study area in autumn, one of which is located southwest of the breeding colony on Helgoland. It is most likely, that this southeasterly concentration area is influenced by the location of the breeding colony, where birds are still concentrated at the beginning of autumn, whereas in winter there are no high densities in the area. Thus, the calculated effect size for region 3 is most likely affected by this natural distribution and cannot be considered as purely an avoidance effect towards OWF. The other notable hotspot occurs in the northwest of the German Bight and there is no immediately apparent reason for Guillemots and Razorbills to concentrate there in high numbers, other than a general preference for offshore areas, their migration from breeding colonies further north or due to a good foraging area. It is possible that an avoidance behaviour of OWF contributed to this distribution.

There was variation in effect radius not just between season and species, but also between regions. The strongest avoidance of OWFs, or largest effect radii were found in autumn in regions 3 (east) and 4 (north), whereas the radii in regions 1 (west) and 2 (south) were about half the size. In winter, significant but smaller radii, were found in region 1 (west) and again in region 4 (north). No significant avoidance was detected in regions 2 and 3 in winter. Analyses divided by species gave similar results.

The comparatively large effect radius calculated for OWF in region 3 in autumn might be due to the long distance to the breeding colony rather than an avoidance of OWF. Both species show the highest avoidance in both seasons towards OWF in region 4. Region 4 is one of the regions located further offshore. The other region further offshore is region 1, the only other region where significant avoidance was determined in both seasons. Altogether, these results suggests that Guillemots and Razorbills might be more sensitive to structural disturbance in areas further from shore. This is also indicated by a study of Leopold et al. (2013), who found stronger avoidance effects of seabirds including Guillemots and Razorbills at the Dutch OWF “Prinses Amalia” (23 km from shore) than “Egmond aan Zee” (15 km). It is generally assumed, that regions further offshore are the preferred habitat for auks in winter and until recently those areas were totally devoid of land-like structures. Auks in areas closer to the coast might be less disturbed by land-like features than on the open sea.

Another factor that could induce an avoidance reaction is the size and density of turbines. It has been suggested that more densely installed turbines might have a greater impact on seabirds (Masden et al. 2012, Leopold et al. 2013), but as far as we know it has only been demonstrated in the Sandwich Tern (van Bemmelen et al. 2023, Thaxter et al. 2024). Earlier wind farms often had smaller turbines that stood closer together, while wind farms with larger turbines tend to have larger distances between turbines. Among the regions in our study, region 4 had the smallest, relatively densely installed turbines and with a total of 232 turbines the second lowest number in all regions. In this region we calculated the largest effect sizes in Guillemots and Razorbills in our study. This might support the hypothesis that more densely arranged turbines increase disturbance. On the other hand, the largest and less densely installed turbines and with a total of 345 turbines the second highest number, were found in region 1. This was the only other region where we found significant avoidance in autumn as well as in winter. The highest number of turbines at 465, some of which were of the largest size, are located in region 2, where Guillemots and Razorbills showed an avoidance in autumn, but not in winter. Overall, there is no consistent pattern with regards to the size and arrangement of turbines on the effect radii for Guillemots and Razorbills in this study. Leopold et al. (2013) studied two neighbouring OWFs in Dutch waters, where Guillemots and Razorbills showed a significant avoidance of “Prinses Amalia” (4.3 turbines/km^2), while the effect was less pronounced or non-significant at “Egmont aan Zee” (1.3 turbines/km^2). However, at “Robin Rigg” in the UK (4.6 turbines/km^2) where turbine densities were comparable to “Prinses Amalia” in the NL, Vallejo et al. (2017) did not detect any avoidance behaviour of Guillemots. As turbine density cannot be independently investigated, but correlates for example with distance from shore (“Egmont aan Zee” (15 km) and “Prinses Amalia” (23 km)), effects of OWF design are difficult to test and demonstrate. An ideal experiment would compare OWF of the same number of turbines in similar habitat with different sizes and densities. However, the OWF in the North Sea were installed without such an experiment in mind. Further and more detailed investigations are required to unravel whether OWF size and design affects the extent of avoidance.

The strong variation in avoidance distance within this study, as characterised by the seasonal and regional differences in effect radii, but also in the published literature, points towards additional factors influencing the birds' reaction towards wind farms. Although they show a clear and strong avoidance in some cases (dependent on species, season, area), in other cases there seems to be little or no avoidance. This result must also be seen against the background of a very robust database. At this point, we can only speculate as to the biological reasons behind the response (or lack thereof). In such a complex environment, our modelling approach has proven to be particularly suitable, as it is not based on single explanatory variables, but rather has the freedom to adapt to the actual species distribution and reducing misinterpretation due to incomplete information.

Table 6-1 Effect radii for Guillemots and Razorbills in literature.

Reference	OWF/Study area	Species	Estimated response distance (effect radii)	Data	Season	Study period	Statistical method	Reference for displacement effect
Petersen et al. (2006)	Horns Rev, Denmark	Guillemot & Razorbill	4 km (flocks)	Aerial surveys	All, controlled for	1999-2005	cumulated distance frequency distribution	Before-after comparison
Lindeboom et al. (2011)	Egmond aan Zee, Netherlands	Guillemot	No effect for birds on the water; Strong avoidance for flying birds	Ship surveys	All, not taken into account	2002-2009	GAM	Before-after comparison
		Razorbill	No effect for birds on the water; Strong avoidance for flying birds					
Mendel et al. (2013)	alpha ventus, Germany		2.4 km	Aerial and ship surveys			GAM	Before-after comparison
Mendel et al. (2015)	alpha ventus, Germany		5 km	Aerial and ship surveys			GAM	Before-after comparison
Vanermen et al. (2015)	Bligh Bank, Belgium	Guillemot	At least 3 km	Ship surveys	All, controlled for season	2008 - 2013	Regression model	Before-after comparison
		Razorbill	0.5 km					
Vallejo et al. (2017)	Robin Rigg, UK	Guillemot	No effect for birds on the water	Ship surveys	All, not taken into account	2001-2012	NB GAMM (Bayesian)	Before-after comparison
Zuur (2018)	Egmond aan Zee and Prinses Amalia, Netherlands	Guillemot	No avoidance	Ship surveys	All, not taken into account	2002-2012	INLA (Bayesian)	None

Reference	OWF/Study area	Species	Estimated response distance (effect radii)	Data	Season	Study period	Statistical method	Reference for displacement effect
Zuur (2018)	Robin Rigg, UK	Guillemot	Weak avoidance, no distance	Ship surveys	All, not taken into account	2010-2013	INLA (Bayesian)	None
Peschko et al. (2020a)	Nördlich Helgoland, Germany	Guillemot	9 km (spring) n.s. (breeding season)	Aerial and ship surveys	spring (21.2-6.5.), breeding season (7.5.-15.7)	2000-2013	Regression model	Before-after comparison
BioConsult SH et al. (2020)	Nördlich Borkum, Germany	Guillemot and Razorbill (combined)	2.5 - 4 km	Aerial and ship surveys	all	2014-2019	GAM	Before-after comparison
Peschko et al. (2024)	22 OWF, German North Sea	Guillemot	18-21 km (autumn) 15-18 km (winter)	Aerial and ship surveys	autumn (16.7.-30.9), winter (1.10.-29.2.)	2003-2020	GAM	Before-after comparison
Grundlehner et al. (2024)	Gemini, Netherlands	Guillemot	10 km	Aerial surveys	winter (Oct-March)	2022-2023	spatial distribution models - INLA (Bayesian)	Modelling distributions in space and time
		Razorbill	2 km					
Trinder et al. (2024)	Beatrice OWF, UK	Guillemot and Razorbill (separately)	No avoidance	Aerial surveys	May-August	2019 and 2021	MRSea	Before-after comparison
This study	22 OWF, German North Sea	Guillemot	6-12 km (autumn) 0.4-2 km (winter)	Aerial and ship surveys	autumn (1.7.-30.9), winter (1.10.-29.2.)	2014-2021	INLA (Bayesian)	Intersection of upper credible interval or model curve with average density
		Razorbill	6-11 km (autumn) n. s. (winter)					

Table 6-2 Effect radii, proportion of reduction and theoretical habitat loss for Guillemots and Razorbills: results of this study in comparison with Garthe et al. 2022 and Peschko et al. 2024 in the same study area. Note that the results are based on different survey data and a different statistical approach.

	Species	Season	Distance from OWF	Results from our study	Results from Garthe et al. 2022 Peschko et al. 2024
Effect radius	Guillemot	Autumn		6-12 km	18 - 21 km
		Winter		0.4 - 2 km	15 - 18 km
	Razorbill	Autumn		6-11 km	-
		Winter		n.s.	0 - 3 km
Proportion of reduction	Guillemot	Autumn	Up to 1 km	65-76 %	91 %
			0 - 5 km	49-66 %	80 %
		Winter	Up to 1 km	5-36 %	67 %
			0 - 5 km	0-8 %	54 %
	Razorbill	Autumn	Up to 1 km	41-56 %	-
			0 - 5 km	31-50 %	-
		Winter	Up to 1 km	n.s.	55 %
			0 - 5 km	n.s.	47 %
Theoretical habitat loss	Guillemot	Autumn		4 – 4.5 km	-
		Winter		0 km	-
	Razorbill	Autumn		2.5-3 km	-
		Winter		0 km	-

6.4 Reduction and loss of habitat

Model results revealed that in both species more than half of the individuals avoided the area inside the OWF and up to 1 km distance in autumn, with Guillemots showing a much higher reduction than Razorbills (Table 5-2). Within an area of 1-5 km radius around the OWF the expected density was still noticeably reduced in autumn. In winter, the reductions were much lower and seemed to be confined to the OWF and up to 1 km distance in both species.

While Guillemots and Razorbills can often be found inside OWFs (e.g. BioConsult SH et al. 2020), our results show that habitat loss is still notable in autumn (Table 5-3). The consequences of an avoidance of OWF areas can be that feeding and resting areas are lost or at least become less attractive for auks, resulting in increased densities in the remaining areas with unknown consequences in terms of e.g. food availability and competition. Avoidance of OWF could also lead to a barrier effect, effectively hindering the movement between different resting areas. This might affect e.g. British, Irish and Norwegian Guillemots and Razorbills that migrate into the German EEZ. However, since a proportion of Guillemots are regularly found inside OWF, the avoidance reaction seems to be less severe than in other species (e.g. divers), so an OWF might not present an unsurmountable barrier to migrating auks. At this point, we can only speculate, and further observations are necessary to show how auks will react to obstacles during migration.

Since fishing is currently prohibited inside OWF, these areas can provide a favourable habitat for invertebrates and fish (e.g. Andersson & Öhman 2010, Leonhard et al. 2011, Lindeboom et al. 2011, Glarou et al. 2020) and might thereby increase prey availability for Guillemots and Razorbills. Although Guillemots and Razorbills are also found inside OWF (e.g. BioConsult SH et al. 2020), the results of this study show that at least in autumn, auks are less likely to enter OWF areas. This could affect the use of foraging areas during the sensitive time of young rearing and moult. Whether the currently observed behaviour is a result of there being sufficient foraging opportunities outside the wind farms, is unknown. It is possible that there is simply no need for auks to enter the wind farms at this moment, so they might prefer to stay outside.

Guillemots and Razorbills are relatively flexible in their habitat choice (Mendel et al. 2008), but they are still dependent on suitable foraging habitats. Particularly food scarcity can strongly affect breeding success as well as adult survival (e.g. Erikstad et al. 2013, Lescure et al. 2023). As a long-lived species with a late age of first breeding (median age 6.6 years in Guillemots; Harris et al. 2016) and a maximum of one young per season, Guillemots and Razorbill populations are very susceptible to a reduction in adult survival (Sæther & Bakke 2000). Even small decreases in adult survival can have a significant effect on population size. Despite this, a model study on the North Sea population estimated a relatively minor change to adult survival and population size of Razorbills and Guillemots due to wind farm expansion (van Kooten et al. 2019). This prediction included a number of environmental covariates, but did not account for other threats to population growth, such as the avian flu epidemic that has been affecting colony breeding seabirds since 2022 (e.g. NABU 2022, Pearce-Higgins et al. 2023) or climate/climate change (e.g. Sandvik et al. 2005, Reed et al. 2015).

Long term effects of habitat loss on Guillemots and Razorbills cannot yet be predicted. It is unclear whether at a certain point in the course of future wind farm expansion an increase in habitat loss could lead to effects on population level.

6.5 Conclusion

The strong variation in effect radii found in different studies and the apparent difference between seasons and possibly regions indicate that there are still many unknown factors in how Guillemots and Razorbills react to OWF. This highlights the importance of continuing site-specific impact assessments to determine which area specific characteristics affect avoidance. The clear differences in the extent of avoidance of OWF between the seasons found in this study emphasise that there are species-specific intra-annual fluctuations in reactions to wind farms, which must be considered in order to estimate effects on the species. Finding ways of reducing habitat loss for Guillemots and Razorbills is an important issue regarding the planned expansion of wind energy generation in the North Sea.

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A APPENDIX

A.1 Data

Table A 1 Names of OWF Clusters and OWFs included in the study

OWF Cluster	OWFs per cluster
Nördlich Borkum	Trianel Windpark Borkum, Borkum Riffgrund 1, Borkum Riffgrund 2, Merkur Offshore, alpha ventus, Nordsee One, Gode Wind 01, Gode Wind 02
Westlich Sylt	Sandbank, DanTysk
Cluster 6	Deutsche Bucht, Veja Mate, BARD Offshore 1
Östlich Austerngrund	Albatros, EnBW Hohe See, Global Tech
Nördlich Helgoland	Amrumbank West, Nordsee Ost, Meerwind Süd|Ost
Butendiek	Butendiek
Nordergründe	Nordergründe
Riffgat	Riffgat

A.2 Results

A.2.1 Total area

A.2.1.1. Spatial distribution for Guillemots and Razorbills combined in the total study area

In autumn Guillemots and Razorbills showed two areas of concentration within the study area, one in the north-western part of the German EEZ and one in the Southeast, close to the island of Helgoland (Figure A 1 A). In winter, the two species were widely distributed in the entire EEZ with a hotspot in the SPA "Borkum Riffgrund" (Figure A 1 B).

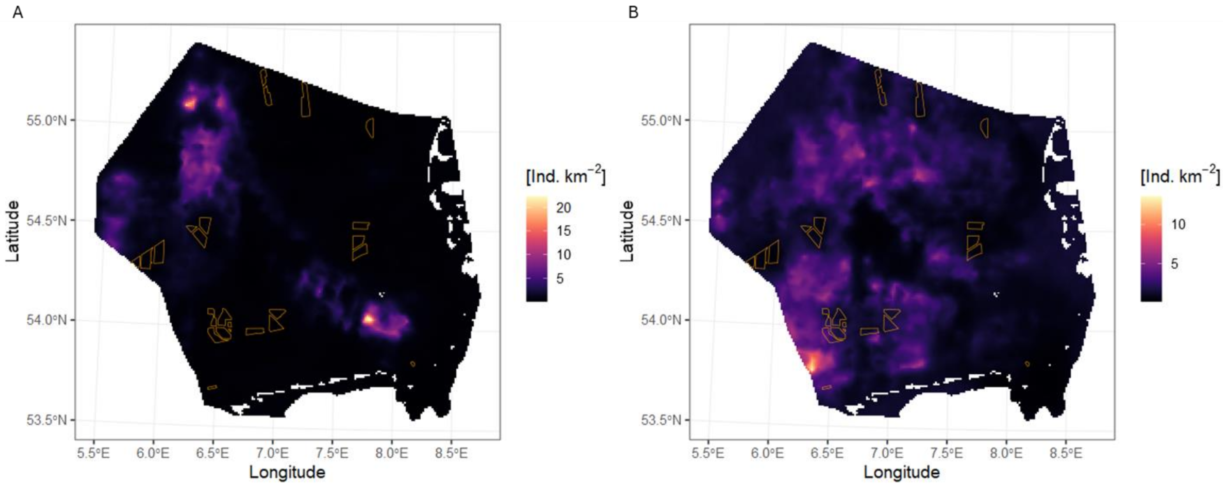

Figure A 1 Distribution of Guillemots and Razorbills (entire dataset) in the total study area during (A) autumn and (B) winter between 2014-2021 (only post-construction data included).

A.2.1.2. Effect radius for Guillemots and Razorbills combined in the total study area

The effect radius of Guillemots and Razorbills combined (including individuals not identified to species level) was significant in the total study area in autumn and winter. In autumn, the upper CI intersected the mean at a distance of 4.94 km from the OWF, the main curve at 11.56 km and the lower CI at 23.86 km (Figure A 2 A, *n*= 52,379 individuals). This means a significant effect up to a distance of at least 5 km and a lower than average density of auks up to 12 km. In winter, the upper CI intersected with the mean at 2.16 km from the OWF, the main curve at 7.94 km and the lower CI at 29.87 km (Figure A 2 B, *n*= 95,022 individuals).

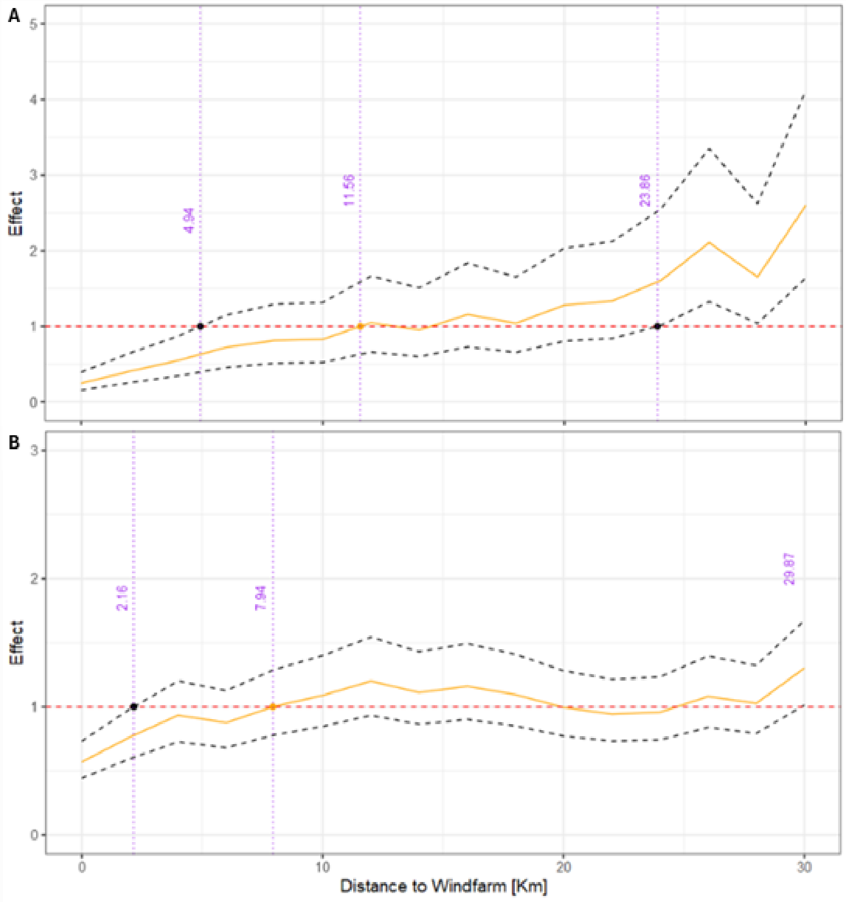

Figure A 2 *Effect of distance to the OWF on relative density of Guillemots and Razorbills (entire dataset) in the total study area in (A) autumn and (B) winter.*

A.2.2 Regional subsets

A.2.2.1. Region 1: West

A.2.2.1.1. Spatial distribution

A.2.2.1.1.1. Guillemot

In autumn there was a hotspot with the highest concentrations in the western part of the study area where the German and Dutch EEZ meet (Figure A 3 A). In addition, Guillemots were scattered in medium to low densities throughout the study area of region 1, with the exception of the OWF areas themselves.

In winter, the concentration of Guillemots in the study area was higher overall. The distribution was also widespread, except in the OWFs themselves (Figure A 3 B). The area with the highest densities in winter was the central southern part of region 1 in the direction of the special protection area "Borkum Riffgrund".

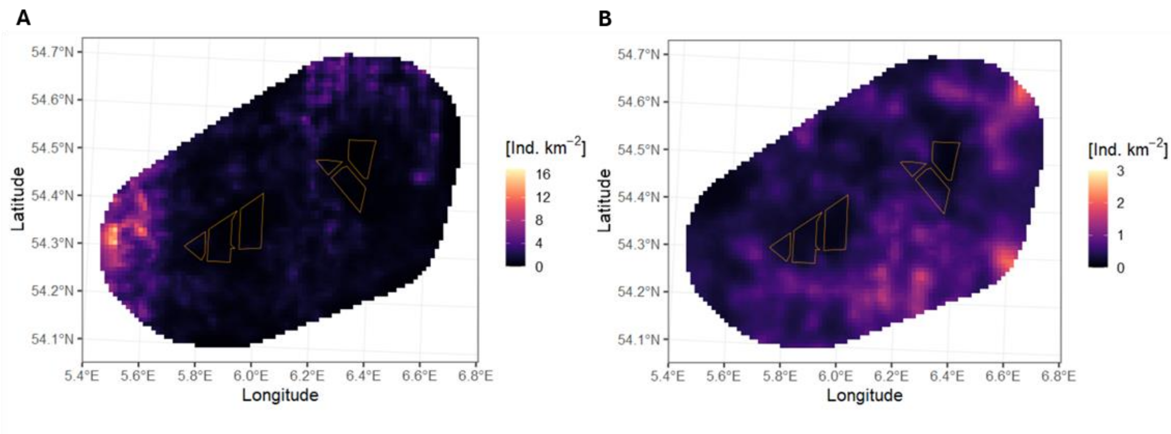

Figure A 3 Distribution of Guillemots within region 1 "West" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

A.2.2.1.1.2. Razorbill

Razorbills were present in very low densities in region 1 in autumn. As with Guillemots, most Razorbills were recorded in a distinct area in the western part of the study area (outside the German EEZ) (Figure A 4 A).

In winter, Razorbills were concentrated in the southern central part of the study area and an additional small hotspot in the eastern part of region 1 (Figure A 4 B).

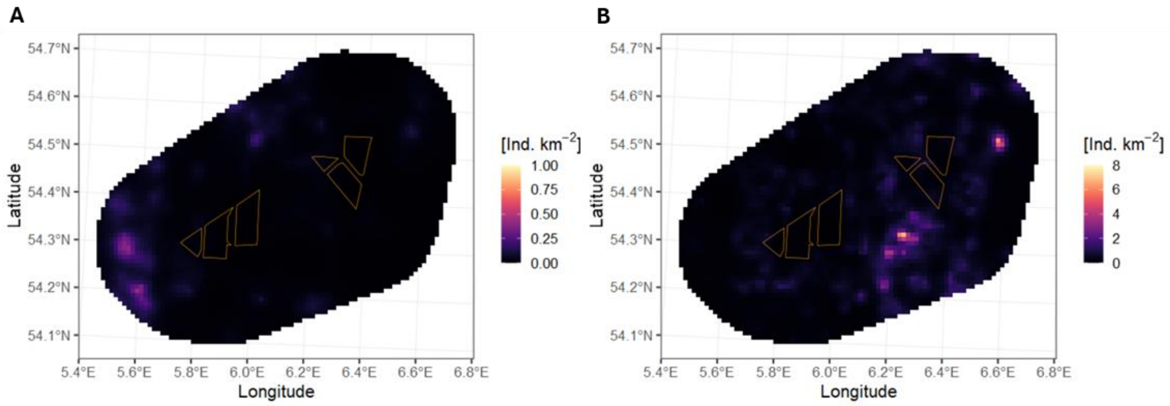

Figure A 4 Distribution of Razorbills within region 1 "West" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

A.2.2.1.2. Effect radius

A.2.2.1.2.1. Guillemot

In autumn the relative density (yellow line) of Guillemots is below the mean (red dotted line) at a distance of 0 km to the OWF and rises with increasing distance to the OWF (Figure A 5 A). The upper CI (grey dotted line) intersects the y-axis below the mean, indicating a significant effect. The upper CI intersects with the mean relative density at 2.45 km and the main curve at a distance of 9.51 km, which indicates an effect radius of ca. 2-10 km. Between 5 km and 20 km the relative density curve is rather shallow, which leads to this large interval.

In winter there was also a significant effect (Figure A 5 B). The upper CI intersected with the mean at 0.80 km, the main curve at 6.37 km. At a distance of around 22 km, the model curve dropped below the mean again. This indicates an effect radius of 1-6 km.

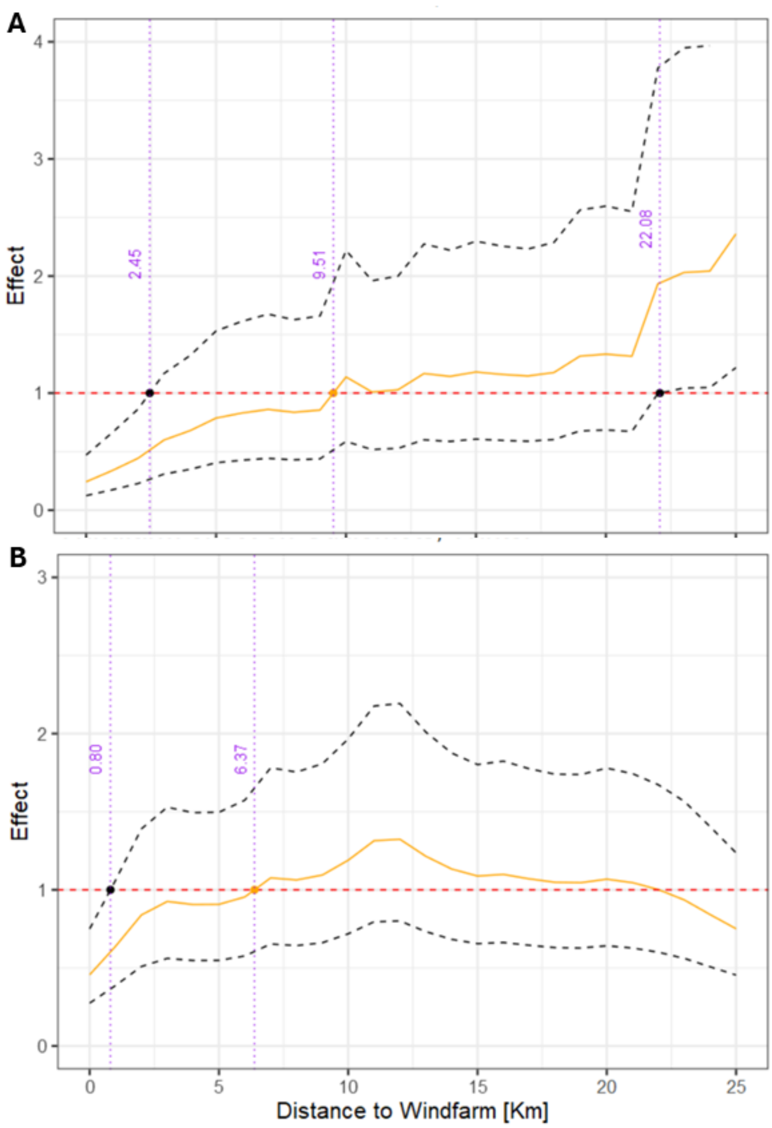

Figure A 5 Effect of distance to the OWF on relative density of Guillemots in region 1 "West" in (A) autumn and (B) winter.

A.2.2.1.2.2. Razorbill

For autumn, no results are presented due to a small sample size.

In winter, the upper CI began above the mean, indicating no significant effect of the distance of the OWF on the distribution of Razorbills in region 1 (Figure A 6). The model curve intersected with the mean at 1.74 km.

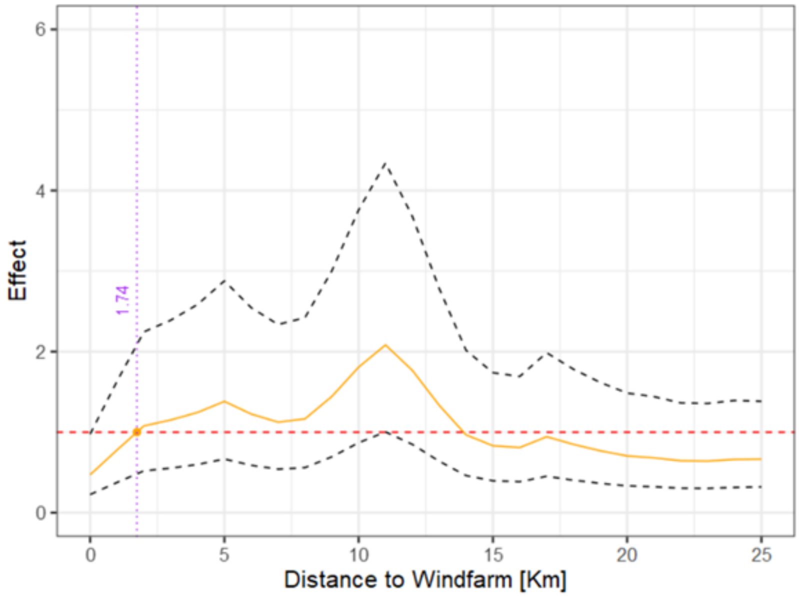

Figure A 6 Effect of distance to the OWF on relative density of Razorbills in region 1 "West" in winter

A.2.2.2. Region 2: South

A.2.2.2.1. Spatial distribution

A.2.2.2.1.1. Guillemot

In autumn, Guillemots showed two distinct areas of high concentration in region 2, one west of the OWF cluster "Nördlich Borkum" in the special protection area "Borkum-Riffgrund" and one in the eastern part of the study area, between the OWF cluster "Nördlich Borkum" and the island Helgoland (Figure A 7 A).

During winter, Guillemot distribution was more widespread, with elevated concentrations in the western, northern and eastern parts of the study area (Figure A 7 B). The central part of region 2 was less populated. Overall, the number of Guillemots in the study area was higher in winter than in autumn.

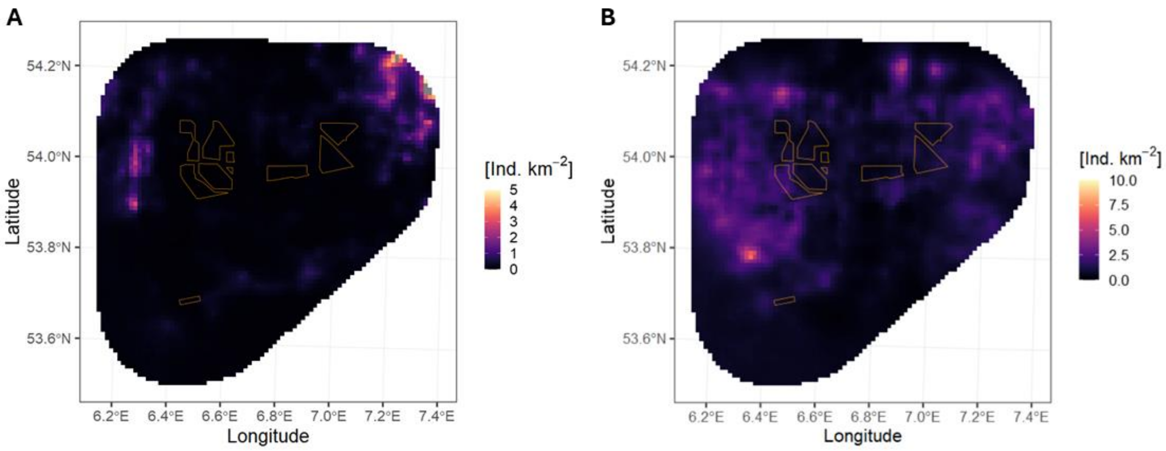

Figure A 7 *Distribution of Guillemots within region 2 "South" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.*

A.2.2.2.1.2. Razorbill

Razorbills were essentially absent from region 2 in autumn (Figure A 8 A).

In winter, elevated concentrations of Razorbills occurred in the western part of the study area, especially between the OWF cluster "Nördlich Borkum" and OWF "Riffgat" in the special protection area "Borkum-Riffgrund" and to a lesser extent to the north and west of the OWF cluster "Nördlich Borkum" (Figure A 8 B). Another spot of high density occurred just south of the OWF "Nordsee One" in the centre of the OWF cluster "Nördlich Borkum" (Figure A 8 B).

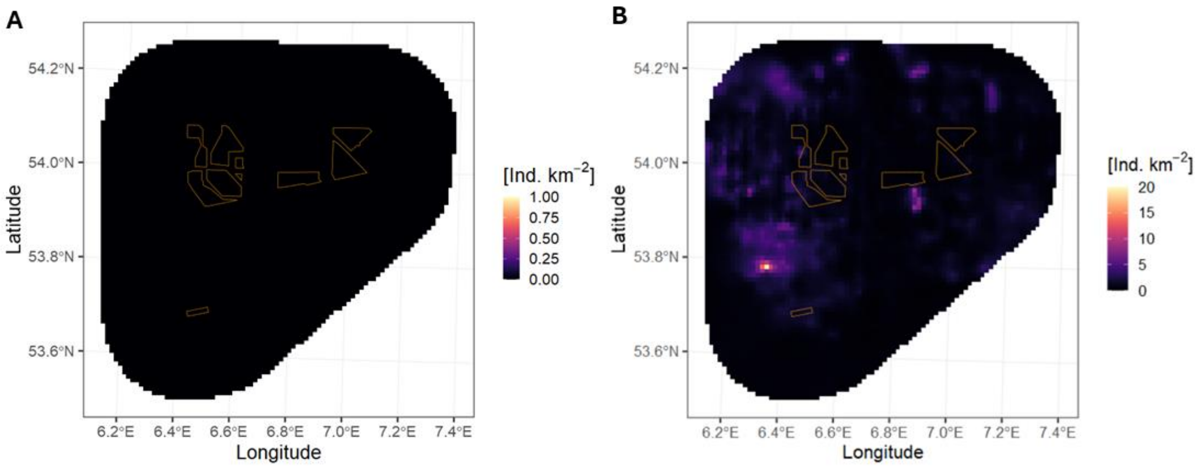

Figure A 8 *Distribution of Razorbills within region 2 "South" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.*

A.2.2.2.2. Effect radius

A.2.2.2.2.1. Guillemot

In autumn, a significant effect was observed up to at least 3.37 km, where the upper CI crossed the mean and up to 7.68 km, where the main curve crossed the mean (Figure A 9 A). However, the curve showed an upward trajectory up to the edge of the prediction at 25 km. In winter, there was no significant effect and the model curve hovered around the mean (Figure A 9 B).

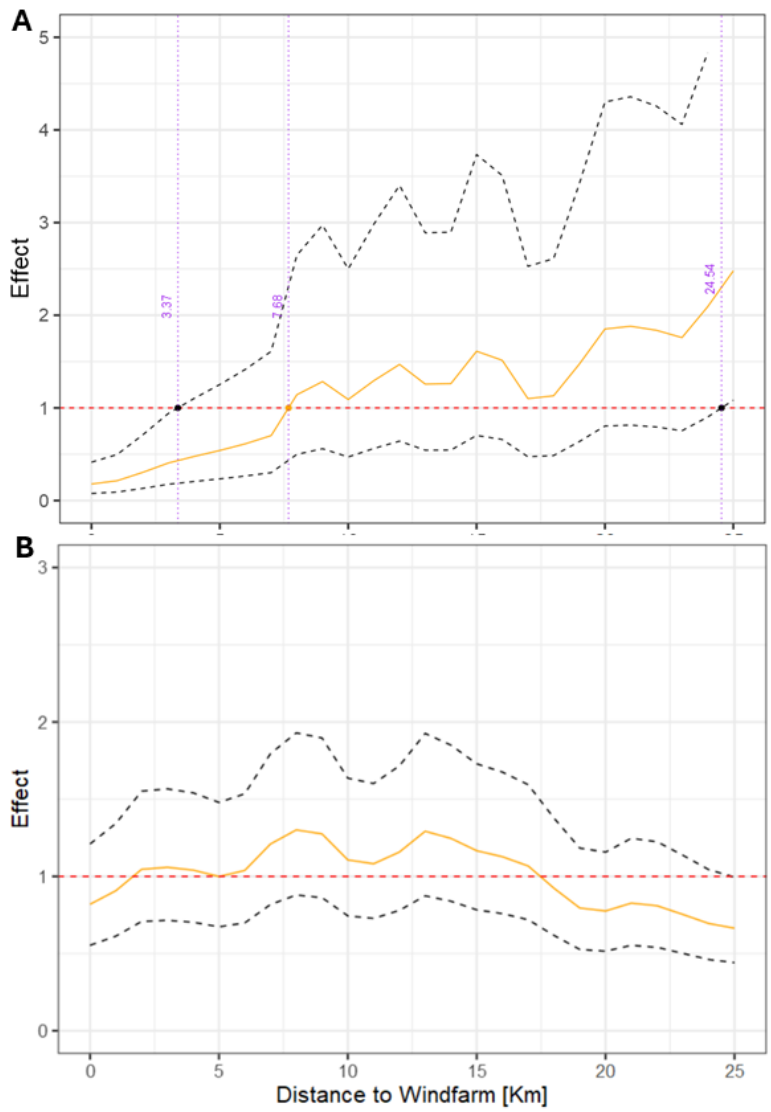

Figure A 9 Effect of distance to the OWF on relative density of Guillemots in region 2 "South" in (A) autumn and (B) winter. Note the different scales in the figures A and B.

A.2.2.2.2.2. Razorbill

For autumn, no results are presented due to a small sample size.

For Razorbills in winter, there was no significant effect for region 2 (Figure A 10).

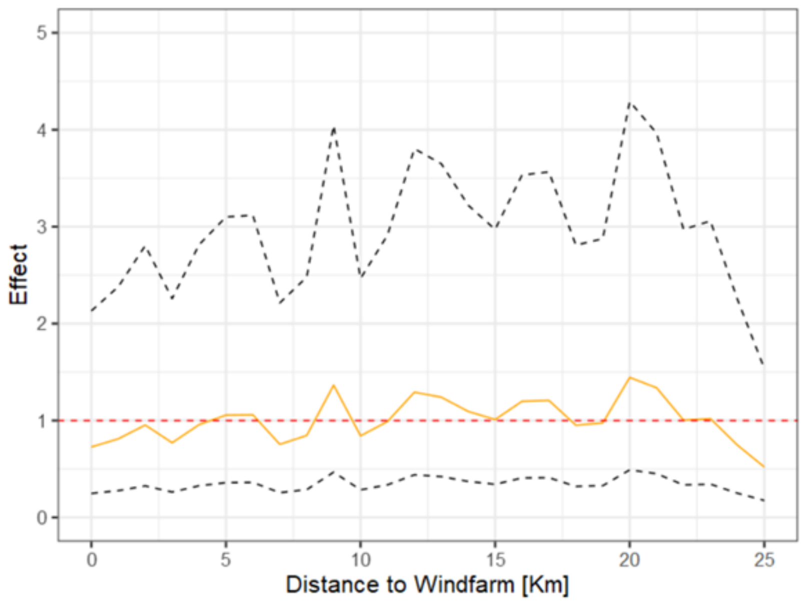

Figure A 10 Effect of distance to the OWF on relative density of Razorbills in region 2 "South" in winter.

A.2.2.3. Region 3: East

A.2.2.3.1. Spatial distribution

A.2.2.3.1.1. Guillemot

In autumn, Guillemots were found almost exclusively in the central part of region 3 (Figure A 11 A), south-west of the island Helgoland, which is home to a breeding colony of Guillemots.

In winter, the highest densities of Guillemots were recorded further north around the OWF cluster "Nördlich Helgoland", especially in the south-west of the cluster or north-west of Helgoland (Figure A 11 B). Lower densities occurred in the southern part of region 3 between Helgoland and the OWF "Nordergründe".

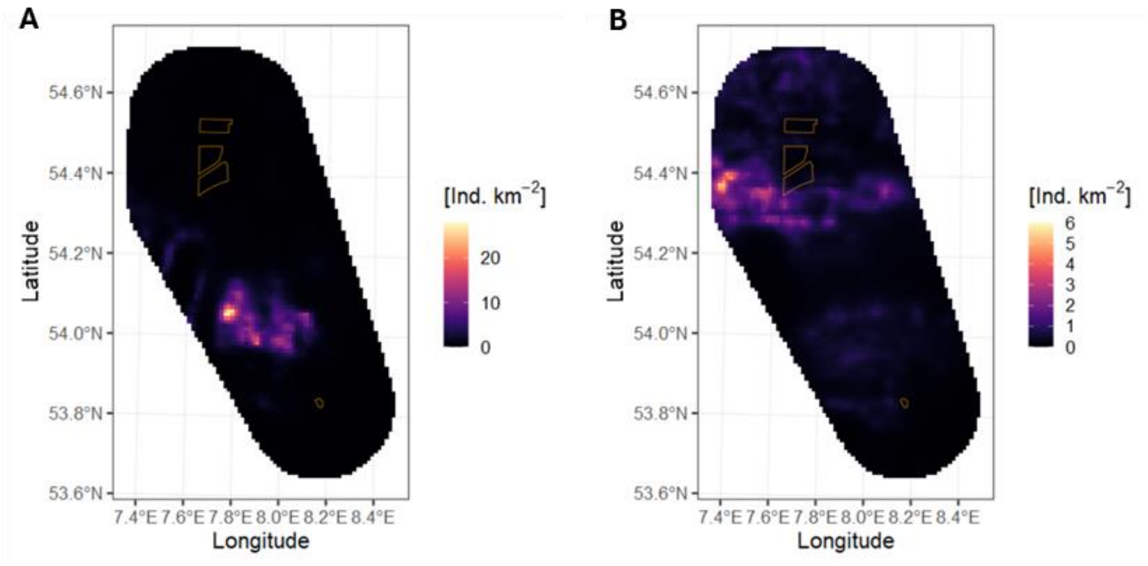

Figure A 11 *Distribution of Guillemots within region 3 "East" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.*

A.2.2.3.1.2. Razorbill

Very few Razorbills were present in region 3 in autumn (Figure A 12 A). They were recorded at the western border of the study area, located south of Helgoland and between the two OWF clusters.

In winter, the distribution of Razorbills was similar to that of Guillemots, albeit at lower densities. Razorbills were mainly found in the northern half of region 3 around the OWF cluster "Nördlich Helgoland" and also in smaller numbers in the southern part of the study area (Figure A 12 B).

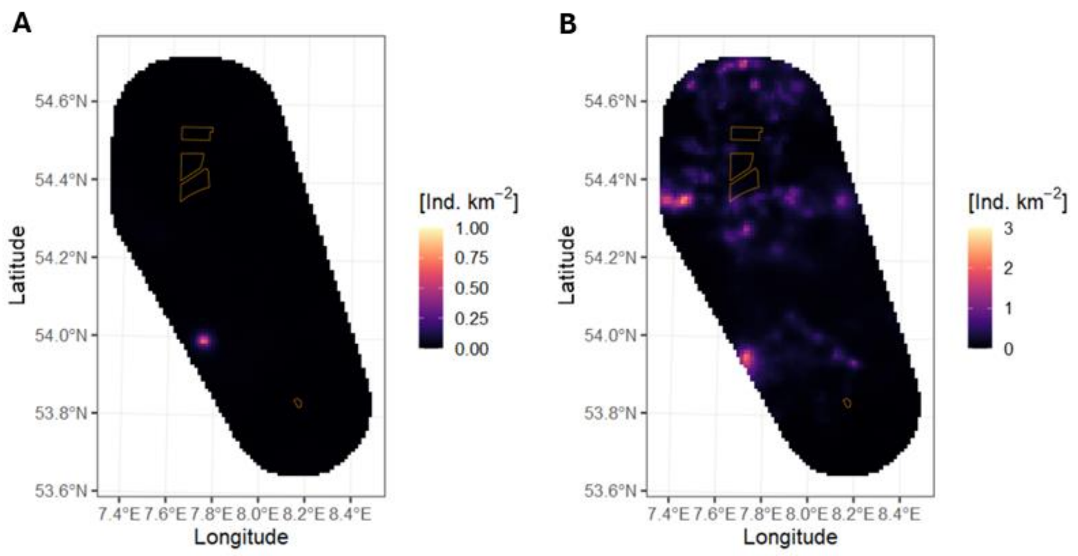

Figure A 12 *Distribution of Razorbills within region 3 "East" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.*

A.2.2.3.2. Effect radius

A.2.2.3.2.1. Guillemot

In autumn, a significant effect was apparent for Guillemots in region 3. The upper CI intersected with the mean at 6.86 km, the main curve at 11.08 km (Figure A 13 A). Therefore, the effect radius was determined between ca. 7-11 km in this area in autumn.

In winter, no significant effect was found (Figure A 13 B).

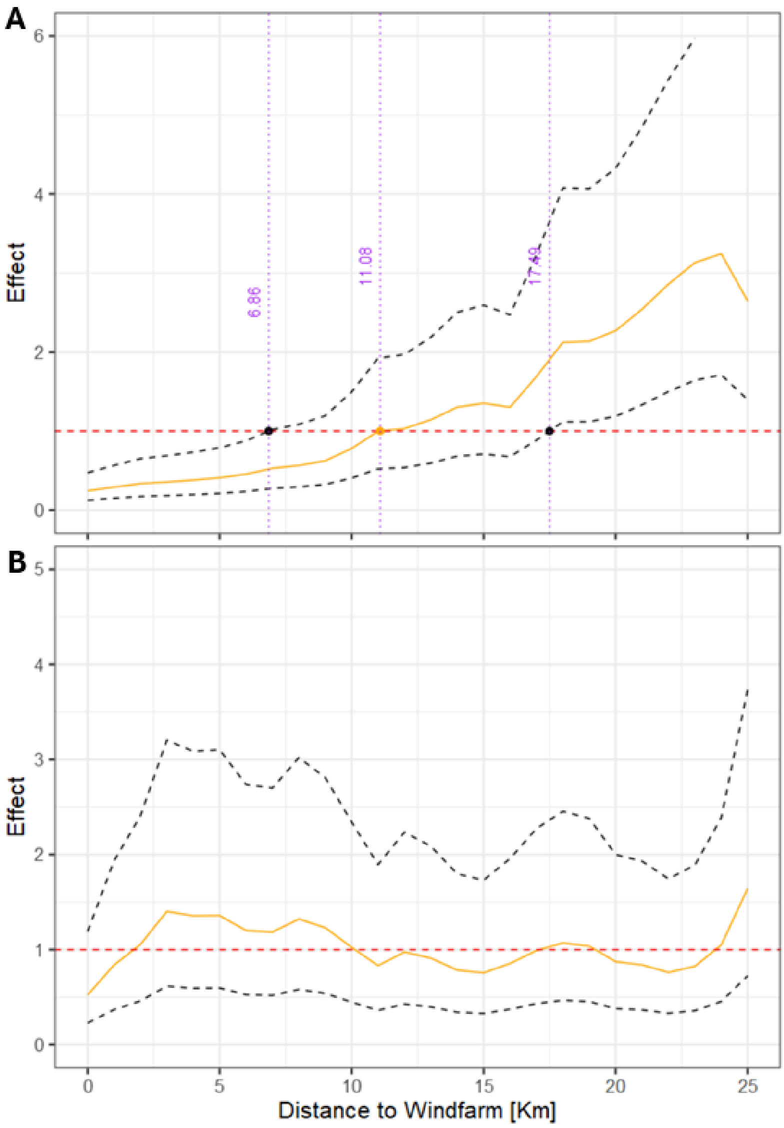

Figure A 13 Effect of distance to the OWF on relative density of Guillemots in region 3 "East" in (A) autumn and (B) winter. Note the different scales in the figures A and B.

A.2.2.3.2.2. Razorbill

For autumn, no results are presented due to a small sample size.

In winter, no significant effect was found for Razorbills in region 3 (Figure A 14). The density hovered around the mean at all distances.

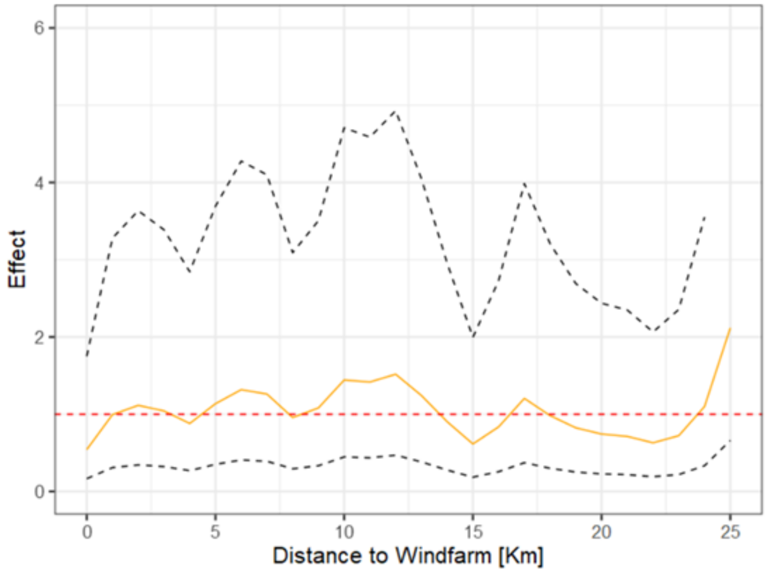

Figure A 14 Effect of distance to the OWF on relative density of Razorbills in region 3 "East" in winter.

A.2.2.4. Region 4: North

A.2.2.4.1. Spatial distribution

The OWFs "Sandbank" and "Dan Tysk" were mainly surveyed by the digital aerial technique DAISI with a lower species identification rate. About 42% of auks were identified to species level in this project. Since identification to species level in the area around Butendiek was high (ca. 76%), the distribution appeared to show far higher densities around Butendiek, which was not accurate to the actual distribution (see distribution for the species combined in chapter 5.3.4.1).

A.2.2.4.1.1. Guillemot

In autumn, Guillemots occurred in two different areas within region 4 (Figure A 15 A). There was an area with a high concentration in the west of the OWF cluster "Westlich Sylt" and a more diffuse concentration in the eastern half of the study area around the OWF "Butendiek".

In winter, the highest concentrations of Guillemots were found in the eastern half of the study area, particularly in the north-west and the south-west of the OWF "Butendiek", but also within the OWF itself (Figure A 15 B). In addition, Guillemots were recorded in far lower densities in the study area between the two parts of the OWF cluster "Westlich Sylt"/ OWFs "Sandbank" and "Dan Tysk".

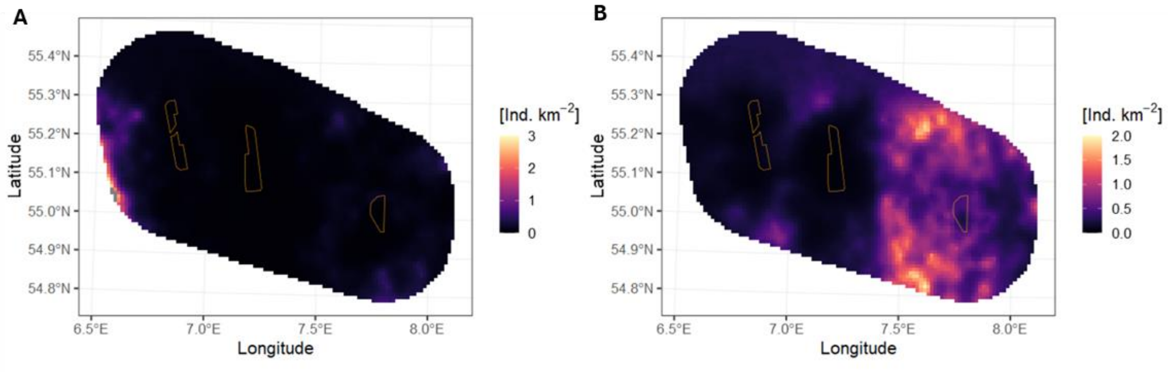

Figure A 15 Distribution of Guillemots within region 4 "North" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

A.2.2.4.1.2. Razorbill

Razorbills were only present in the eastern half of region 4 in both autumn and winter. In autumn, numbers of Razorbills were very low with records of individuals mainly east of the OWF "Butendiek" (Figure A 16 A).

In winter, Razorbills were more numerous in region 4 and showed a distribution very similar to that of the Guillemot. They were widespread in the eastern part around the OWF "Butendiek", although less so inside the OWF (Figure A 16 B). The highest densities of Razorbills were recorded in the area south of the OWF.

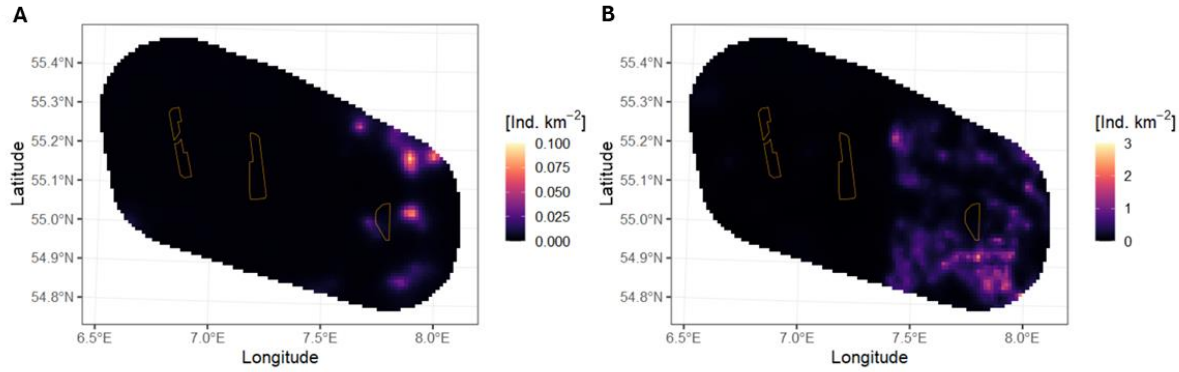

Figure A 16 Distribution of Razorbills within region 4 "North" during (A) autumn and (B) winter between 2014-2021 (only post-construction data included). Note the different scales in the figures A and B.

A.2.2.4.2. Effect radius

A.2.2.4.2.1. Guillemot

In autumn in region 4, a significant effect was observed. The upper CI intersected at 7.38 km, the main curve at 15.84 km (Figure A 17 A). This means an effect radius between ca. 7-16 km.

In winter, a significant effect was apparent only up to 0.85 km, where the upper CI intersected the mean (Figure A 17 B). The main curve, however, only crossed the mean at a distance of 10.21 km, which indicates a lower than average density of Guillemots up to that distance.

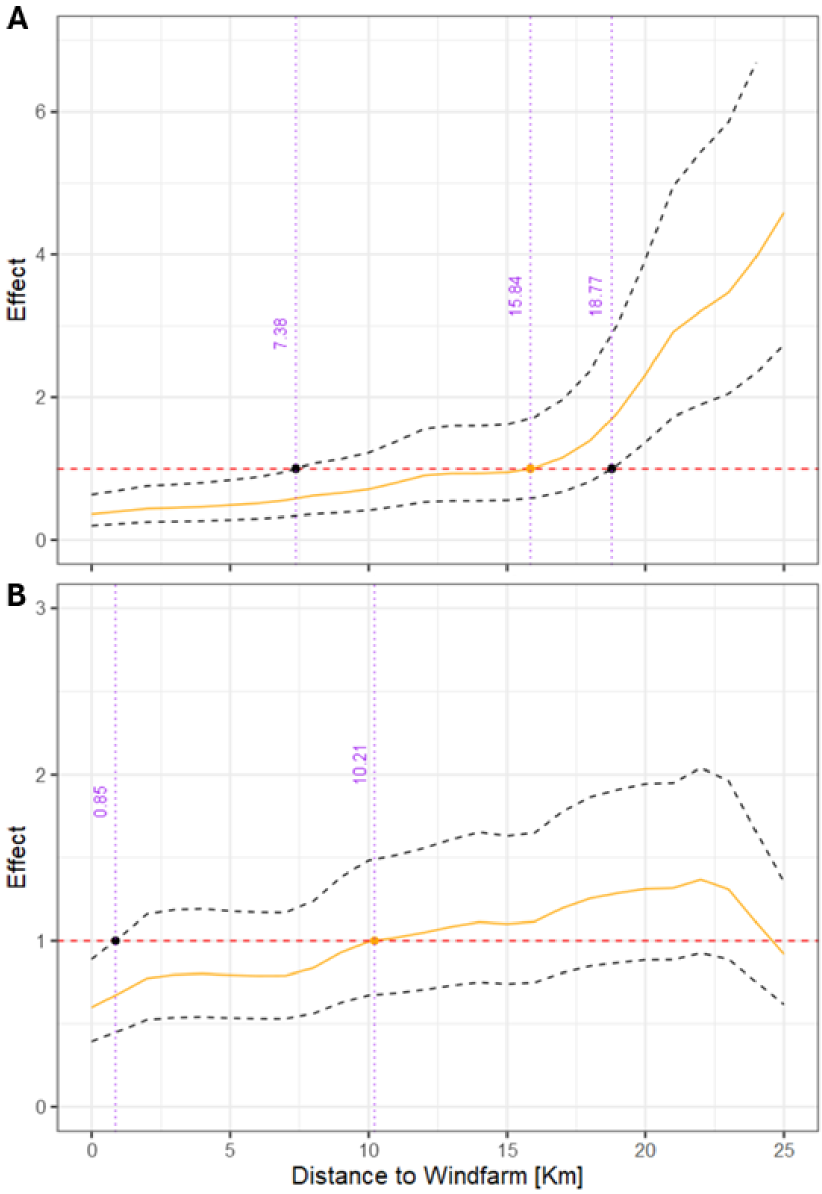

Figure A 17 Effect of distance to the OWF on relative density of Guillemots in region 4 "North" in (A) autumn and (B) winter. Note the different scales in the figures A and B.

A.2.2.4.2.2. Razorbill

For autumn, no results are presented due to a small sample size.

In winter, a significant effect was apparent up to around 2 km. The upper CI crossed the mean at 1.80 km, the main curve at 3.43 km (Figure A 18). At further distances the main curve hovers around the mean. The lower CI never crossed the mean.

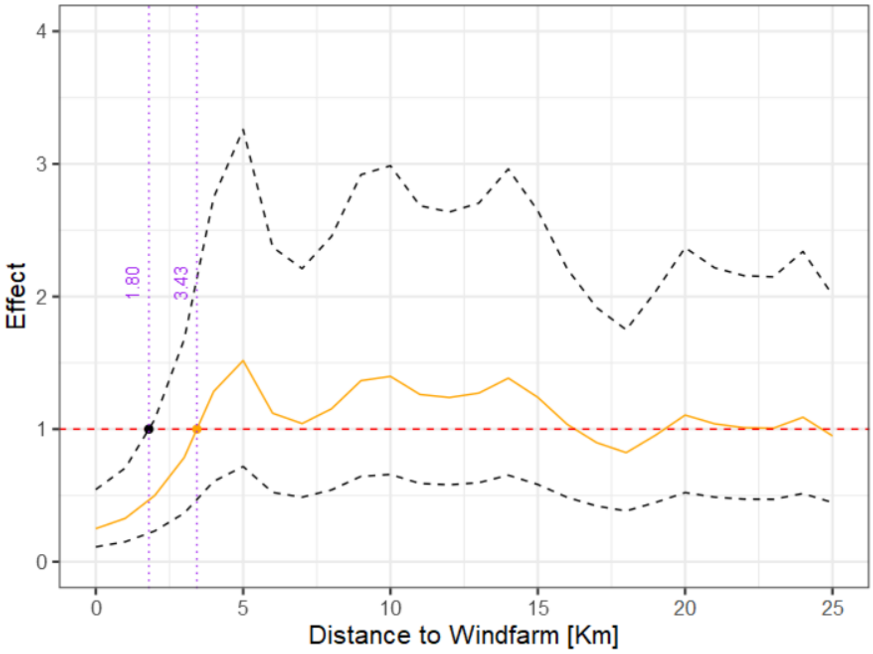

Figure A 18 Effect of distance to the OWF on relative density of Razorbills in region 4 "North" in winter.