



Wind farms in proximity to marine protected areas put conservation targets at risk

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ABSTRACT

Special Protection Areas (SPAs) are an important EU legislative tool to protect species biodiversity. Red-throated loons *Gavia stellata* and black-throated loons *G. arctica* are the key species in the designation of the SPA 'Eastern German Bight', located in the German Exclusive Economic Zone of the North Sea; however, one offshore windfarm (OWF) has been constructed within and four OWFs just outside this SPA within the last few years. The current study integrated previous findings on the strong avoidance of OWFs by loons to assess the effects of these developments on the SPA. OWFs affected on average half of the SPA. We observed a major change in the overall distribution of loons in the study area; the area with the highest densities had shifted southwest and the spatial extent of the high-density area had decreased. The northern third of the SPA, which previously often included the highest concentrations, had been almost abandoned by loons. Variability in loon distribution was significantly restricted after the OWFs became operational. These findings have important implications for the functioning of this Marine Protected Area. The construction of OWFs within the loons' foraging habitats has increasingly restricted their spatial flexibility and thus their foraging behaviour. We conclude that the establishment of OWFs inside and even adjacent to a protected area counteracts its conservation targets. Ignoring such effects may lead to a loss of such retreats for threatened species and habitats.

1. Introduction

Human activities are having increasing impacts on marine ecosystems worldwide (Halpern et al. 2019). The current study area located in the North Sea, in northwest Europe, is located in one of the most intensively used regions of the world (Halpern et al. 2008; Korpinen et al. 2021). It is impacted by virtually all global and regional developments, with human interventions dating back to around 1,000 years ago (Emeis et al. 2015). Globally acting trends include temperature and associated sea-level rises and stratification, as well as changes in the CO₂ system, while overfishing and trawling, industrial and agricultural pollution, dredging, human-induced eutrophication, construction in coastal breeding and feeding grounds, sand and gravel extraction, offshore construction, heavy shipping traffic, fisheries by-catch, visual disturbance, and the introduction of non-indigenous species represent

more direct human threats (Emeis et al. 2015; BfN 2017). In addition to these activities, there is a continuing huge increase in energy production by offshore wind energy installations (Ostend Declaration 2023).

The European Union established the Natura 2000 network of protected areas to maintain species and habitats. The only offshore Bird Protection Area in German waters, a so-called Special Protection Area (SPA), is located at the eastern border of the German Exclusive Economic Zone (EEZ). The key species in the designation of this SPA 'Eastern German Bight' are the red-throated loon *Gavia stellata* and the black-throated loon *G. arctica* (Garthe et al. 2012). Both these species use the area for wintering, but mainly use it as a spring staging area (Garthe et al. 2015; Heinänen et al. 2020; Kleinschmidt et al. 2022), before migrating to their breeding grounds towards Greenland, Svalbard, Scandinavia, and northern Siberia (Kleinschmidt et al. 2022). Both species are listed in Annex 1 of the European Birds Directive as species in

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need of special protection.

The offshore windfarm (OWF) 'Butendiek', located inside the SPA 'Eastern German Bight', as well as four other OWFs located just outside this SPA, were controversial from the outset, given that loons had already been shown to avoid OWFs over a wide area, resulting in substantial habitat loss (Petersen et al. 2006; Percival 2014). A series of studies on the spatial distribution of loons was therefore conducted in this area after installation of the OWFs, which confirmed strong avoidance of the OWFs by loons (Mendel et al. 2019; Heinänen et al. 2020; Vilela et al. 2020; Dierschke and Mercker, 2022; Garthe et al. 2023).

The presence of OWFs in and around the SPA, combined with the strong avoidance behaviour of these SPA target species, raises the question of whether the SPA can now fulfil its purpose (Garthe et al. 2023). However, it is difficult to quantify the impacts of pressures, and assessments of the degree of disturbance thus have a high level of uncertainty. In contrast, the current study utilized comprehensive datasets (OWF monitoring, biodiversity monitoring, research projects) that were collected systematically both before and after the establishment of the OWFs, thus allowing the disturbance effects to be quantified both numerically and spatially. These datasets provide an important tool and a rare opportunity to assess environmental impacts. We therefore aimed to quantify the extent to which OWFs affected the area designated for loons, as the most important species group in the SPA. We subsequently considered if the management plan for the SPA (BfN 2020), which came into force in 2020, has the potential to counteract the problem.

2. Material and methods

2.1. Study area

The study area was the German Bight in the south-eastern North Sea, Europe (Fig. 1). The German Bight hosts the SPA Eastern German Bight, comprising 3,135 km², which was designated in 2004 (BMU 2004). Since 2017, the SPA has also been protected under German law as part of the nature conservation area 'Sylter Außenriff – Östliche Deutsche Bucht' (NSGSylV, BGBl. I p. 3423), and a management plan applies to the entire protected area, including the SPA (BfN 2017, 2020). During the study period up to 2020, 22 OWFs have become operational in the German Bight (source: Bundesnetzagentur Marktstammdatenregister), five of which are located within or adjacent to the SPA (Fig. 1).

2.2. History of SPAs and OWFs in the EEZ of the German North Sea

The Natura 2000 network of protected areas was created within the framework of the Habitats and Birds Directives (EU 1992; EU, 2009), as a fundamental instrument for the protection of nature in the European Union. Some of these protected areas are marine areas located in territorial waters and in the EEZs of the Member States, and simultaneously form part of the network of Marine Protected Areas (MPA) of the Regional Sea Conventions. In this context, SPAs have been designated for seabirds according to the EU Birds Directive, covering either breeding sites or feeding and resting areas used during the breeding season and/or outside the breeding season (<https://natura2000.eea.europa.eu>).

When planning SPAs in German marine waters, the bird species to be

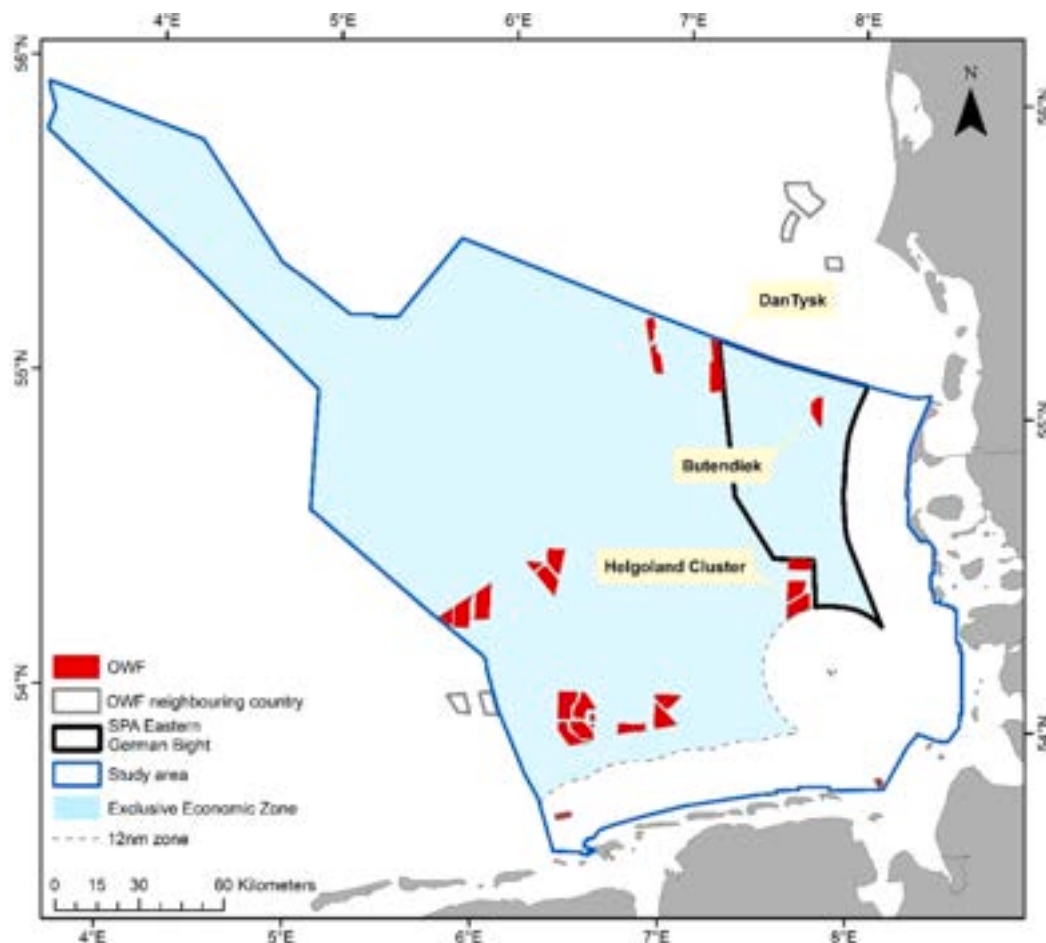


Fig. 1. Study area in the south-eastern North Sea, Europe. OWFs operating in 2020 shown (data from: BSH CONTIS Facilities: Offshore_Windfarm).

considered were first identified (Gellermann et al. 2003), and the occurrence of these species determined by ship-based (from 1990) and aerial surveys (from 2002) was then used to outline the boundaries of the proposed SPAs (Garthe 2003; Garthe et al. 2012). The SPA Eastern German Bight (DE 1011–401), the only SPA in the German EEZ of the North Sea, was notified to the European Commission in 2004. Creation of this SPA means that appropriate measures must be taken to avoid habitat degradation and disturbance of these birds.

However, at the same time as SPAs were being created, planning for OWFs in the German North Sea started, with the first OWF in German waters being built and starting operation in 2009. The further expansion of wind-energy generation led to the construction of the “Butendiek” OWF, with 80 wind turbines covering an area of 33 km² in the middle of the SPA Eastern German Bight, becoming operational in 2015.

2.3. Seabird responses to OWFs

Previous studies have gathered data on the displacement effects of OWFs on loons (Mendel et al. 2019; Heinänen et al. 2020; Vilela et al. 2020; Garthe et al. 2023), and no new analysis of this effect was therefore performed in this study. We calculated the area of the SPA Eastern German Bight affected by displacement effects, based on the distances calculated in these previous studies. Affected areas were considered to be areas where loon abundances were significantly reduced.

2.4. Seabird distribution

We analysed the distribution of loons in the study area, based on a 21-year data series including all available data for the entire German Bight for the spring period (1 March – 30 April) from 2000 to 2020. These data were gathered from environmental impact studies, monitoring during the construction and operation of wind farms, the German Biodiversity Monitoring Programme, and research projects. All loon data were analysed jointly, not separated by species (red-throated loons make up > 90 % of the sightings, Garthe et al. 2015). The survey data were collected and prepared (e.g., spatial pooling of data and distance-related detection correction) as described by Garthe et al. (2023). This included the harmonization and combination of data from different counting platforms (ship, aircraft, digital aerial surveys) for joint analysis.

The generation of spatial distribution plots was based on 2-year data blocks to ensure high temporal resolution and spatial coverage. We used appropriate regression-based approaches, namely generalized additive models (GAMs) (Garthe et al., 2023; Mercker et al., 2021) using the R-package *mgcv* (Wood, 2015). In particular, as (fixed-effect) predictors, we used a spatial 2d smooth based on geographical coordinates, smooths dependent on water depth and the nearest distance to the coastline, and two detection-related categorical variables considering the survey method (observer-based ship and aerial surveys and digital-based surveys) and sea state, respectively. OWF locations were not provided to the model, to guarantee an objective approach with respect to the spatial patterns interpreted in the light of OWF locations. We used a negative-binomial probability distribution to account for overdispersion in the data (Linden and Maentyniemi, 2011). GAMs were fitted separately to pooled survey data with respect to 2-year blocks. Years with sparse data or major OWF construction activities were omitted. For each separate GAM fit, the optimal amount of smoothness was determined for each nonlinear predictor based on generalized cross-validation methods (Wood, 2017). Loon densities were finally predicted based on the methods of Garthe et al. (2023) and Mercker et al. (2021).

To quantify the spatial variability between subsequent 2-year blocks, we calculated a distance measure between corresponding spatial patterns. We first normalized the predicted abundances for each 2-year block by dividing them by the mean value, and then summed the pointwise differences in rescaled abundance for each two consecutive

blocks, calculating the difference for each pixel. We thus obtained a time series of summed differences in spatial pixels (SumS), which we then normalized for a better interpretation to the first calculated SumS value in the time series (years 2002–2003 vs. 2004–2005). Hence, the SumS values quantified the strength of change between spatial patterns between two consecutive year blocks relative to the strength of change in 2002–2003 vs. 2004–2005.

3. Results

Disturbance effects by OWFs on loons were shown to affect huge proportions of the SPA Eastern German Bight, ranging from more than a third to around two thirds of the SPA, depending on which disturbance distance was used (Table 1, Fig. 2). On average, half of the SPA was affected, with approximately half of this affected area impacted by the four wind farms located entirely outside the SPA (Table 1, Fig. 2).

We observed a major change in the overall distribution of loons in the study area (Fig. 3). The core distribution shifted to some degree in the five 2-year periods before the establishment of the OWFs, and remained almost identical in the three 2-year periods after OWF operations commenced. Furthermore, the area with the highest densities shifted southwest and the spatial extent of the high-density area decreased. The northern third of the SPA, which had often exhibited the highest concentrations, has been almost completely abandoned by loons (Fig. 3). The spatial variability between subsequent 2-year periods varied over time (Fig. 4). The two lowest values coincided with the operational stage of the OWFs, while spatial variability was higher in all five periods before establishment of the OWFs, and much higher in four cases (Fig. 4).

4. Discussion

The results of this study show that huge proportions of the SPA Eastern German Bight were affected by displacement effects caused by OWFs located both inside and outside the SPA. The extremely low abundances of loons within and close to OWFs (Mendel et al. 2019; Heinänen et al. 2020; Garthe et al. 2023) indicate massive habitat loss, as well as re-distribution of these birds. Analysis of 6 years' of post-construction data showed that this re-distribution was not just a short-term effect, and there are currently no signs of habituation effects to reduce the spatial extent of the disturbance. This re-distribution results in concentrations of birds in the areas furthest away from any OWF, leading to reduced spatial flexibility: before the establishment of the OWFs, loons were able to use different local hotspots, whereas they are now largely restricted to OWF-free zones. This coincides with a partial retreat of the birds from the SPA.

These findings have important implications for the functioning of this MPA. During their spring aggregation in the study area, loons occupy a zone between low-salinity coastal and higher-salinity marine waters, which is highly variable in location and extent (Skov & Prins 2001; Heinänen et al. 2020). Loons require wide undisturbed foraging areas to allow them to exploit their highly mobile prey of benthic-pelagic schooling fish (Kleinschmidt et al. 2019) in this spatially dynamic water zone. It is plausible that fish abundance increases in OWFs, at least in most species, due to new habitat structures and reduced fishing pressure (e.g. Gill & Wilhelmsson 2019), and this may offer better feeding opportunities to piscivorous bird species. However, the construction of OWFs in their foraging habitats increasingly restricts their spatial flexibility and thus their foraging behaviour. Thus, loons would not be able to take advantage of these changes inside/near OWFs because they do not approach these possibly food-rich sites due to their avoidance of OWF. Displacement by OWFs and the consequent spatial restrictions may thus have energetic consequences, e.g., birds may aggregate at higher densities than before OWF construction, potentially impacting their efficient prey exploitation (Thompson et al. 2023). Furthermore, loons may use marine areas less protected or not protected at all,

Table 1

Area within the SPA Eastern German Bight (total area 3,135 km²) affected by the five operating wind farms, based on different disturbance distances impacting loon abundance. Construction periods of turbines taken from Bundesnetzagentur Marktstammdatenregister.

Disturbance distance (km)	Wind farm (construction period of turbines)							Method	Reference	
	Dan Tysk (1 OWF; April 2014 – August 2014)		Butendiek (1 OWF; September 2014 – June 2015)		Helgoland cluster (3 OWFs; July 2013 –September 2015)		Total			
	Area affected within SPA (km ²) – proportion of SPA (%)									
	km ²	%	km ²	%	km ²	%	km ²			%
10.2	233.9	7.5	593.1	18.9	381.6	12.2	1208.6	38.6	Aerial and digital surveys	Vilela et al. (2020)
10.5 (9–12)	242.6	7.7	614.7	19.6	397.4	12.7	1254.7	40.0	Aerial, digital, and ship-based surveys	Garthe et al. (2023)
12.5 (10–15)	303.2	9.7	749.5	23.9	507.5	16.2	1560.3	49.8	Satellite tracking	Heinänen et al. (2020)
16	419.5	13.4	967.8	30.9	698.6	22.3	2085.9	66.5	Aerial, digital, and ship-based surveys	Mendel et al. (2019)
Mean	299.8	9.6	731.3	23.3	496.3	15.8	1527.4	48.7	Above-mentioned studies	

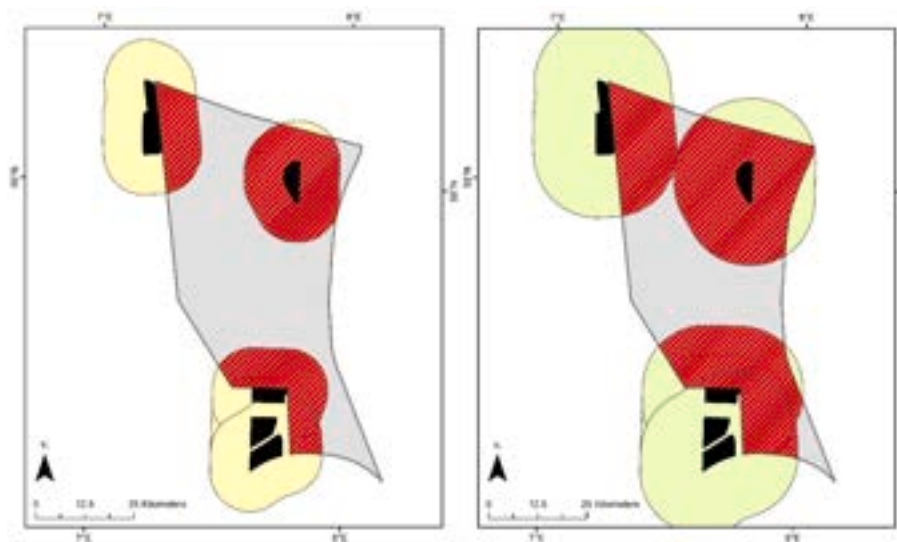


Fig. 2. Locations of five operating wind farms in relation to the SPA (grey colour) and areas around the wind farms within which loon abundance is significantly impacted (yellow/green: outside SPA, red: inside SPA). Figure shows effects for 10.2 km (left) and 16.0 km buffers (right), according to the minimum and maximum disturbance distances shown in [Table 1](#). For larger-scale map see [Fig. 1](#).

exposing them to likely higher disturbance and possibly causing additional energy expenditure and decreased energy intake. Such negative effects on the energy budget may lead to poorer body condition, which may in turn prohibit migration, reduce breeding success (e.g., due to arrival in insufficient body condition), and may even result in death (e.g., [Ebbinge & Spaans 1995](#)). These changes could reduce the overall annual survival and productivity of the population, leading to decreased population growth ([Dierschke et al. 2017](#)).

OWFs located inside or at the boundary of the SPA Eastern German Bight may also have other effects. Displacement effects of OWFs can also be verified for the most important seabird species breeding on Helgoland, the only seabird cliff in the study area, located in the coastal SPA 'Helgoländer Bucht'. Although these displacement effects during the breeding season are not as strong as for loons in spring, they can still affect the distributions of common murres *Uria aalge*, northern gannets *Morus bassanus*, and black-legged kittiwakes *Rissa tridactyla* ([Peschko et al., 2020a; Peschko et al., 2020b; Peschko et al., 2021](#)), all of which are listed as important species in the SPA 'Eastern German Bight'. Notably, OWFs in the Helgoland cluster in the south of the SPA may act as a barrier for commuting breeding birds, counteracting the connectivity of protected areas as required by the EU Birds Directive.

Protected areas are currently more important than ever, given that most, if not all shallow marine waters in the south-eastern North Sea

outside MPAs and shipping lanes are being occupied by OWFs, thus losing their function as important foraging and resting habitats for sensitive seabird species. The directive designating the protected area addressed in this study under national law (Verordnung über die Festsetzung des Naturschutzgebietes "Sylter Außenriff – Östliche Deutsche Bucht", September 2017) defines conservation targets. They include the preservation or, where necessary, the restoration of a favourable conservation status for loons (and other seabird species) and their habitats and food base, as well as the maintenance of non-fragmented habitats and connectivity with surrounding marine areas. As noted above, the effects of OWFs are currently challenging these conditions, and this human activity thus represents an obstacle to achieving these conservation targets. Although any disturbance, damage, or change to the protected area and its components is not allowed in principle, there are noteworthy allowances for human activities that existed prior to the establishment of the protection act, e.g., fishing, shipping, and military training. There is thus a management plan ([BfN 2020](#)) that specifically addresses activities that might conflict with the conservation targets, including fishing regulations for a large part of the protected area starting in 2023. Nature conservation NGOs have complained about the construction of OWFs, as the predominant threat to loons, especially in the protected area, and legal procedures have resulted in a precautionary application for an exemption for the operation of OWFs by the

BEFORE OWF CONSTRUCTION

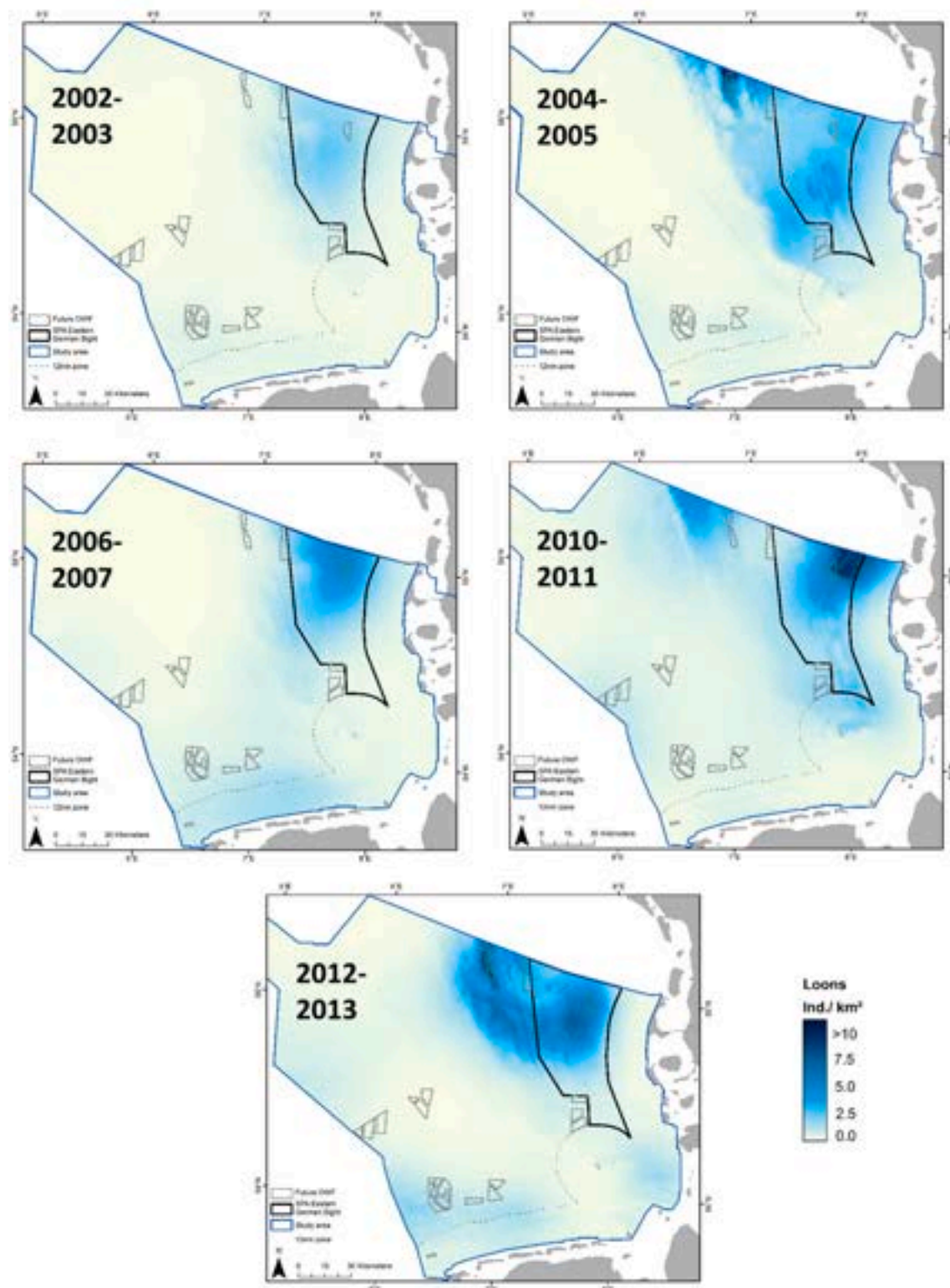


Fig. 3. Distribution of loons in the south-eastern North Sea during different 2-year periods in March and April over the last 20 years, separated into phases before and after construction of OWFs. Years with sparse data and years with major OWF construction activities were omitted.

AFTER OWF CONSTRUCTION

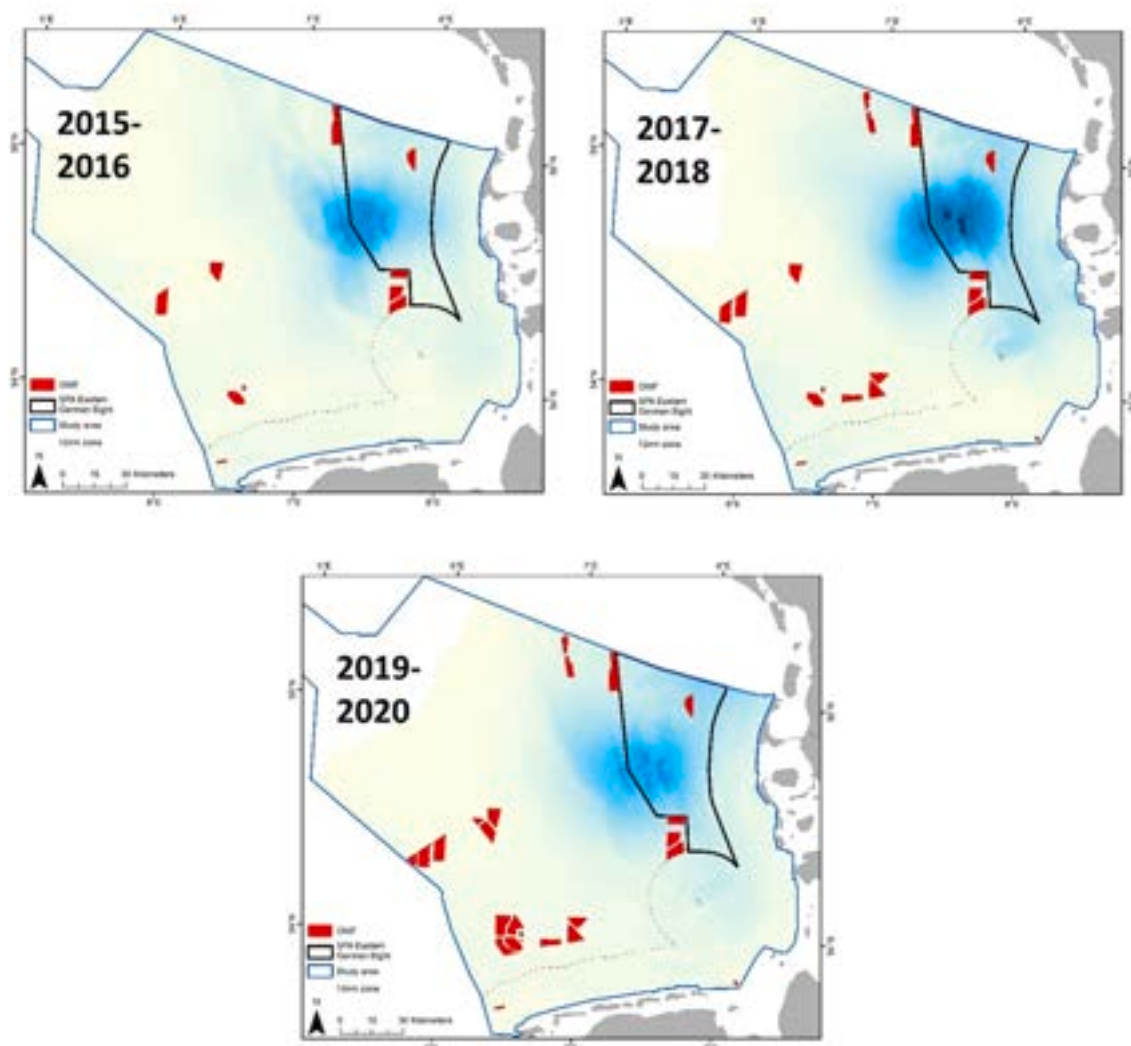


Fig. 3. (continued).

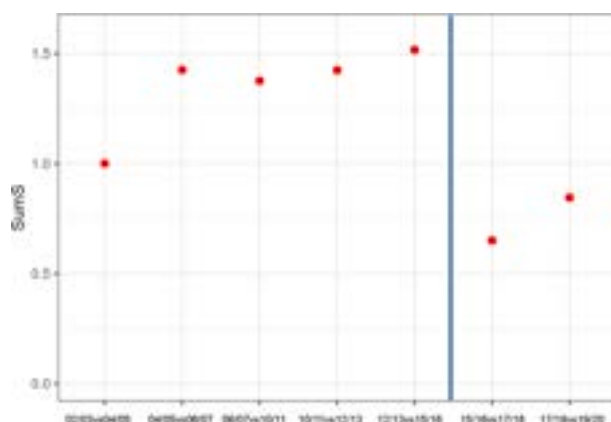


Fig. 4. Spatial variability between subsequent distribution patterns shown in Fig. 3. SumS on Y-axis corresponds to sum of pointwise differences between distribution patterns of 2-year blocks plotted on X-axis: a higher value on the X-axis indicates greater difference in loon distributions. Vertical blue line indicates time when OWFs became operational. Years with sparse data were excluded.

operator, which was confirmed by the responsible nature conservation authority under the condition that the impact would be compensated for by an extension of the protected area for loons. Notably however, the compensation area has not yet been legally secured and will primarily help to prevent future impacts.

In conclusion, the current studies demonstrated that the establishment of wind farms inside and adjacent to an MPA may counteract its conservation targets. Ignoring such effects may lead to a loss of retreats for threatened species and habitats.

CRediT authorship contribution statement

Stefan Garthe: Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Henriette Schwemmer:** Writing – review & editing, Visualization, Validation, Project administration, Data curation. **Moritz Mercker:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Volker Dierschke:** Writing – original draft, Validation. **Nele Markones:** Writing – review & editing, Validation, Project administration, Funding acquisition. **Verena Peschko:** Writing – review & editing, Validation, Project administration, Funding acquisition. **Philipp Schwemmer:** Writing – review &

editing, Validation. **Jochen C. Krause:** Writing – review & editing, Validation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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