Final Report

Divers (Gavia spp.) in the German North Sea: Recent Changes in Abundance and Effects of Offshore Wind Farms

A follow-up study into diver abundance and distribution based on aerial survey data in the German North Sea

Version v1.0

Husum, August 2022

Prepared for Bundesverband der Windparkbetreiber Offshore (BWO) e.V.

Divers (*Gavia spp.*) in the German North Sea: Recent Changes in Abundance and Effects of Offshore Wind Farms

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Funding partners:

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2. Ørsted Wind Power Germany GmbH
3. OWP Butendiek GmbH & Co. KG
4. OWP Nordergründe GmbH & Co. KG
5. Vattenfall Europe Windkraft GmbH
6. WindMW GmbH
7. IBERDROLA Renovables Deutschland GmbH
8. RWE Renewables GmbH
9. BWO e.V.

Scientific partners:

10. Dan Tysk Sandbank Offshore Wind GmbH & Co. KG
11. Northland Deutsche Bucht GmbH
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1 SUMMARY

The German North Sea is an important wintering and spring staging habitat for the two diver species, red-throated (*Gavia stellata*) and black-throated diver (*Gavia arctica*). Due to continued expansion of offshore renewable energy and current plans to achieve climate neutrality in Germany by 2045, there are serious concerns for the protection and preservation of these species.

A previous study (BioConsult SH et al. 2020) examined the effects of offshore wind farms on population size, distribution, as well as displacement effects in the German North Sea. The analysis was based on a unique large-scale and long-term dataset (16 years for spring) of aerial surveys. This is the follow-up study, with an additional 3 years of data from 10 wind farm projects, leading to a 21-year study period with 19 years of data for spring.

The two main aims of this study were

1. Estimate and analyse trends in the diver population in spring in the study area of the German North Sea as well as sub-areas (north, south, main concentration area and SPA "Eastern German Bight")

2. Visualise and analyse potential changes in diver distribution over the last 21 years, before and after the expansion of OWF in the German North Sea.

We found that the spring abundance of divers fluctuated between years without any trend and population numbers were stable between 2001 and 2021. There appeared to be no connection between the abundance of divers in spring each year and the number of wind turbines in the German North Sea in the study period. This was true for the area as a whole as well as each sub-area. An average of 14,442 divers were estimated as the spring abundance in the study area of the German North Sea. Within this area, the northern part, which includes the main concentration area for divers (BMU 2009) as well as the SPA "Eastern German Bight", accounts for ca. 60% of the total spring population. The southern area of the German North Sea generally saw much lower densities over the study period, but two years of higher density coincided with the start of OWF development in the area. Since then, the estimated abundance has remained at a slightly lower but stable level in that area than before OWF expansion.

Unlike the population numbers, the spatial distribution of divers within the study area of the German North Sea does seem to have changed after the expansion of offshore wind farms (OWF). Within the northern part and specifically in the main concentration area, the highest density hotspot would vary considerably between the years before construction of the first OWF, showing a wide-ranging use of the habitat. After the expansion of OWF, a much less variable distribution of divers was apparent, with concentrations relatively consistently in a central area of the main concentration area at a distance to existing OWF.

Results of the current study are in line with the results from the earlier study. Overall, population estimates are slightly lower, which is due to modelling uncertainties, but the annual fluctuations and distribution patterns remained similar after inclusion of the additional data. The three additional years showed a continuation of the stable population size and reduced variability in spatial distribution that was observed in the first diver study (BioConsult SH et al. 2020).

The results confirm that there is no decrease in the spring population of divers in the study area of the German North Sea and that abundances within the main concentration area as well as the SPA "Eastern German Bight" has remained stable. The importance of the main concentration area for resting divers during migration is once again confirmed by the consistently high densities in the area in spring.

2 ZUSAMMENFASSUNG

Die deutsche Nordsee ist ein wichtiges Überwinterungs- und Durchzugshabitat für die beiden Seetaucherarten Sterntaucher (*Gavia stellata*) und Prachttaucher (*Gavia arctica*). Aufgrund der fortschreitenden Entwicklung der Offshore-Windenergie und den aktuellen Plänen bis 2045 die Klimaneutralität zu erreichen, ergeben sich mögliche Konflikte mit dem Erhalt dieser beiden Arten.

Eine frühere Studie (BioConsult SH et al. 2020) untersuchte die Effekte der Offshore-Windparks auf die Populationsgröße, die räumliche Verteilung sowie Meideeffekte in der deutschen Nordsee. Die Analyse basierte auf Flugtransekt-Erfassungen, welche großräumig über die Nordsee verteilt stattfanden und insgesamt 16 Frühjahre abdeckte. Dies ist die Folgestudie, in der drei zusätzliche Jahre mit Daten aus 10 OWP-Projekten ausgewertet werden. Insgesamt stehen für diese Studie über einen Zeitraum von 21 Jahren Daten aus 19 Frühjahren zur Verfügung.

Die beiden Hauptziele dieser Studie waren

1. Die Kalkulation der Seetaucher-Population und Analyse von Trends im Frühjahr im Untersuchungsgebiet der deutschen Nordsee, sowie von Teilgebieten (Nord, Süd, Seetaucher-Hauptkonzentrationsgebiet und dem SPA "Östliche Deutsche Bucht")

2. Die Visualisierung und Analyse der räumlichen Verteilung der Seetaucher über die vergangenen 21 Jahre, vor und nach dem Ausbau der Windkraft in der deutschen Nordsee.

Die Seetaucher-Bestände im Frühjahr fluktuierte zwischen den Jahren ohne Trend und die Populationsgröße war zwischen 2001 und 2021 stabil. Es zeigte sich kein Zusammenhang zwischen dem Bestand der Seetaucher im Frühjahr der einzelnen Jahre und der Anzahl von Windenergieanlagen in der deutschen Nordsee im erfassten Zeitraum. Dies zeigte sich sowohl in der gesamten Fläche als auch in jedem der Teilgebiete. Im Durchschnitt wurde eine Frühjahrspopulation für das Untersuchungsgebiet der deutschen Nordsee von 14.442 Seetaucher-Individuen ermittelt. Hiervon befanden sich ca. 60 % im nördlichen Teilgebiet, in dem auch das Seetaucher-Hauptkonzentrationsgebiet (BMU 2009) und das SPA "Östliche Deutsche Bucht" liegen. Im südlichen Teilgebiet wurden generell deutlich geringere Dichten nachgewiesen. Es zeigten sich zwei Jahre mit höheren Dichten, die jedoch mit dem Beginn des OWP-Ausbau im Gebiet zeitlich zusammenfielen. Seitdem liegt der ermittelte Bestand im Gebiet auf einem leicht geringerem, aber stabilen Niveau.

Anders als die Populationsgröße zeigte die räumliche Verteilung der Seetaucher in der deutschen Nordsee eine Veränderung nach dem Ausbau der OWP. Im nördlichen Teilgebiet, und hier speziell im Hauptkonzentrationsgebiet, bewegte sich jedes Jahr ein Konzentrationspunkt der höchsten Dichte weitläufig über die gesamte Fläche des Gebietes, bevor hier die ersten OWP errichtet wurden. Nach dem Ausbau im Gebiet zeigte sich eine weit weniger weitläufige Verteilung und der Konzentrationspunkt blieb relativ konstant im Zentrum des Hauptkonzentrationsgebietes, mit Abstand zu den OWP.

Die Ergebnisse der Folgestudie stimmen mit denen der ersten Studie weitgehend überein. Insgesamt sind die ermittelten Populationsgrößen etwas geringer, jedoch im Rahmen der vom Modell geschätzten Unsicherheiten. Die jährlichen Fluktuationen und räumliche Verteilung blieben auch nach der Datenerweiterung sehr ähnlich. Die drei zusätzlichen Erfassungsjahre zeigten eine Fortführung des stabilen Bestandes trotz einer reduzierten Raumnutzung, die bereits in der ersten Studie festgestellt wurde.

Damit bestätigen die Ergebnisse, dass der Frühjahrs-Bestand der Seetaucher im Untersuchungsgebiet der deutschen Nordsee nicht abnimmt und die Bestände innerhalb des Hauptkonzentrationsgebietes sowie des SPA „Östliche Deutsche Bucht" stabil sind. Die Bedeutung des Hauptkonzentrationsgebietes für auf dem Zug rastende Seetaucher wurde durch die beständig hohen Frühjahrs-Dichten im Gebiet erneut bestätigt.

3 INTRODUCTION

In a report in 2020, the effects of large-scale offshore wind farm developments in the German North Sea on the population of two protected diver species, red-throated diver (*Gavia stellata*) and black-throated diver (*Gavia arctica*), were investigated with regard to displacement effects and changes in population size (BioConsult SH et al. 2020). The analysis was based on a unique large-scale and long-term dataset of aerial surveys which were mostly collected as part of the mandatory monitoring programs for German offshore wind farms and spanned a total of 17 years (with data of 16 spring seasons). This report is a follow-up study, regarding an additional 3 years of data from 10 wind farm projects.

Due to ongoing national efforts to increase the proportion of renewable energies (EEG 2014), the number of offshore wind farms in the German North Sea has increased markedly since the installation of the first German offshore wind farm alpha ventus in 2009, consisting of 12 turbines with a capacity of 5 MW. By early 2022, there were a total of 1,268 wind turbines erected with a further 204 turbines currently under construction or planned, some with capacities exceeding 8 MW [1]. Under the current government's plans to achieve climate neutrality by 2045, a total of 70 GW is planned to come from offshore wind (current capacity: ca. 7.7 GW).

As the planned number and size of offshore wind farms will cover a significant proportion of the German North Sea area (BSH 2021), there are concerns about the possible impacts on bird populations that rely on the area as their resting or migratory habitat. Several seabird species have been found to show displacement due to the visual and acoustic disturbance of unfamiliar land-like structures, rotor movements and increased ship traffic, resulting in habitat loss (e.g. Bailey et al. 2014, Dierschke et al. 2016, Cook et al. 2018). Species that do not avoid the wind farms can be subject to mortality due to collision with turbines (e.g. Desholm & Kahlert 2005, Krijgsveld et al. 2009, Band 2012, Hill 2012, Johnston et al. 2014, Hüppop et al. 2016).

One of the seabird groups most sensitive to disturbance in the North Sea are members of the diver family (e.g. Dierschke et al. 2012, 2016, Allen et al. 2020, Heinänen et al. 2020). The two diver species that most commonly occur in this area, red-throated diver and black-throated diver, are subject to special conservation measures under German and EU law. Both diver species are listed in Annex I of the EU Birds Directive (Europäisches Parlament und Rat der Europäischen Union 2013) as species of special conservation concern, as well as in the Agreement on the Conservation of African-Eurasian Migratory Waterbirds (UNEP / AEWA Secretariat 2016). A Special Protection Area and bird reserve (SPA Östliche Deutsche Bucht) was established within the European Natura 2000 network in the Eastern part of the German Bight where divers show their highest density (BMUB 2017). However, and despite a globally decreasing population trend, the species are not threatened on a global scale due to a wide distribution and large populations in some areas (BirdLife International 2017, 2018a, 2018b).

Divers have long been known to exhibit early displacement behaviour due to ship traffic (Bellebaum et al. 2006, Fliessbach et al. 2019) and areas of high human activity consistently show lower

[1] BSH: https://www.bsh.de/DE/THEMEN/Offshore/Offshore-Vorhaben/Windparks/windparks_node.html (accessed: 14.03.2022)

densities (Schwemmer et al. 2011, Burger et al. 2019). Similarly, divers show strong displacement behaviour towards wind farms. The previous diver study (BioConsult SH et al. 2020) estimated a displacement distance of 10.2 km in spring. Other recent studies came to similar conclusions (Webb et al. 2015, Heinänen 2016, Garthe et al. 2018, Heinänen et al. 2020), while Mendel et al. (2019) estimated an effect range of up to 16 km as evaluated from the post-construction period of the dataset but also including the effects of ship traffic.

The highest numbers of individuals of both species occur during spring migration (Mendel et al. 2008). Divers that migrate through the German Bight belong to the North-west European wintering population. The European winter population consists of an estimated 90,000 red-throated divers and around 31,250 black-throated divers (BirdLife International 2004), of which an estimated 18% and 6% respectively cross the German North Sea during spring migration (Dierschke et al. 2012). The German North Sea diver population was estimated at ca. 20,000 individuals for the period of 2002-2013 (Garthe et al. 2015) and more recently at ca. 35,000 individuals for the period before and ca. 25,000 individuals for the period after offshore wind farm development in the area (Garthe et al. 2018). A trend analysis estimated population sizes of red-throated diver in the German North Sea of between 3,200 and 31,000 individuals from 2002 to 2017 with a decreasing trend since 2013 (Schwemmer et al. 2019). The analysis conducted in the previous diver study estimated an average abundance of 16,500 divers (range: 8,835 - 21,994) and no declining trend for the study area of the German North Sea (BioConsult SH et al. 2020).

Based on the same Bayesian spatial modelling method as was used in the previous analysis and with additional data of 3 years from 10 wind farm projects, the following aspects are examined:

1. Calculating reliable estimates of diver population size in spring over a 21-year study period (with 19 years of data for the spring period) for the study area of the German North Sea as well as for a northern and a southern sub-area, the main concentration area and the SPA “Eastern German Bight”
2. Investigation of the spatial distribution of divers in relation to the location of offshore wind farms in spring, considering possible local (north/south) differences.

4 METHODS

4.1 Data

The updated analysis was based on the same database as the first diver study (BioConsult SH et al. 2020) as well as an additional three years. Thus, the data set comprised aerial survey data for spring in the German North Sea from between 2001 and 2021, with the exception of the years 2006 and 2007, where no data was available for spring. All surveys included in the present study took place between 1.3. - 15.5. of each year which corresponds with the species-specific season "spring" as defined by Garthe et al. (2007). The survey flights were carried out on different dates, depending on the weather, so the amount of effort behind each spring season may vary. In total, 262 days of aerial surveys were available.

Out of these, 123 surveys were conducted as conventional (visual) surveys and 139 surveys were conducted as digital flights. In total, 171,419 divers were observed during all surveys. Data sources comprised data from wind farm monitoring (~ 80%), Natura2000 Monitoring (FTZ, 15%), research projects (~ 5%) and other sources (< 5%). Details about specific projects can be found in the appendix (A.1). In total 19 years of data were available for spring.

Since the identification on species level for red- and black-throated divers is often not possible using aerial (digital and visual) surveys, all diver individuals of these two species were included equally in the analysis. However, according to previous studies (e.g. Mendel et al. 2008, Garthe et al. 2015) as well as the wind farm monitoring projects it is known that the majority of divers (~ 90%) in this area are red-throated divers (*Gavia stellata*).

4.2 Study Area Wind Farm Projects

The study area covered most of the German North Sea, including coastal waters as well as the Exclusive Economic Zone (EEZ). The Special Protected Area (SPA; DE 1011-401) “Eastern German Bight” covering 3,100 km^2 is of high importance for divers. Additionally, a main concentration area of divers has been defined, covering 7,000 km^2 (BMU 2009), which largely overlaps with the SPA. This area was defined by BMU (2009) based on an analysis including data between 2000 and 2006 (Garthe et al. 2007). The study area as well as protected areas are shown in Figure 4.1.

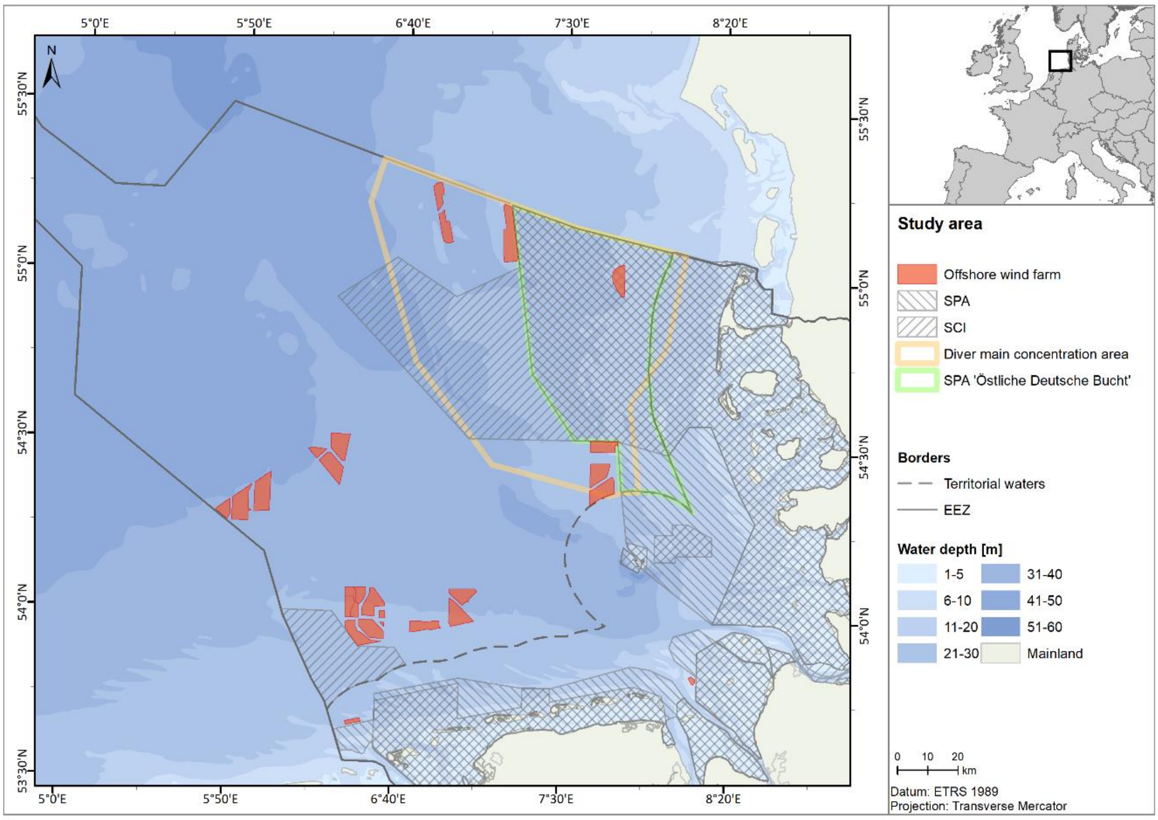

Figure 4.1 *Overview of the study area, with EEZ and protected areas, including diver main concentration area and SPA "Eastern German Bight".*

*Table 4-1	Data coverage in all years (spring only).*

Year	Area covered in spring
2001	16 %
2002	19 %
2003	35 %
2004	52 %
2005	17 %
2008	89 %
2009	50 %
2010	99 %
2011	88 %
2012	91 %
2013	72 %
2014	93 %
2015	92 %
2016	97 %
2017	83 %
2018	87 %
2019	100 %
2020	95 %
2021	69 %

Data coverage for the study area varied between time periods (Table 4-1, Figure 4.2). The year of maximal coverage was defined as 100%. For the early years, 2001 to 2005, coverage was low to medium. No data was available for spring in the years 2006 and 2007. For the years 2008 to 2021, coverage was medium to very high (up to 100% in 2019).

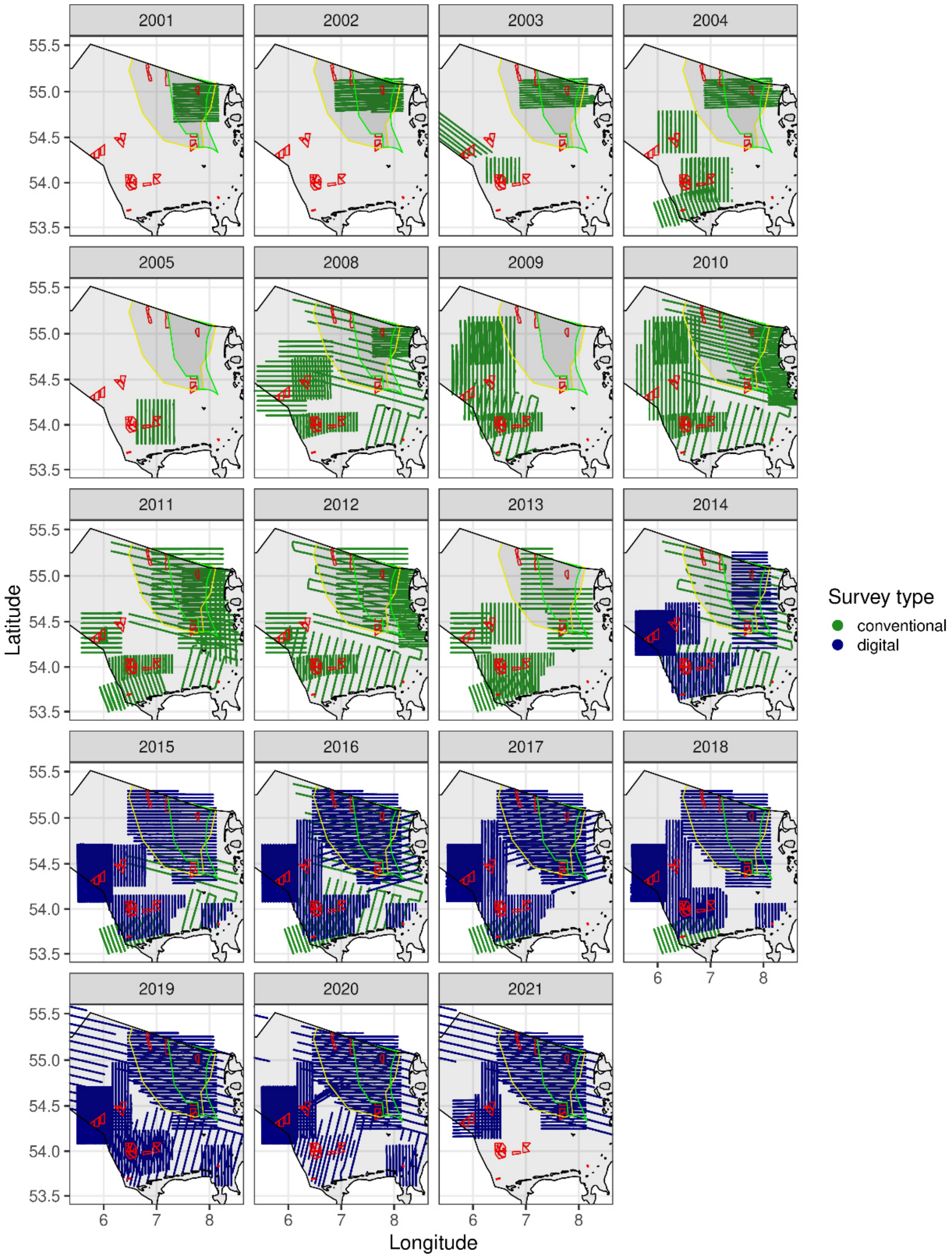

Figure 4.2 Survey effort for analyses between 2001 and 2021 (spring) for conventional (green) and digital (blue) surveys.

Since the results of the last diver study indicated some differences between the northern and southern regions of the German Bight, the data set was once again divided into two areas (Figure 4.3). The northern area includes the main concentration area for divers in spring (BMU 2009), where the highest densities are found. The southern area covers regions of mostly low or medium densities. The two areas do not overlap. Both areas included the coastal areas as well as the EEZ and data reaching beyond the EEZ borders into Denmark and the Netherlands were also included in the models. However, for all figures and the calculation of stock size the area was cut at the EEZ border. The spatio-temporal model included all data, but separate predictions were made for the two sub-areas and the main concentration area. The total prediction area was 28,625 km², which included 12,782 km² for the northern sub-area (including the main concentration area defined by BMU (2009) of 7,000 km²) and 13,375 km² for the southern sub-area (Figure 4.3).

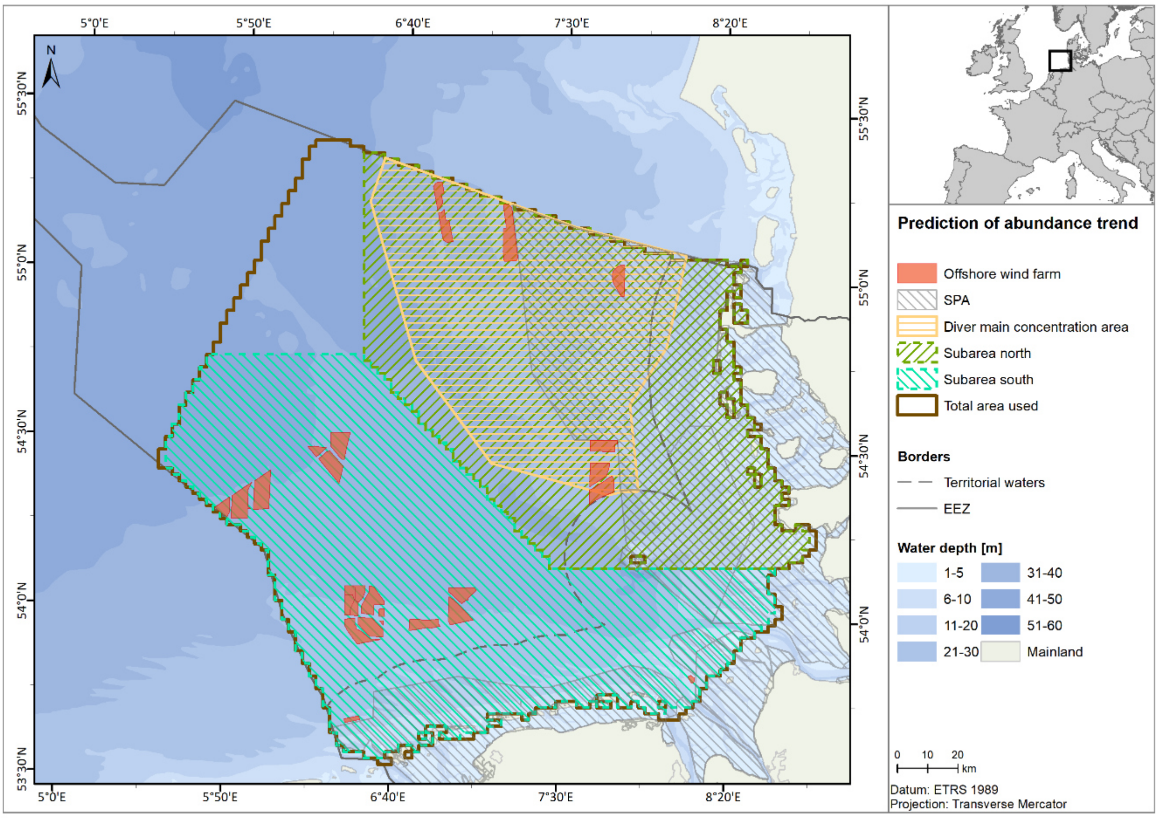

Figure 4.3 Total prediction area with northern and southern sub-areas and diver main concentration area (BMU 2009), as well as operational wind farms as of 2021. Blank area in the north-western corner was not included for predictions of north and south, but was part of the total study area.

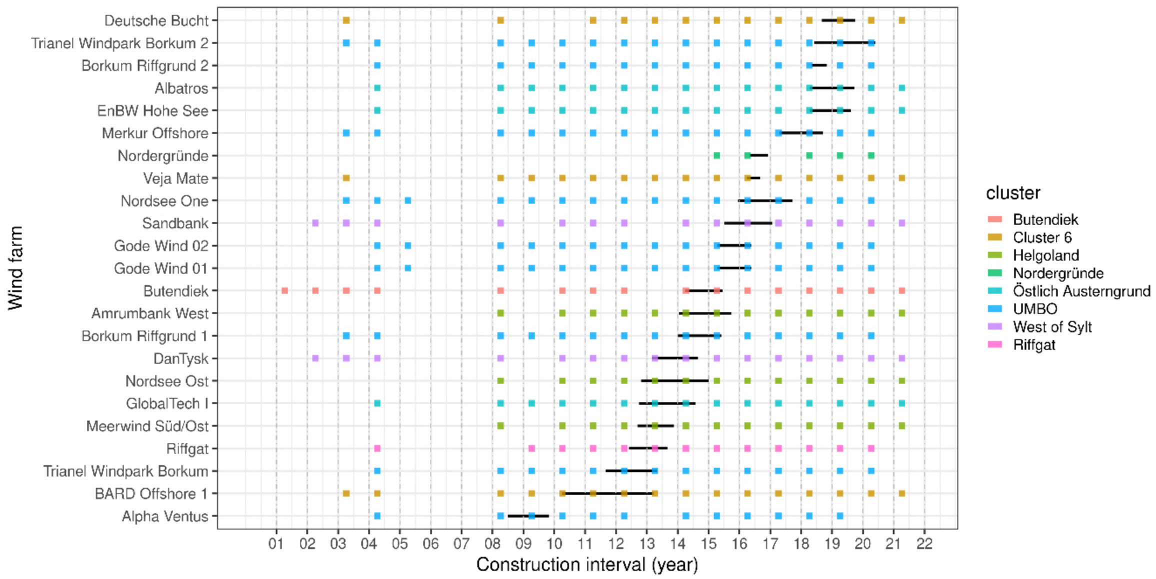

Figure 4.4 Years with survey data for wind farm projects during spring within the German North Sea and indication of construction periods (black line).

Monitoring data from 20 different wind farm projects, from baseline (before construction), construction, and operational phases, were included in the analyses (Figure 4.4). For each wind farm, periods were defined as belonging to the phases before or after construction and the complete spring period of all surveys was assigned to one phase. In some cases, for OWF starting construction in spring, surveys taking place before the exact start of construction were still assigned to the construction phase. This applied to 16% (digital) and 3% (visual) of surveys in the data set.

4.3 Digital Aerial Monitoring

The digital aerial surveys were conducted according to the standards set by the German Federal Maritime and Hydrographic Agency (BSH 2013) and subdivided into three different techniques: “APEM”, “DAISI” and “HiDef”. Generally, the survey method stayed consistent per survey area, however in some areas, i.e. DanTysk/Sandbank and Cluster Östlich Austerngrund, more than one method was used. This kind of monitoring was based on digital image recordings (pictures or film) collected in the survey area, which were examined later. Unlike in the visual surveys, species identification was done based on recorded images, not 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 greater than in visual survey flights, so survey aircraft could fly over the wind turbines and disturbance to birds was minimised. In all digital surveys, a twin-engined 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 seastate, glare, cloud cover, air and water turbidity were recorded and pictures of insufficient quality were excluded from analysis. Survey technique was also included in the model, to account for any differences in detection rates.

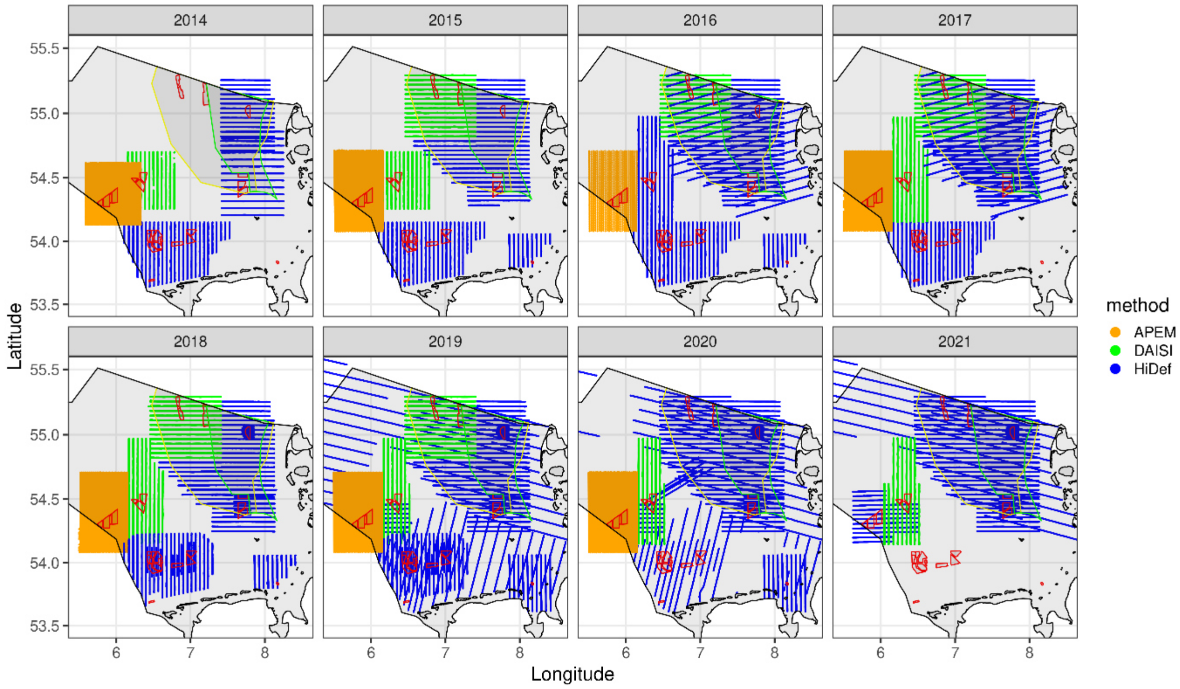

Figure 4.5 Coverage for the three techniques of digital aerial surveys APEM, DAISI and HiDef.

APEM

The APEM[2] technique (APEM Ltd.; Busch 2015) is based on still image recordings along transect lines in the survey area. Four cameras take images simultaneously and constantly. The four frames are then merged into one image with a resolution of ca. 3 cm (2 cm since January 2017 and 1.5 cm since January 2020) on the sea surface. Flight height was approximately 400 m (1,300 ft) at a speed of 120-130 knots. This method includes narrow transect lines (ca. 1.6 km spacing), which are close enough to allow the forming of a grid. This is one of the main differences to the other two survey methods described below (see also McGovern et al. 2019).

Cluster 6 was surveyed exclusively by the company APEM Ltd., with species identification and quality control done by APEM Ltd. APEM Ltd. also surveyed the DanTysk/Sandbank area in March and April 2014 with image analysis done by APEM Ltd. Here, the transect lines of the survey area were used rather than a grid.

DAISI

The surveying technique DAISI[3] ("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

[2] https://www.apemltd.co.uk/ (accessed 13.06.2022)

[3] https://www.ifaoe.de/daisi (accessed 13.06.2022)

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. The transect lines in the area DanTysk/Sandbank were oriented East-West, whereas transect lines in Cluster Östlich Austerngrund were oriented North-South. Dan-Tysk/Sandbank was surveyed by APEM for two months in spring 2014, and Cluster Östlich Austerngrund was surveyed by HiDef in selected month. Species identification and quality control was done by IfAÖ.

HiDef

The HiDef[4] 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). Depending on the survey area, species identification and quality control was done by BioConsult SH, IfAÖ, or IBL Umweltplanung.

The survey areas Butendiek, Cluster Helgoland, Nordergründe, Cluster Nördlich Borkum were exclusively covered using HiDef video systems. Cluster Östlich Austerngrund was partly surveyed by DAISI and HiDef. The survey areas included either North-South or East-West transect lines that were around 3-4 km apart. Digital survey data made available to the project via the Federal Agency for Nature Conservation (BfN) is also based on the HiDef method.

4.4 Model description

Similarly to the first study, we applied an INLA-SPDE approach for spatio-temporal geostatistical data (Bachl et al. 2019) by integrating the observed intensities and effort on the mesh nodes. The data was fitted by means of a negative-binomial family distribution, where the intensity of the observed process is the main driver of the posterior probability. As an advantage, the use of environmental predictors is generally not required for this model but it is possible to include them, if desired.

4.4.1 Creating mesh structure

A constrained refined Delaunay triangulation spatial mesh (Figure 4.6) was constructed for the entire surveyed area and digital and visual flight data was integrated on the mesh nodes for computational convenience. Information regarding data collection method, number of sightings, effort, season and year was preserved for modelling purposes.

[4] https://hidef.bioconsult-sh.de/ (accessed 13.06.2022)

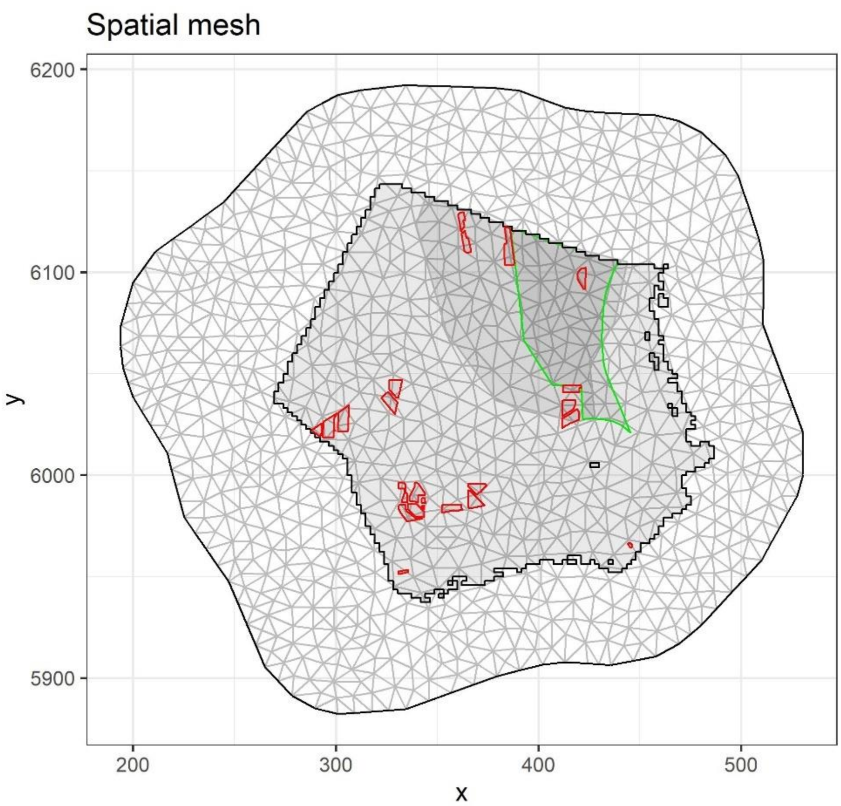

Figure 4.6 *Spatial mesh used for the spatio-temporal model. Total prediction area with main diver concentration area (grey line) and SPA "Eastern German Bight" (green line) are depicted.*

4.4.2 Data structuring

The dataset was restricted to only the spring season (1st March to 15th May). Diver abundance and wind farm displacement were assessed for the total study area. In addition, due to the different distribution pattern found in the north-east and south-west areas of the German North Sea, results were also presented for the northern and southern area separately, as well as for the main diver concentration area (BMU 2009) and the SPA "Eastern German Bight".

4.4.3 Model development

To answer the research questions, an explicit spatio-temporal model was developed to assess changes in the spatial distribution and to estimate trends in abundance.

The model assumptions were: 1. Perfect detection for HiDef method (see also section4.3) 2. Independence of spatial and temporal processes 3. No persistence (individuals move around) 4. Time is discrete (e.g. years).

To incorporate an accurate assessment of the model error and properly account for the property that an observation is more correlated with an observation collected at a neighbouring location than with another observation that is collected farther away, we used a spatially-structured random effects model which incorporates such spatial dependency.

In the spatio-temporal model, data were not only spatially but also temporally indexed. As such, the interest is not only the species' spatial distribution, but also in assessing how the spatial distribution changes over time. To incorporate all such dependencies into one modelling framework, we construct a spatio-temporal multivariate Gaussian Random Field (GRF) with a Matérn covariance for the spatial domain, and an autoregressive process of order 1 (AR(1)) to describe the temporal dependence. We take an integrated nested Laplace approximation (INLA) approach (Rue et al. 2009) for Bayesian inference, coupled with a Stochastic Partial Differential Equation (SPDE) model (Lindgren et al. 2011) to account for the spatial autocorrelation. Data collection methods were included into the model as categorical covariates.

Regarding the selection of priors, 15 models with different priors were run (with 15, 20, 25, 30, 35, 40 and 45 km range with different sigma priors and prior confidence). The model with the best overall correlation score (observed-predicted) and best performance from visual inspection of the abundance trend was a model using an uninformative prior with a range of 15 km and sigma 0.2.

Calculations were performed in the R statistical software using the inlabru package (R Core Team 2019, Bachl et al. 2019).

4.4.4 Model validation using cross-validation

To assess the model's predictive performance, the dataset was randomly split into two subsets: a training dataset including 80% of the total observations, and a validation dataset containing the remaining 20% of the data. The model was performed using the training dataset and its predictive accuracy for each year was assessed using the validation dataset. We repeated this calibration-validation procedure 20 times and model performance was assessed using the correlation index between the observed and predicted values at the testing dataset locations.

5 RESULTS

5.1 Model validation

5.1.1 Results of cross-validation

The overall CV score based on 20 random runs (80% training - 20% testing) was 0.71 (Figure 5.1). However, although most years performed very well, other performed poorly (2001, 2002 and 2009). Excluding these 3 years, mean predictive accuracy reaches 0.76. Although years with lower sampling effort and unusual distribution pattern scored lower, years from 2010 onwards all performed very well.

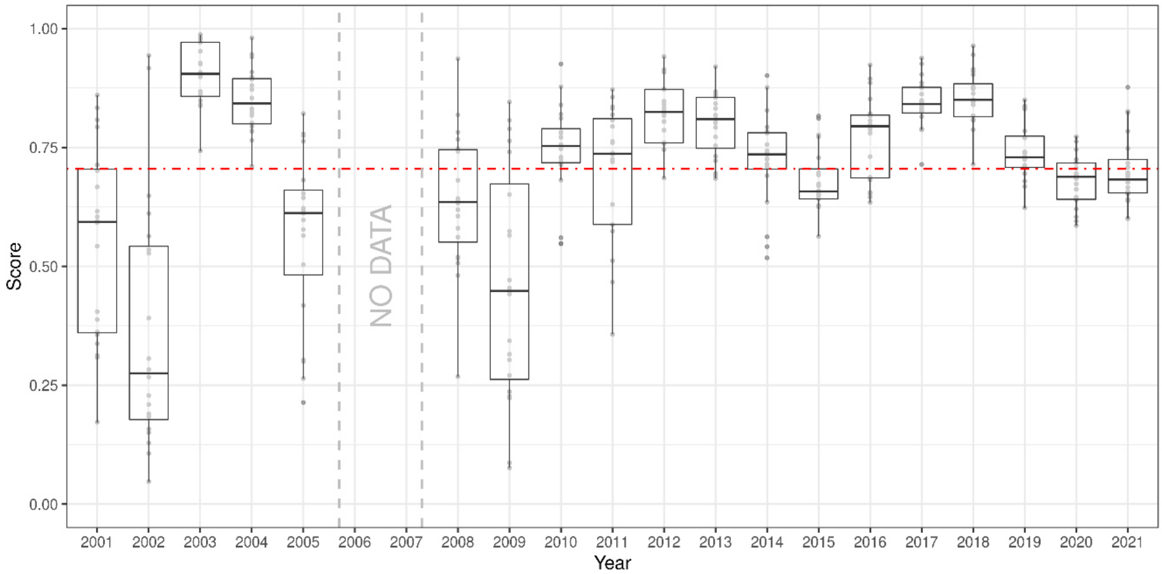

Figure 5.1 Results of the cross-validation for all data during spring. Dashed horizontal red line indicates average score among all years.

5.2 Population size during spring

Figure 5.2 and Table 5-1 show the estimated spring diver abundance for the study period 2001-2021 in the total prediction area. The lowest diver abundance was estimated for 2008 at 8,636 individuals, the highest abundance was estimated for 2003 at 20,387 and 2014 at 19,765 individuals. There were strong fluctuations between the years throughout the study period. As data coverage was low in the early years, abundances between 2001 – 2005 show high confidence intervals, in later years the estimates showed lower confidence intervals. From 2018 onwards, the estimates of diver abundance remained relatively stable (Figure 5.2), dipping a little lower in 2019 and 2020 and then increasing again to levels similar to 2018 by the year 2021 at a level of 15,784 individuals (Table 5-1). The average estimated annual diver abundance was 14,442 individuals over the entire study period.

Since the highest densities occur in the northern sub-area, the annual abundance estimates and the annual fluctuations were similar to the total study area (Figure 5.3). The average estimated spring abundance for the study period in the northern sub-area was 11,229 individuals. The highest abundances were estimated for the years 2003 at 17,097 and 2014 (after construction of the first wind farms in the area) at 16,991 individuals.

For the southern sub-area, estimated abundances were considerably lower. Numbers in the early years from 2001-2010 ranged between ca. 2,000 and 3,300 individuals (Table 5-1). The highest abundance was estimated for 2012 at 5,901 individuals (Figure 5.4). Afterwards, numbers declined again to around the level they were before. The lowest abundance was found in 2016, at 1,716 individuals and 2017 at 1,831 individuals. The average estimated spring abundance in the southern sub-area was 2,752 individuals over the entire study period.

Diver abundance in spring was also calculated for the main diver concentration area, as defined by BMU (2009). Here, patterns were again similar to the northern and total study area (Figure 5.5), showing no decline in abundance but annual fluctuations. The highest abundances were estimated for 2003 at 14.888 and 2016, after construction of wind farms in the area, at 12,166 individuals (Table 5-1). On average, 60% (range: 45-74%) of divers in the German North Sea were found within this main concentration area (n=8,671).

Within the SPA “Eastern German Bight”, abundances were slightly lower in the years between 2008 and 2013 (average n=3,193), reached a peak in 2014 at 8,771 individuals and then settled on a slightly higher average than before between 2015 and 2021 (average n=5,593). The average over the entire study period was 5,113 individuals. On average, 35% (range: 18-53%) of divers in the German North Sea were found within this SPA (n= 5,113).

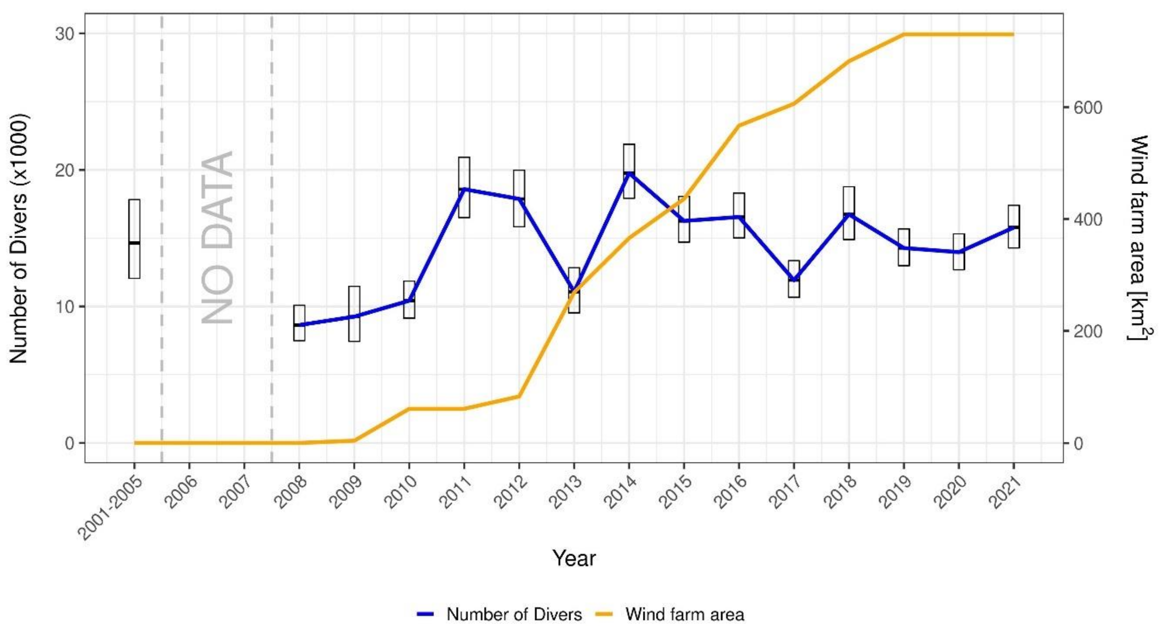

Figure 5.2 Diver abundance during spring for the total study area. Error-bars show 95% confidence intervals given by the model. For reference, the total wind farm area (km²) was included for each year.

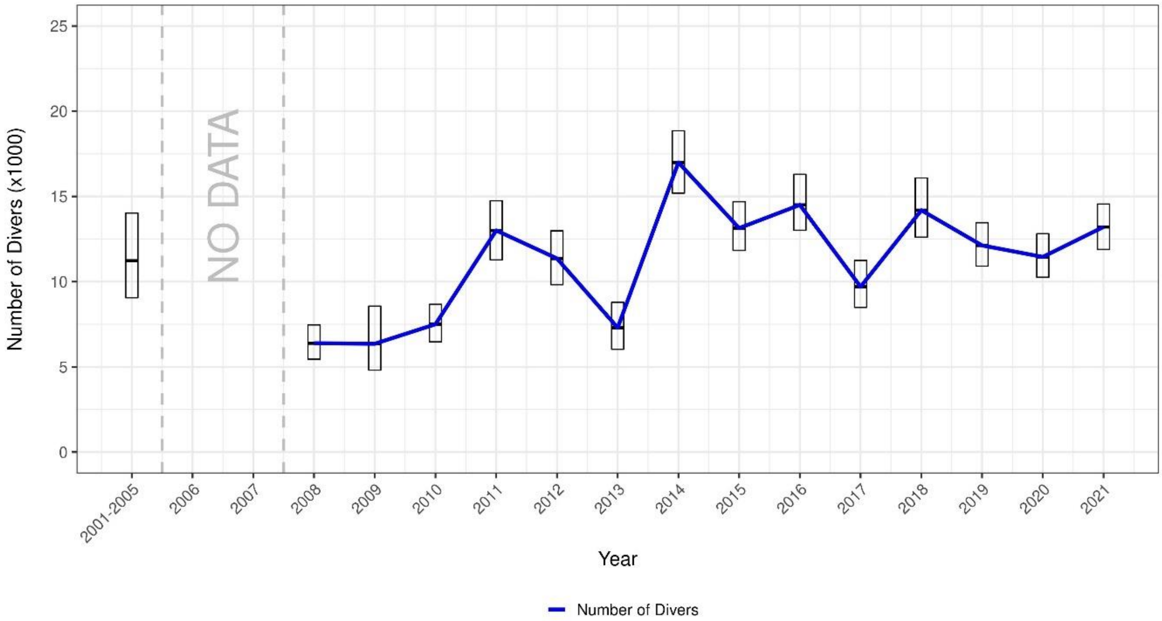

Figure 5.3 *Diver abundance during spring for the northern area. Error-bars show 95% confidence intervals given by the model.*

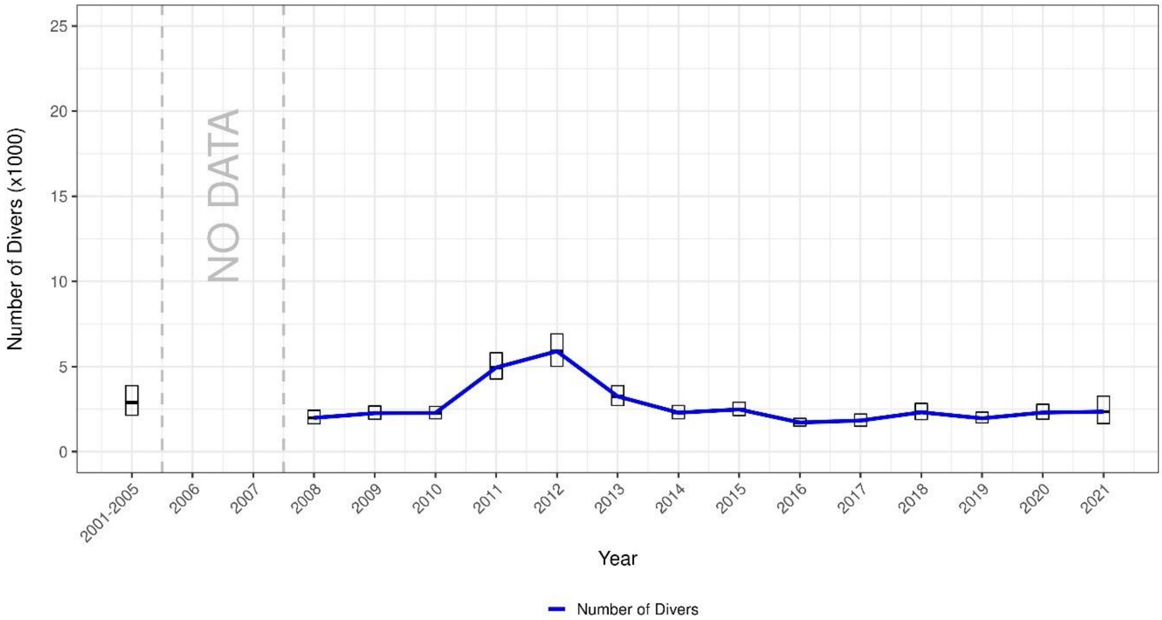

Figure 5.4 *Diver abundance during spring for the southern area. Error-bars show 95% confidence intervals given by the model.*

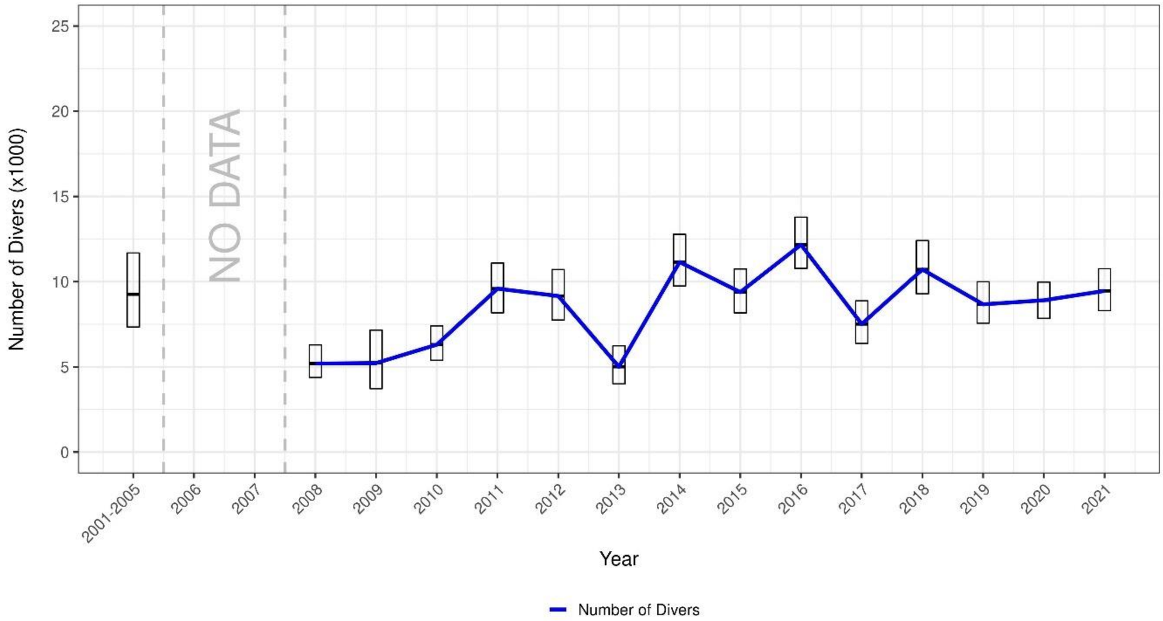

Figure 5.5 *Diver abundance during spring for the diver main concentration area (BMU 2009). Error-bars show 95% confidence intervals given by the model.*

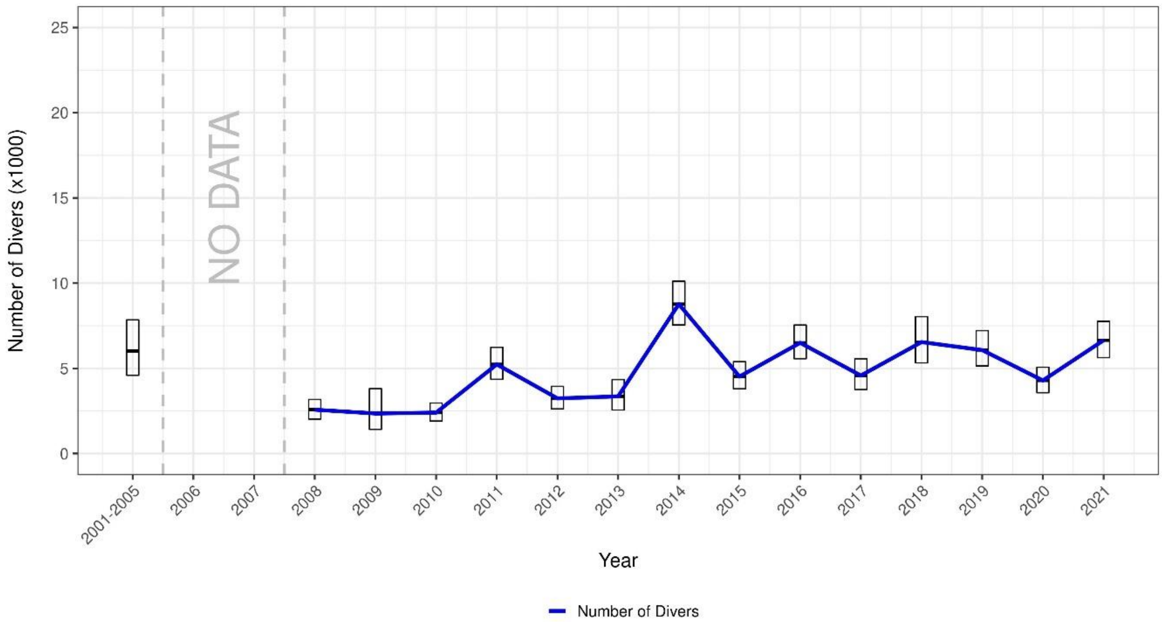

Figure 5.6 *Diver abundance during spring for the special protected area SPA "Eastern German Bight". Error-bars show 95% confidence intervals given by the model.*

Table 5-1 Diver abundance as predicted from the spatio-temporal model, for spring – total prediction area, north and south, main concentration area and SPA. Part of the area covered by the total study area is not included in the sub-areas north and south. Therefore, numbers from north and south do not sum up exactly to total numbers and might in some cases slightly exceed total numbers due to the inherent randomness of the modelling process.

Year	Spring total	Spring north	Spring south	Spring BMU main concentration area	SPA "Eastern German Bight"
2001	14,455	10,639	3,226	8,586	5,476
2002	12,172	8,685	2,890	6,657	3,778
2003	20,387	17,097	2,628	14,888	10,758
2004	15,537	11,781	3,295	9,752	6,445
2005	10,722	7,932	2,378	6,424	3,617
2008	8,636	6,388	1,990	5,196	2,574
2009	9,252	6,356	2,262	5,222	2,352
2010	10,420	7,502	2,278	6,304	2,403
2011	18,584	13,004	4,945	9,589	5,233
2012	17,876	11,361	5,901	9,159	3,239
2013	11,076	7,297	3,246	5,008	3,358
2014	19,765	16,991	2,292	11,150	8,771
2015	16,264	13,142	2,484	9,386	4,519
2016	16,552	14,503	1,716	12,166	6,500
2017	11,922	9,700	1,831	7,514	4,578
2018	16,745	14,191	2,316	10,714	6,542
2019	14,279	12,126	1,960	8,669	6,073
2020	13,977	11,451	2,301	8,907	4,289
2021	15,784	13,212	2,351	9,460	6,648
Average	**14,442**	**11,229**	**2,752**	**8,671**	**5,113**

5.3 Spatial distribution: Observation effort and densities during spring

The following set of figures (Figure 5.7 to Figure 5.12) show the distribution of divers over the total study area per year. Depicted are the predicted densities from the spatio-temporal model on a constant scale (left) and on a variable scale (right) for each year. The locations of the wind farms were added into the graphs as they appeared successively over the study period. This helps to visualise a possible change in diver distribution in response to the growth of wind farm developments.

The results show that in each year, the highest densities occurred in the northern part of the study area within the main diver concentration area (BMU 2009). Within this area, the location of the highest diver densities was variable, especially in the years between 2001 and 2012, before wind farms were built in the area. After construction of the three wind farms/wind farm clusters within the main concentration area (Figure 4.1) between 2013 and 2015 (Figure 4.4), the location of the highest densities began concentrating in areas at some distance from those wind farms. Often these concentrations also fell into the area of the SPA "Eastern German Bight", as it overlaps to a great extent with the eastern half of the main concentration area.

A similar pattern continued to be visible in the spring of the years 2019 to 2021, where the highest diver densities were detected within the main concentration area at the maximum possible distance from the wind farm clusters in the area. The year 2021 also showed comparatively high densities in the area West of the OWF Butendiek compared to most previous years and a slightly more widespread distribution of low densities around the OWF Helgoland and even some very low densities between the OWF Sandbank and DanTysk where between 2016 and 2019 no divers were detected (Figure 5.10 to Figure 5.12).

Additionally, there were incidences of higher density within the northern sub-area but outside the main concentration area, mainly in the years 2011-2015 and 2018-2021. These occurred in the coastal seas of Schleswig-Holstein and along the southern edge of the main concentration area. Before 2011, they were absent or far less pronounced (Figure 5.7 to Figure 5.12).

The southern sub-area showed few years with high densities. The early years from 2001-2003 showed very low diver densities there (Figure 5.7). Between 2004-2008 a medium density occurrence of divers was visible in that area (Figure 5.8, Figure 5.9). Most notable were the years 2011 to 2013, after construction of the first wind farms in the area, where high densities were observed in the southern sub-area (Figure 5.9). After 2013 and concurrently with the increase in wind farm clusters in the area, instances of high densities of divers in spring were not found in the area (Figure 5.10 to Figure 5.12).

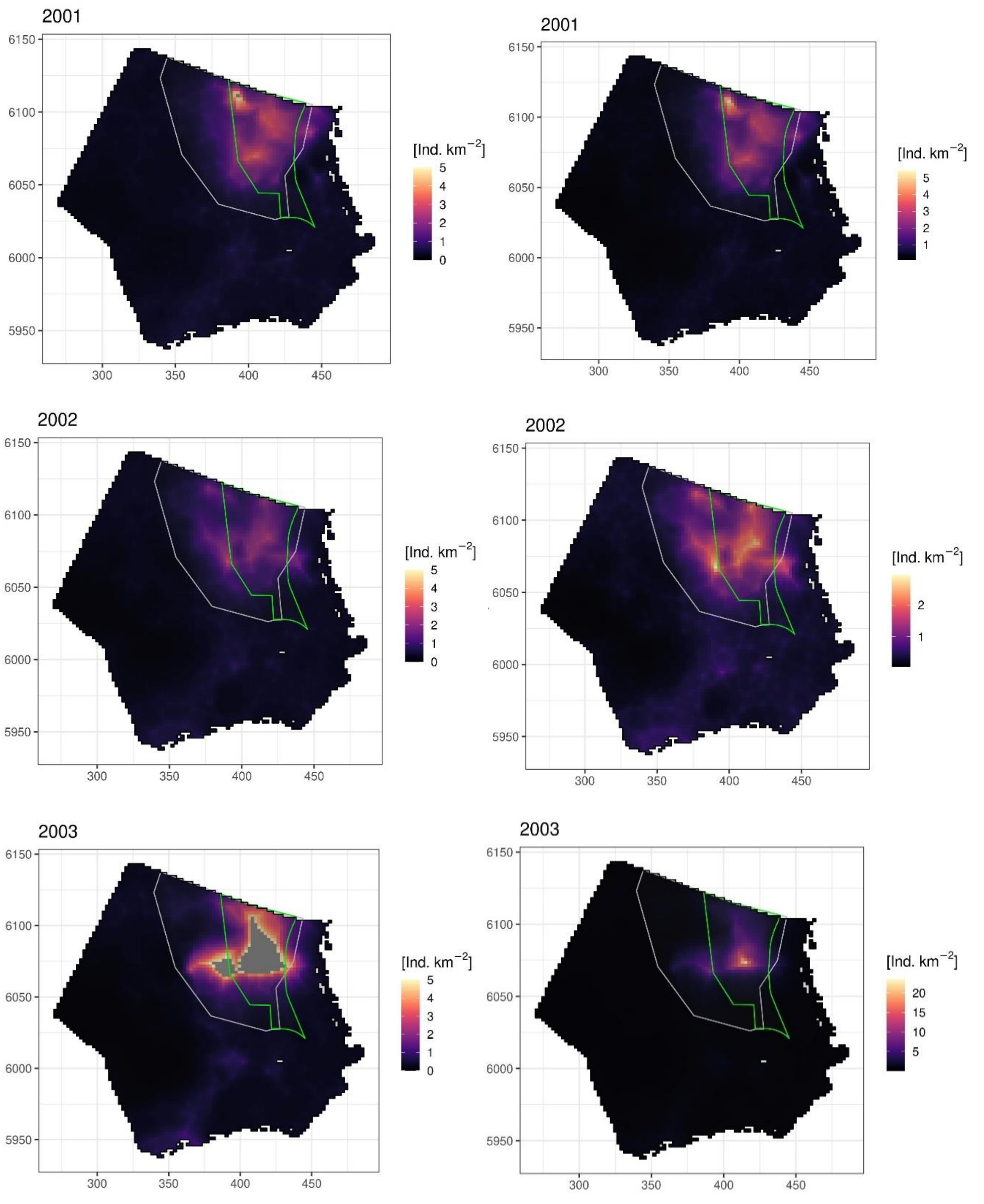

Figure 5.7 *Predicted densities for spring for the total study area (2001 – 2021). Densities are given on a constant scale (left) and on a variable scale (right) for each year. Values exceeding the maximum value of the constant scale, are shown in grey. Red borders indicate wind farms under construction or in operation. Green line depicts border of SPA "Eastern German Bight", white line depicts main concentration area for divers as defined by BMU (2009). Figures for sub-areas (spring, with adjusted scale) can be found in the appendix.*

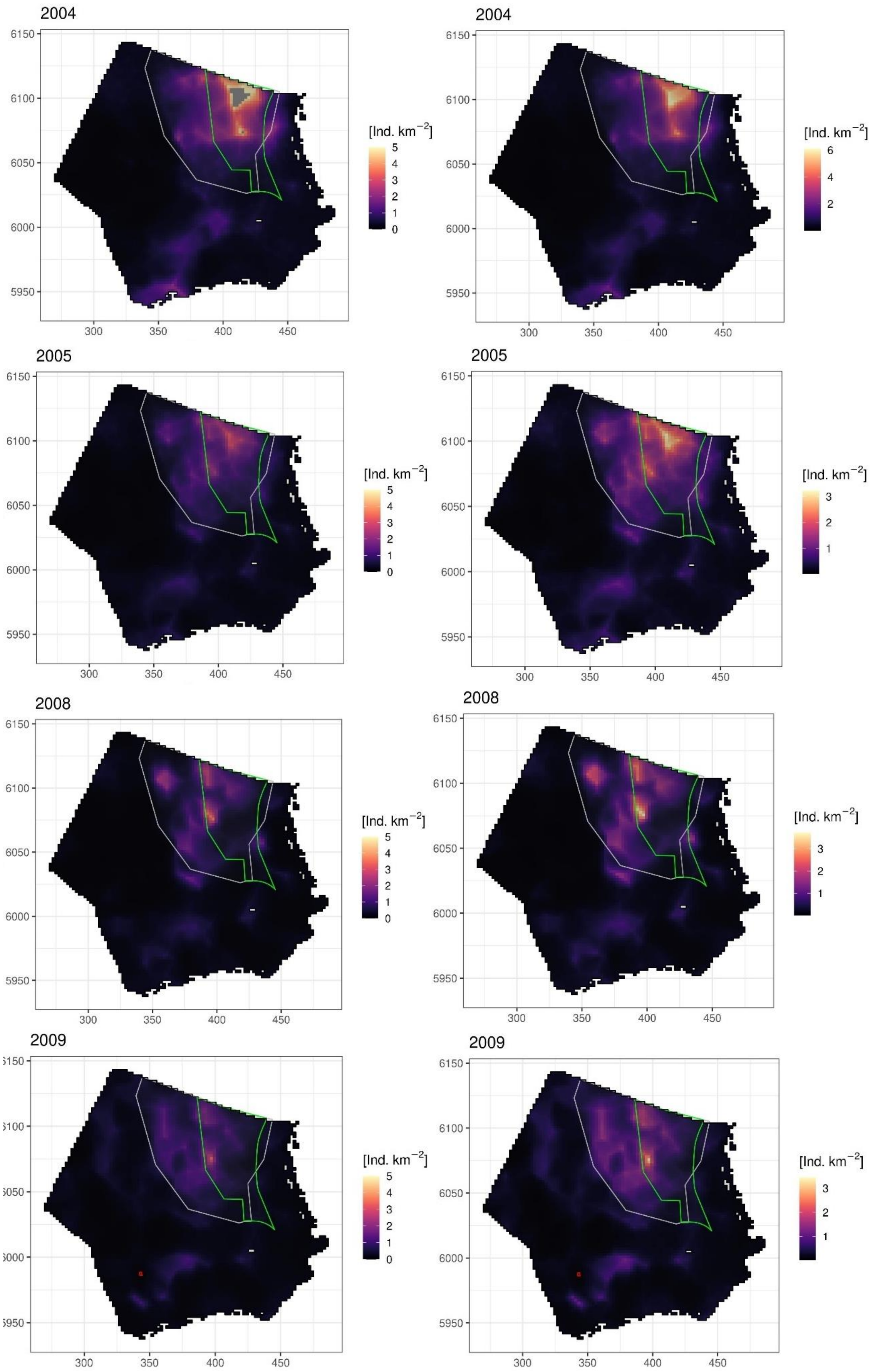

Figure 5.8 Predicted densities for spring for the total study area (years 2004 – 2009; 2006+2007 were not covered). For more details see Figure 5.8.

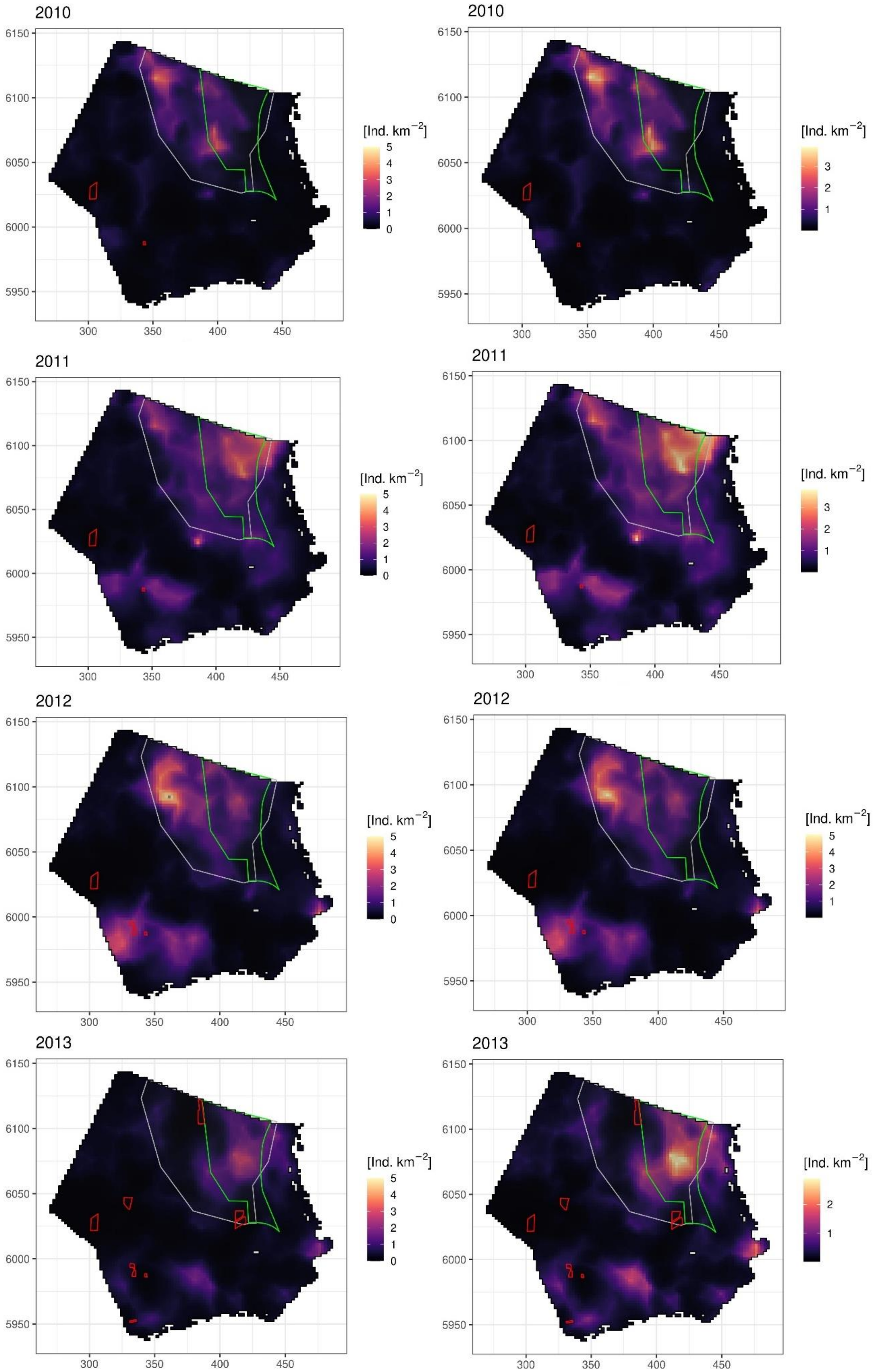

Figure 5.9 Predicted densities for spring for the total study area (years 2010 – 2013); For more details see Figure 5.8.

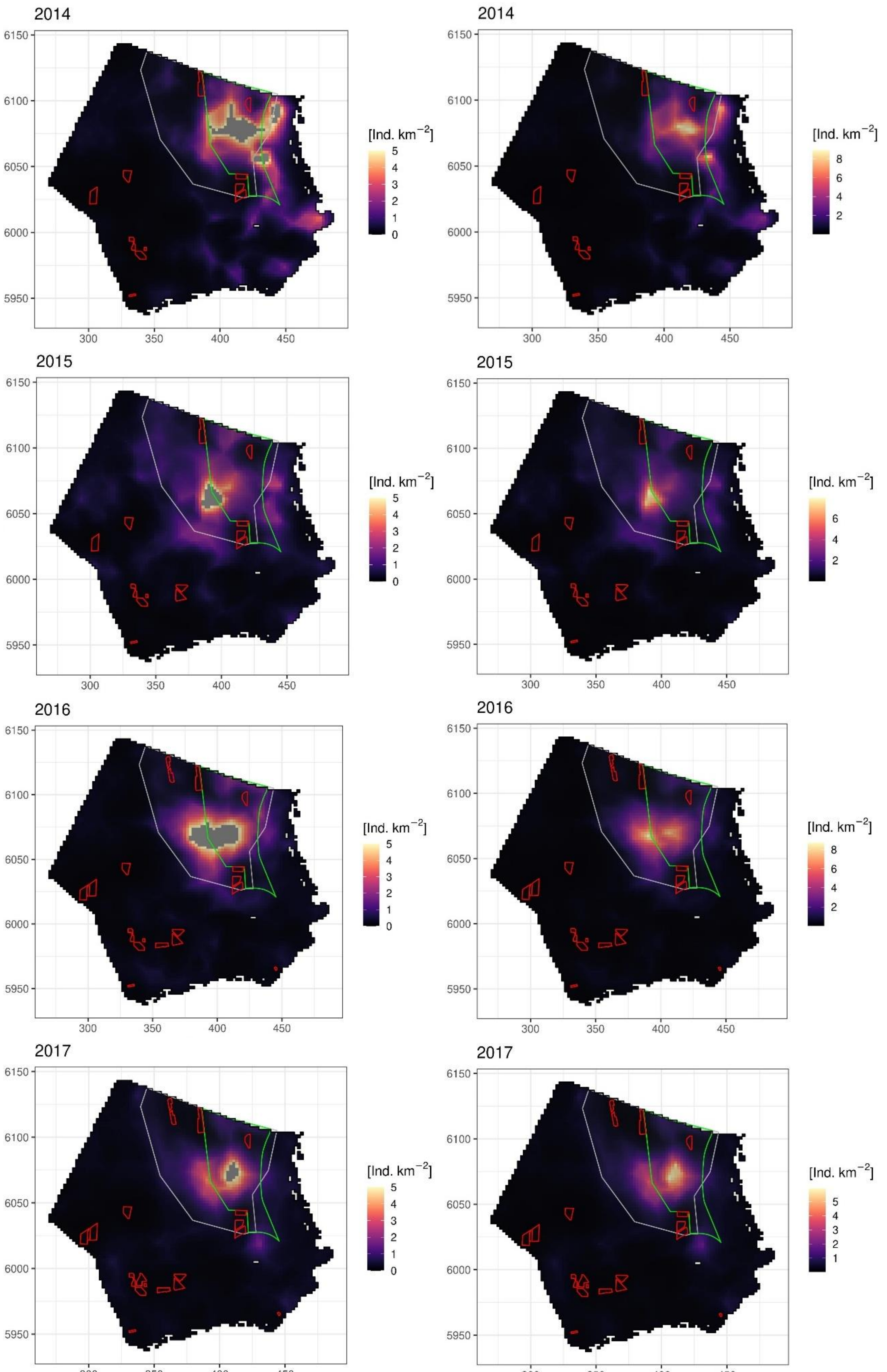

Figure 5.10 *Predicted densities for spring for the total study area (years 2014 – 2017). For more details see Figure 5.8.*

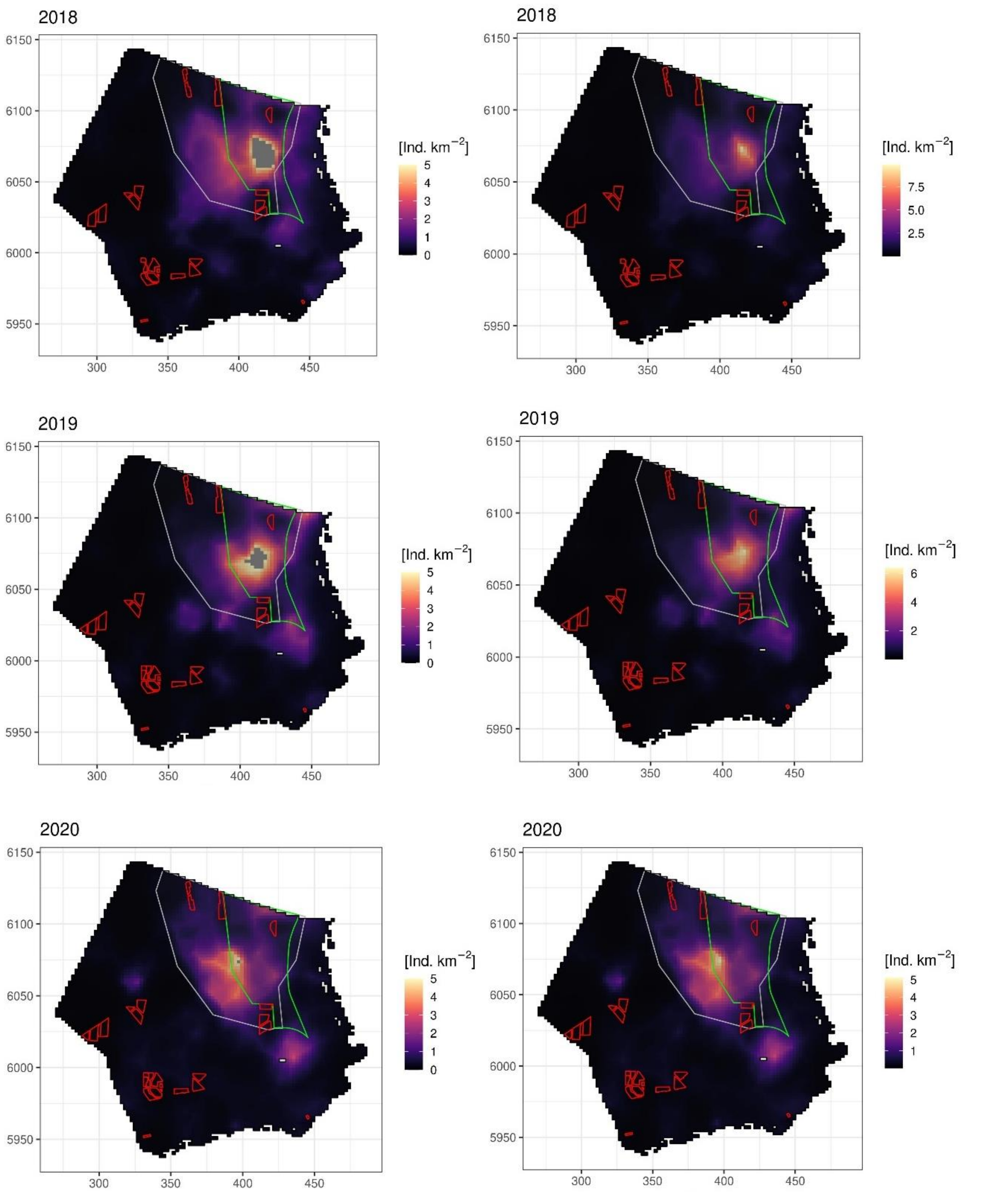

Figure 5.11 *Predicted densities for spring for the total study area (years 2018 – 2020). For more details see Figure 5.8.*

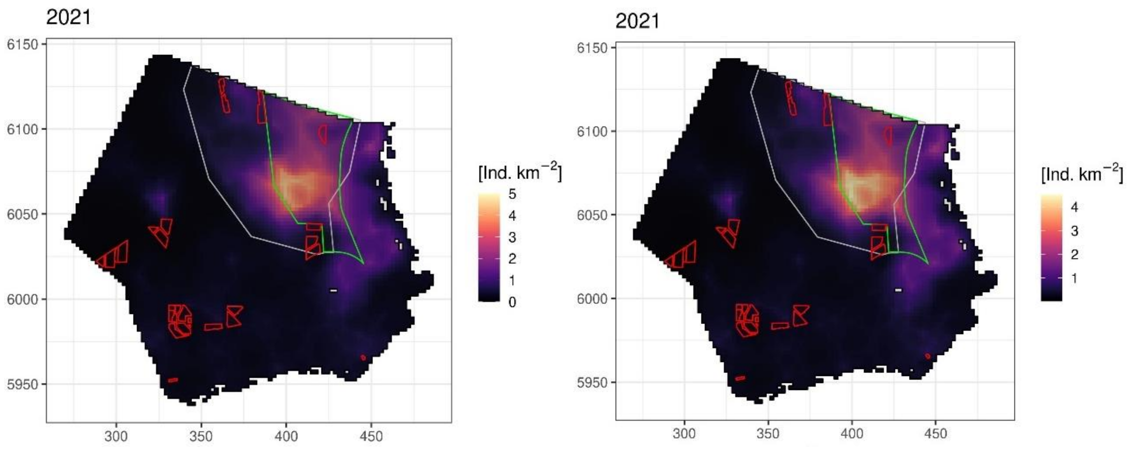

Figure 5.12 Predicted densities for spring for the total study area (2001 – 2021). For more details see Figure 5.8.

5.4 Comparison with previous study

The renewed analysis with an extended data set resulted in comparable results to the previous diver study (BioConsult SH et al. 2020).

Model results for population size from the years that had previously been analysed as part of the first diver study (BioConsult SH et al. 2020) matched relatively well with the earlier results.

The incorporation of 3 years of new data meant that the priors used in the previous report did not work well with the updated dataset. Therefore, new priors had to be tested and the set of priors (range and sigma) with the best predictive performance was selected.

As a result, the range prior (range of maximum spatial autocorrelation) was reduced in the current model from 45km to 15km. This change showed a more accurate adjustment of the initial years (2001-2005) with low spatial coverage and data obtained by conventional methods. This better adjustment during the first years reduced the model uncertainty and provided more realistic values for the first years, reducing the average population size in this period from 18,601 individuals to 14,654 individuals, a value more in line with the most recent observations. Between the period 2007-2018, the new estimate reduced the mean population size by 8%, from 15,545 to 14,281 individuals and the last 3 years (2019-2021) not included in the previous report reported a population average of 14,680 individuals, showing a stable population size since the beginning of the monitoring program.

Overall, the population size average for the full time period was 14,442 individuals compared to the previous estimate of 16,500 but biased by the high mean abundances with high uncertainty of the 2001-2005 estimation.

In any case, and despite the differences in the total average numbers, the change of the model priors did not affect the observed spatial distribution, temporal trends or main conclusions reached in the previous report and the new estimates remained within the confidence limits of the previous model.

The analysis of the distributions of divers also came to similar conclusions as the first diver study (BioConsult SH et al. 2020). As had previously been shown, the highest densities occurred consistently within the main diver concentration area (BMU 2009) and showed a variable distribution between 2001 and 2012. After constructions of wind farms in the area, divers began concentrating in a central location at a maximum distance from the wind farms. Under repeated analysis with additional data, the pattern that was observed in the first diver study (BioConsult SH et al. 2020) was still visible. The highest densities were detected at a central location, however the distribution appeared slightly more widespread with some low densities around OWF especially in the year 2021. The three additional years of data confirmed the conclusion from the previous study, as the same general pattern continued to be visible between 2019 and 2021.

6 DISCUSSION

The first diver study (BioConsult SH et al. 2020) used an extensive data set of offshore monitoring data to analyse the population size development and distribution of divers in the study area of the German North Sea in relation to the increase of offshore wind farms in the area. This study expands upon the previous one with an additional three years of monitoring data, resulting in an unprecedented 19-year data set (19 years of spring data over a 21-year study period) for divers in the German North Sea.

6.1 Population size development pre- and post-construction

As a long-lived migratory bird species, divers and their population size are affected by many factors over the course of the year and over their entire lifespan. Conditions during wintering, migration and breeding all affect individual survival and fitness (Schreiber 2002, Weimerskirch 2002, Newton 2004). Negative impacts on any aspect of survival or fitness can take many years to be visible in population size unless it involves direct mortality of adult individuals (Sæther & Bakke 2000, Sibly & Hone 2002, Norris 2005, Desprez et al. 2018). This makes it difficult to discern the impacts of OWF, as indirect effects can take a long time to be measurable and be masked by other factors that affect divers in other parts of their life cycle. For these reasons, long-term datasets are so important, as they are the only way to identify changes that occur over long periods of time.

Divers occur in the German North Sea during spring and winter, but the highest densities are consistently recorded during spring migration (1st March to 15th May; Garthe et al. 2007). Many factors affect survival and breeding success over the course of the year, so strong interannual fluctuations are natural and common. These factors include weather conditions, food availability and predation among others (Schmutz 2014, Rizzolo et al. 2014, Lehtonen 2016). Although divers spend only a comparatively small part of their life in the German North Sea, conditions here can still have a significant impact on diver population size. As a spring migration stopover site, the German North Sea is an important part of their life cycle, as it is one of the last stops before the breeding areas. If the birds' body condition is reduced due to stress or unfavourable foraging conditions at the staging site, breeding success could be reduced (e.g. Harrison et al. 2011, Szostek & Becker 2015, Hovinen et al. 2019, Steenweg et al. 2022). Equally, if adult body condition is not optimal pre-breeding, adult long-term survival might be affected as well (e.g. Harrison et al. 2011, Duriez et al. 2012).

Over the 21-year study period, no trend was visible in population size during spring, neither in the total study area nor the northern and southern sub-areas, the main concentration area or the SPA "Eastern German Bight", indicating a stable population over the study period in all areas. There were strong fluctuations between the years, both pre- and post-construction, but on average post-construction (2014-2021) population size was similar to the first years (2001-2004) of the study period and generally higher than the pre-construction years in total (2001-2013). This is true for the entire study area as well as the northern sub-area, the main concentration area and the SPA. Within the southern sub-area, post-construction population size estimates are lower than pre-construction.

Overall, abundances were on a roughly average level or slightly higher during the post-construction years, except for 2017 when numbers were lower and 2014 when they were considerably higher. The estimated population size in the most recent years 2019-2021 were on an average level or higher in all areas, except in the southern sub-area, where the most recent population estimates were lower than the average for the entire study period. For this area, numbers were comparatively low overall, with the highest abundances for the years 2011 and 2012 and a subsequent return to relatively stable population levels that are slightly lower overall. Despite a lower average population size post-construction, there is no declining trend in this area either.

The results confirm that there is no negative trend in population size for the study area of the German North Sea and that the population size within the main concentration area for divers as well as the SPA "Eastern German Bight" has remained consistent. The importance of the main concentration area is once again confirmed by the consistently high densities in the area in spring.

6.2 Spatial distribution of divers within the German North Sea

The main concentration area (BMU 2009) consistently showed the highest densities of divers in the spring season. On average around 60% (range: 45-74%) of all divers were found to be present within this area during spring during all years. Pre-construction, there were annual hotspots of diver density which moved around within the main concentration area. In some years there was one centralised concentration, in other years there were multiples. It is likely that prey distribution affected the annual diver distribution and divers were free to move with their prey and adapt to local conditions. In the post-construction period, there was noticeably less variation in distribution and a concentration towards the centre of the main concentration area, where no wind farms are present and comparatively little ship traffic occurs (Burger et al. 2019). Displacement of divers due to OWF has been well documented (e.g. Webb et al. 2015, Garthe et al. 2018, Mendel et al. 2019, BioConsult SH et al. 2020, Heinänen et al. 2020), so it is to be expected that divers would seek out areas at a distance from existing OWF. However, distribution maps show clearly that the area previously widely used by divers has been considerably reduced due to the erections of OWF. Since the population size has remained stable since the expansion of OWF, the same number of divers are now concentrated in a much smaller area. This can lead to density dependent effects, if the carrying capacity of the area at the centre of the main concentration area is not sufficient to support the higher density of divers that are now present there annually (Croxall & Rothery 1991, Newton 1998, Del Monte-Luna et al. 2004). Since the divers' ability to follow their prey around the north-east of the German EEZ seems to be limited due to OWF displacement, it is possible that food resources might not be sufficient to sustain the entire spring population of divers. This could result in poorer body condition, reduced breeding success (e.g. Szostek & Becker 2015) and further displacement into other areas in search of food. Possible fitness consequences due to the reduced spatial distribution of divers (Gill et al. 2001), could be determined through (individual-based) physiological studies and a longer time series. Individual-based studies are vital to estimate risks to the species due to disturbance, since many details about the divers' life cycle, such as site fidelity to staging sites, individual adaptability to changing habitats, dependence on resources and weather conditions etc., are not yet known (but see Dorsch et al. 2019, www.divertracking.com).

Some higher density occurrences in the northern area outside the main concentration area were visible in some years, such as concentrations along the coastal areas of Schleswig-Holstein as well as along the southern edge of the main concentration area. These were more pronounced in the years 2011-2015 and 2018-2021 and occurred much less before 2011. It is possible that this is a sign of divers moving into areas outside the main concentration area, possibly due to a density effect, but so far densities are still relatively low and these areas have sporadically shown higher densities in earlier years as well. It must be considered though, that data coverage on the Schleswig-Holstein coast was relatively low. Also, the years 2020 and especially 2021 showed a generally more widespread distribution within the main concentration area as well as outside, so the observed shift towards the areas outside the main concentration area might be due to the same conditions that led to the generally less centralised distribution in recent years. Although there is not yet a clear sign that divers are spreading outside the main concentration area, further observations of their spatial distribution in this area are important, as a shift might happen gradually. Continued displacement into other areas in future years could be a sign that carrying capacity in the main concentration area has been reached. Since the German North Sea is only a stopover site for these birds, if the carrying capacity is reached, divers might choose to spend less time there or move to a different area (such as the nearby Danish EEZ) for their migratory stopover. A significant part of divers registered in the German North Sea during spring already uses the area as a short-term migratory resting area, while others spend several weeks or months there before migrating onwards to their breeding grounds (Dorsch et al. 2019). The main concentration area itself is only a relatively small part of the divers' spring resting area. Telemetry studies found that divers during spring have very large home ranges and that individuals often move over areas that exceed the size of the main concentration area (Dorsch et al. 2019). Tagged divers were found to be highly mobile and they move frequently between Danish and German resting areas. Despite this, the main concentration area is an important site for divers on their annual migration and if divers are found to be redistributing into other, possibly less suitable areas, this could be cause for concern. However, since we found no signs of a change in population size and the main concentration area is still consistently showing the highest densities, there is no indication that the carrying capacity of the main concentration area has been reached.

Although divers are known to avoid OWF and tend to stay a long distance away, more recent data has given some evidence that this strong avoidance reaction might be mitigated under certain circumstances. One flight in late March 2021 (Figure A- 1) showed very high numbers of divers in close proximity to the OWF Butendiek, especially the western edge of the OWF. This was the first time in our dataset that such high numbers of divers were clustered around any OWF, in what looks like an attraction to the OWF. The density of divers was generally very high in the main concentration area on this day and there were high densities in other areas as well. Although it is uncertain what caused this unusual behaviour, an initial supposition could be an unusually favourable foraging condition around the edge of the OWF which caused high numbers of divers to overcome their usual avoidance response to take advantage. Another possibility would be that a migration wave from the West encountered the OWF and the observed pattern is a barrier effect. Although this finding seems very promising, it is important to note that it is a unique case and nothing similar has been found anywhere in our long-term data of the German North Sea nor has anything similar been described in the literature. It is therefore too early to speculate that this might be a sign of habituation. However, it does seem to indicate that under some circumstances, divers can overcome their strong avoidance reaction and utilize areas closer to an OWF. Similarly, in 2020 and more strongly in 2021 low densities of divers were observed between Sandbank and DanTysk for the first time since construction of these two OWF. Although densities were very low, it is notable, as the area between two OWF in close proximity should be very unattractive to divers. There is no explanation for this observation as yet, but continued long-term studies are the only way to determine whether these kinds of observations are pure coincidences, due to specific environmental circumstances or signs of a possible habituation.

The southern part of the German North Sea has always shown much lower diver densities than the northern area. Despite this, a considerable number of individuals is found there annually. The years 2011 and 2012, both years with comparatively very high density overall, showed high densities in the southern part of the German North Sea as well. During these years, the first and second wind farms were erected in the area. Prior to that, there were mostly low to medium densities observed in the area. After 2013, densities in the area remained low. Population size estimates show an overall slightly lower number of divers in the area after the two years of very high densities compared to before, although no declining trend was detected. It is possible that 2011 and 2012 were exceptional years where an overall high density of divers in the German Bight spilled over into normally lesser used areas. Since the southern area was not utilised strongly before, it seems likely that it was not the preferred habitat for spring staging. However, since the rise in densities and the construction of wind farms in the area occurred at the same time, it is impossible to tell whether an increase in usage of the area by divers would have occurred in the absence of OWF development.

6.3 Limitations

Although the extensive data set allows for an in-depth analysis, there are still limitations to the study due to the methods of data collection. Over the course of the study period, survey techniques were switched from visual to digital aerial surveys. Detection rates and accuracy in species classification are likely different between visual to digital aerial surveys. For visual surveys, a distance correction is needed to accurately estimate bird densities. Since there was a sufficient overlap in the use of all different survey techniques, we were able to further correct for differences in the data set. Although there were minor differences in the survey methods, we found that all techniques (including visual surveys) can detect divers reliably (cf. Mendel et al. 2008, Zydelis et al. 2019).

6.4 Comparison with literature

Several earlier studies have estimated diver population size in the German North Sea or parts thereof, based on similar sets of data as were used in this study (Garthe et al. 2015, 2018, Schwemmer et al. 2019). Although different statistical methods were used the resulting values for population size were mostly similar. Inconsistencies mostly arose where survey effort or coverage of the study area were low or patchy. The most recent comparable study on population size and development is Schwemmer et al. (2019). This study described an increase in spring abundance up to the year 2012 followed by a constant decline until 2017. This pattern was not found in this study: both earlier years and years between 2012 and 2017 showed abundances as high as 2012 and although 2017 was a year of comparatively low diver abundance, the following years showed considerably higher population size estimates from 2018 to 2021. The very high abundance that Schwemmer et al. (2019) estimated for spring 2012 was explained by an unusually high abundance of divers in the southern area of the German North Sea, specifically the Natura2000-area “Borkum

Riffgrund". The present study also found the highest diver abundance for the southern sub-area in the year 2012 and the spatial distribution maps show a high density in the "Borkum Riffgrund" area in this year, although this was already the case in 2011. However, numbers in the southern sub-area were still low compared to the northern sub-area and did not impact total population size estimates very strongly. Consequently, 2012 was not the year of highest diver abundance in this study. Despite clear fluctuations in numbers, no trend was found for diver abundance in the total study area or any sub-area of the German North Sea in this study. For the main concentration area, Schwemmer et al. (2019) also described no trend in population size after 2010, which is consistent with our results here.

The differences in estimates and conclusions drawn show that the most important issue regarding population size estimations is the data base which is used. Especially if inter-annual variation is high, as seems to be the case in this species, long-term data sets are especially important. The conclusions that were drawn in Schwemmer et al. (2019) might have been influenced by the fact that the data set happened to end on a year of comparatively low population size. Upon the inclusion of further years of data, we cannot confirm the conclusion of Schwemmer et al. (2019) of a decline in diver population size. Other differences might arise from the specific monitoring data and methodology. The present analysis included aerial survey data from wind farm monitoring, which was not available to other studies, while other studies included ship survey data in their analysis, which was not done here. Since ships cause disturbance to divers (Bellebaum et al. 2006, Fliessbach et al. 2019) and ship surveys cover smaller study areas, these data might not be suitable for the analysis of diver populations. The inclusion of ship surveys might cause substantial bias in the analysis, which could explain some of the differences found in this compared to previous studies.

Our results cannot confirm the hypothesis of Schwemmer et al. (2019) and Garthe et al. (2018) that a significant decline in the local diver population has been observable since the expansion of offshore wind power in this area. Our results show no trend for the population size of divers in the spring, neither in the study area of the German North Sea as a whole, nor in the main concentration area for divers, nor in the SPA. No trend had been found in the first diver study and this conclusion still stands after the analysis of an additional three years' worth of data.

The spatial distribution of divers was previously described by Garthe et al. (Garthe et al. 2015, 2018). In Garthe et al. (2015), a similar distribution was found in spring (March to April) for the years 2000 to 2013 as in this study, with particularly high densities in the main distribution area and lower densities in the southern parts of the German EEZ. A similar annual variability in high density areas within the northern sub-area was also observed in this study, as well as the higher densities in the southern sub-area in the years 2011 and 2012 (Garthe et al. 2015). The study hypothesises that the higher densities in these years represented a new emerging distribution hotspot. This could not be confirmed or disproven in further studies, as the continued construction of further OWF in the area makes it impossible to distinguish whether divers would have established a new distribution hotspot in that area if it had remained undisturbed. A follow-up study covering the years 2000 to 2017 (Garthe et al. 2018) focused on the distribution of divers in relation to OWF and came to similar results regarding the displacement within the main concentration area and a more concentrated aggregation at a maximum distance to each of the OWF in the area (Garthe et al. 2018). With regards to spatial distribution therefore, our extended data set confirms earlier findings on the importance of the main concentration area for divers despite the reduced area use of the species within this space since the expansion of OWF.

6.5 Conclusions

This extended study builds upon an earlier study to verify the conclusions drawn. Since divers are highly sensitive species, a continued monitoring of their population size and development is very important, as adverse effects due to stressors such as OWF might take many years to manifest in population numbers. This study confirmed the results of the previous study, that no trend in population size is detectable for the study area of the German North Sea as a whole or the main concentration area. The population size in the southern sub-area seems to be stable, but at a lower level than before the expansion of wind farms in the area. Spatial distribution maps showed increased densities outside the main concentration area in recent years, which might indicate that divers are moving into other areas, possibly due to density effects or the movement of prey species. However, since no effect was found at population level, we might conclude that the carrying capacity of the available habitat - especially of the northern sub-area - has not been reached. Further studies into habitat quality and food availability could help our understanding of the delicate population dynamics in the area. Individual tagging and behavioural studies could also further improve our knowledge on individual responses and inter-annual variations. The long-term monitoring of divers in the area in the form of aerial surveys has provided a valuable dataset which allowed to describe the effects of OWF on divers with much more accuracy than a shorter dataset could have allowed. Since there is strong fluctuation in abundance and annual variation in distribution, a short snapshot could lead to misinterpretation of data. Due to the long-term monitoring efforts in the area, it was possible to show that despite a displacement effect and interannual fluctuation, the diver population in the study area remained stable over the years. The three additional years of data confirmed the general conclusions, but also indicated the possibility of a further fluctuating distribution.

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A APPENDIX

A.1 Supplementary material

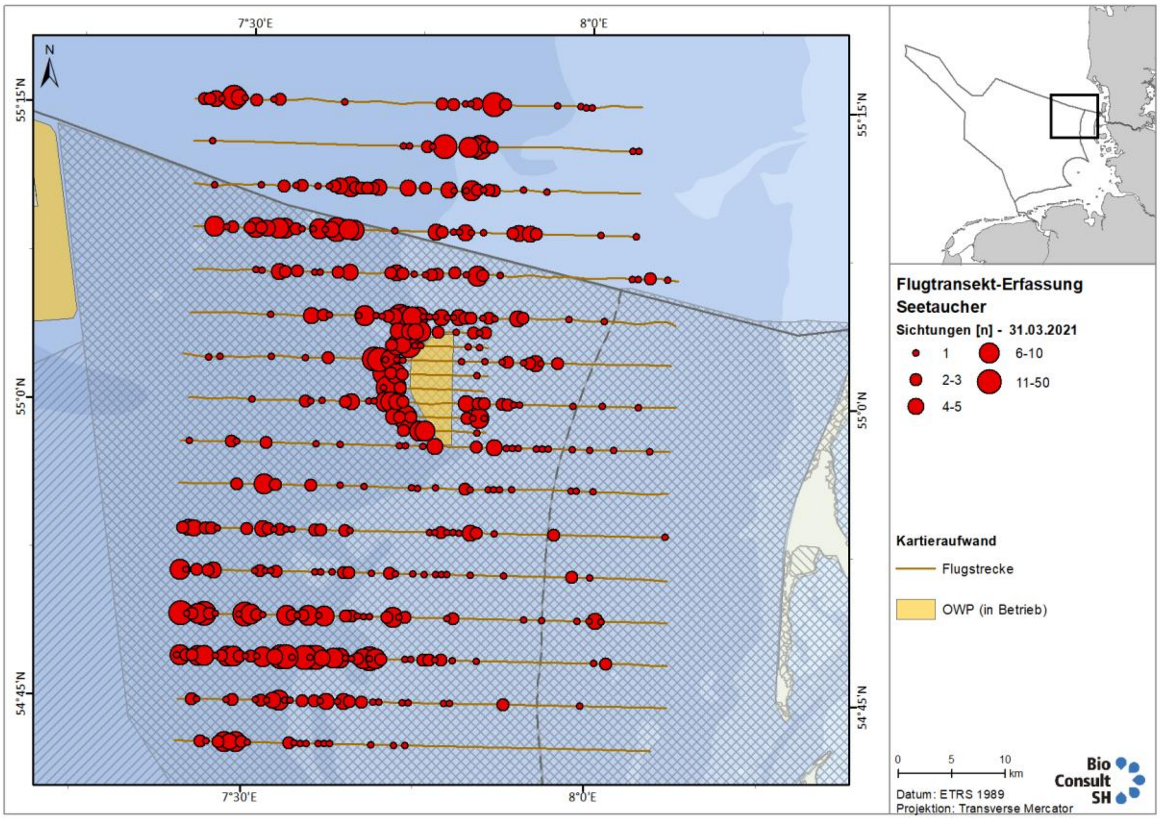


Figure A- 1 Diver observations during OWF Butendiek flight on 31.03.2021.

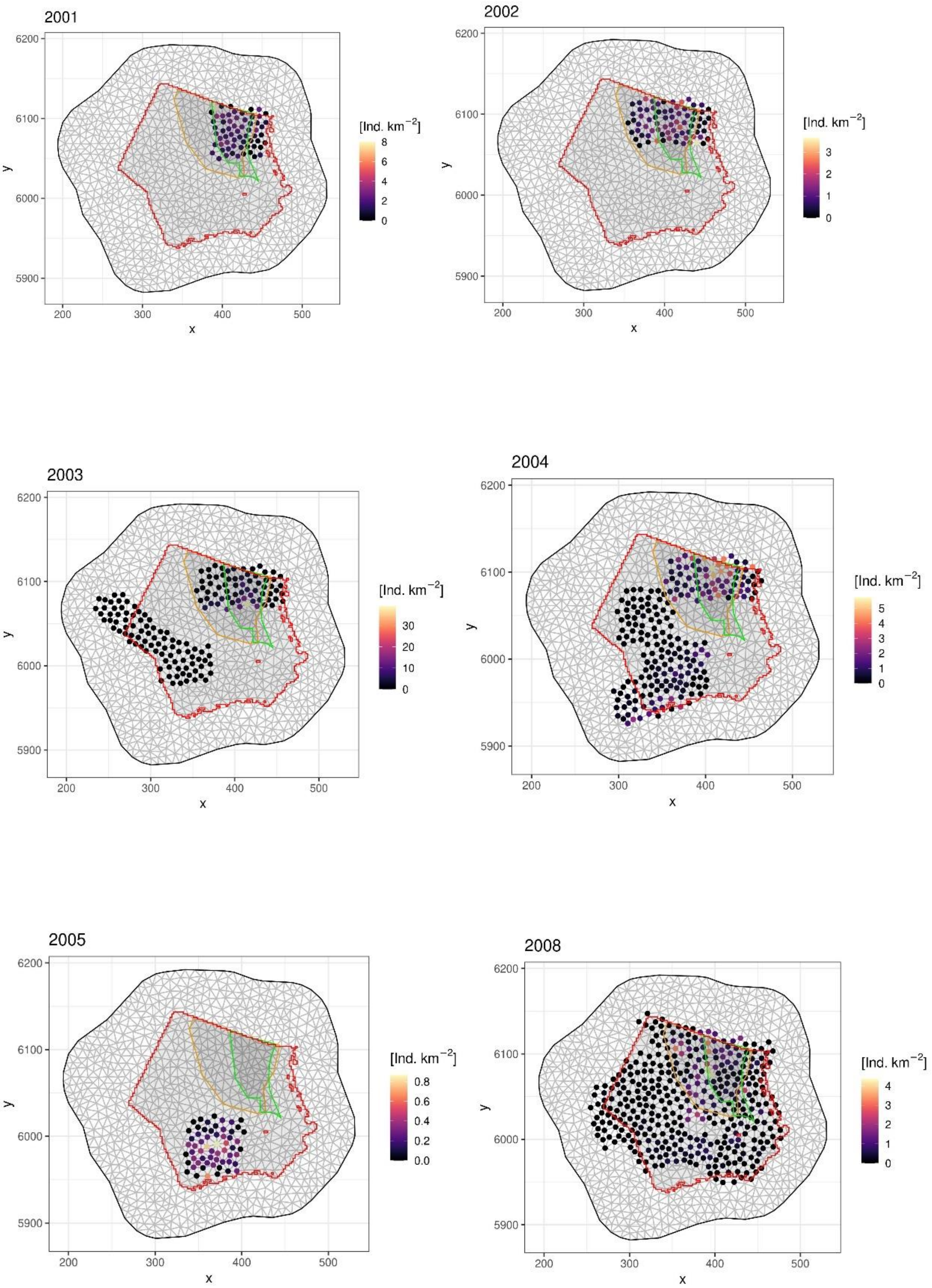
A.1.1 Visual aerial surveys

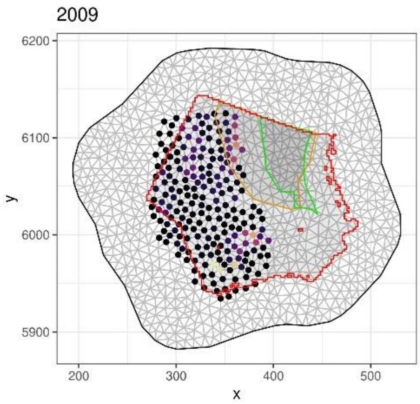
Table A- 1 Overview.

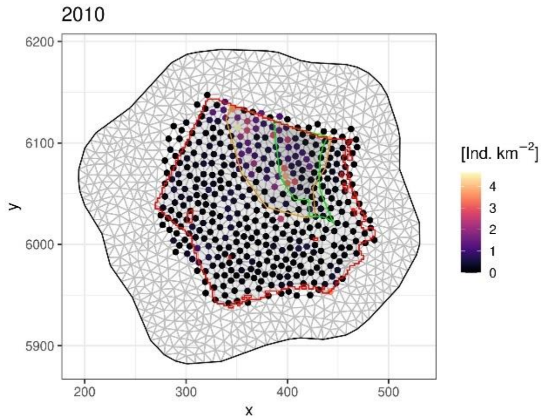
Source	years	N divers observed
IBL	2004-2010	706
IfAÖ GmbH	2003-2018	3186
BioConsult SH	2001-2010 (period 1) 2010-2014 (period 2)	3519 2167
FTZ Westküste	2002-2016	2378

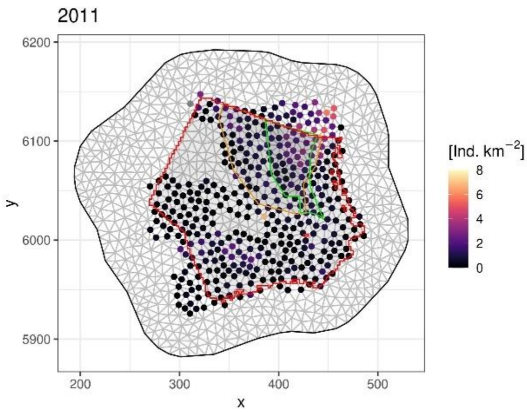
A.1.2 Results

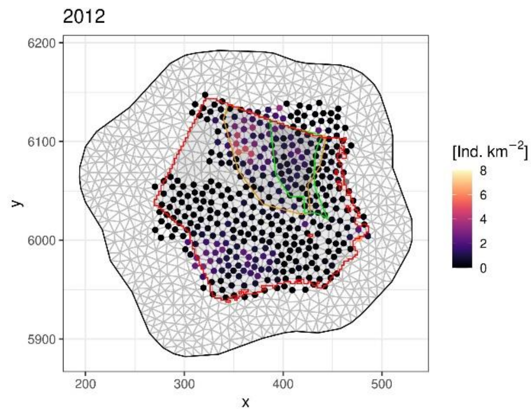
A.1.3 Observation effort

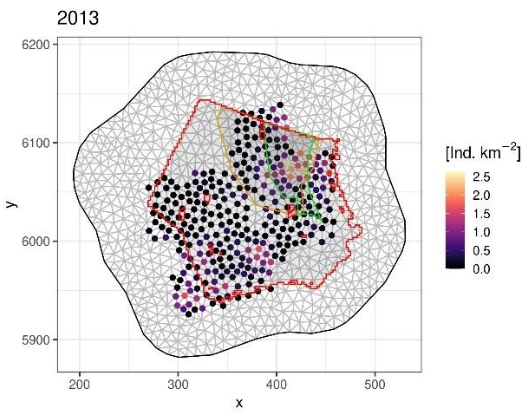

2001
2002
2003
2004
2005
2008
[Ind. km^{-2}]
x
y
6200
6100
6000
5900
200
300
400
500
8
6
4
2
0
3
2
1
0
30
20
10
0
5
4
3
2
1
0
0.8
0.6
0.4
0.2
0.0
4
3
2
1
0

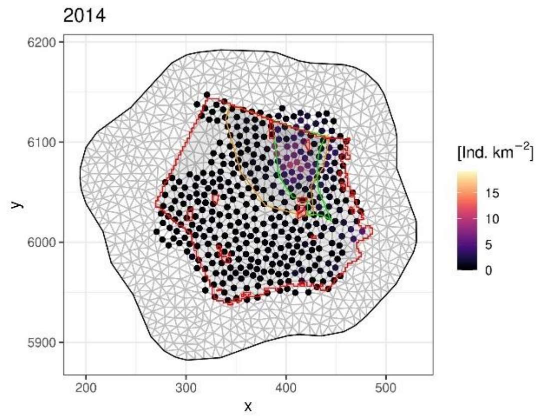

2009
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
2.0
1.5
1.0
0.5
0.0

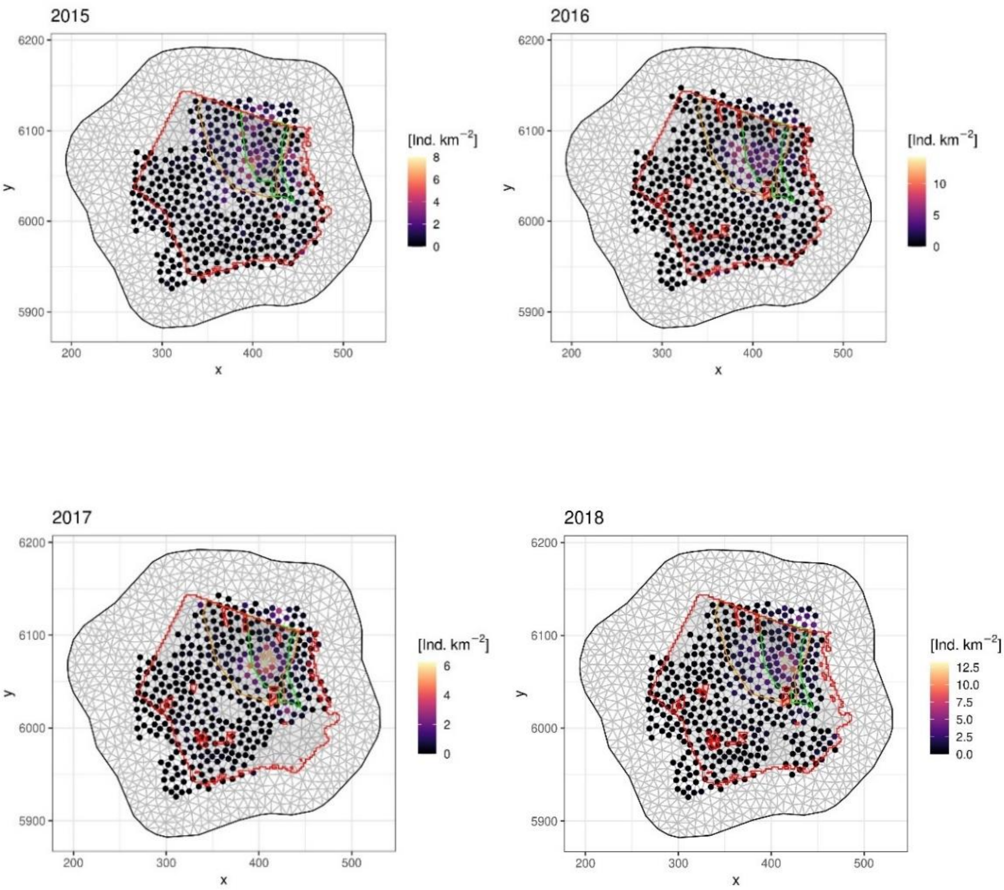

2010
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
4
3
2
1
0


2011
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
8
6
4
2
0


2012
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
8
6
4
2
0


2013
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
2.5
2.0
1.5
1.0
0.5
0.0


2014
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
15
10
5
0


2015
2016
2017
2018
6200
6100
6000
5900
y
200
300
400
500
x
[Ind. km^{-2}]
8
6
4
2
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0
12.5
10.0
7.5
5.0
2.5
0.0

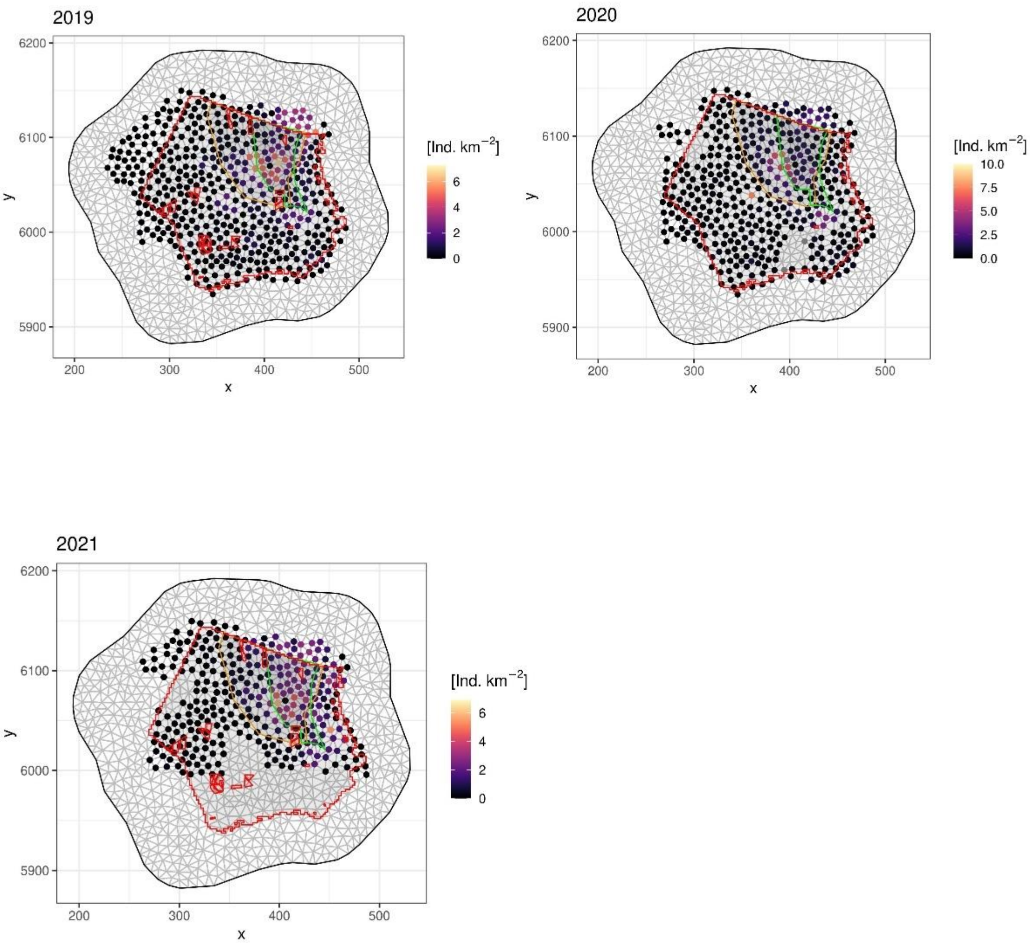
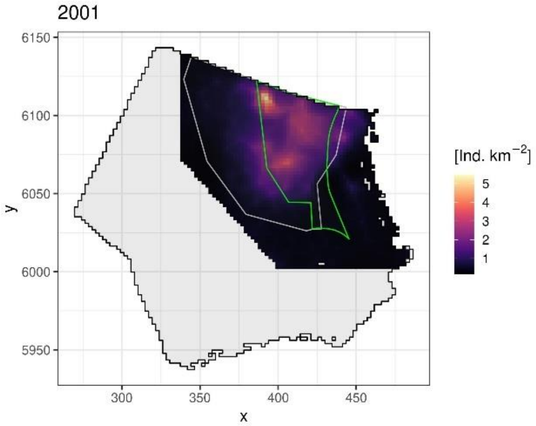
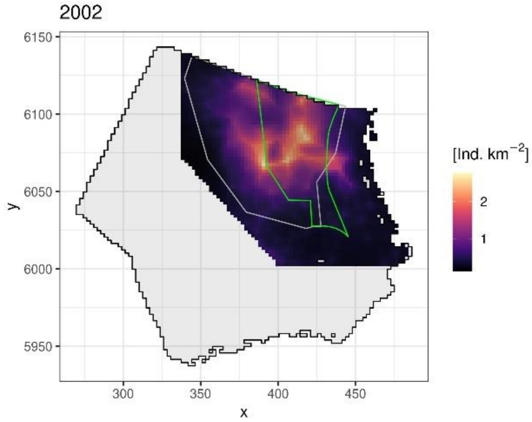
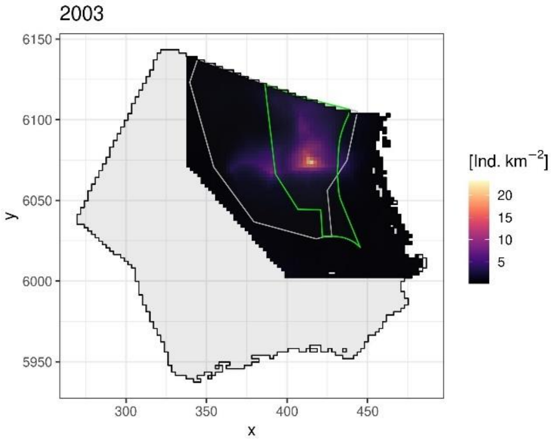


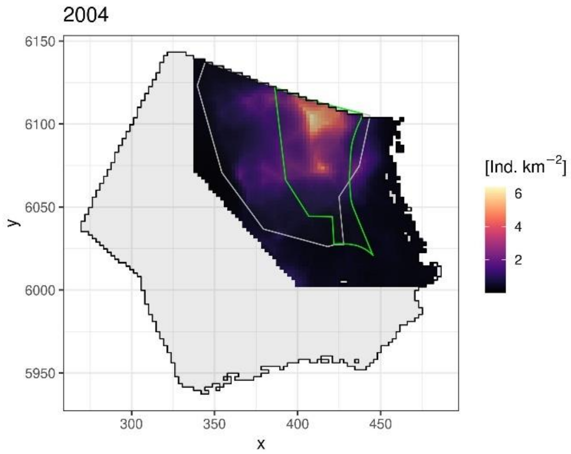
Figure A- 2 5-km mesh for spatio-temporal model for spring. Colours mark nodes where data was available and give densities for that location.

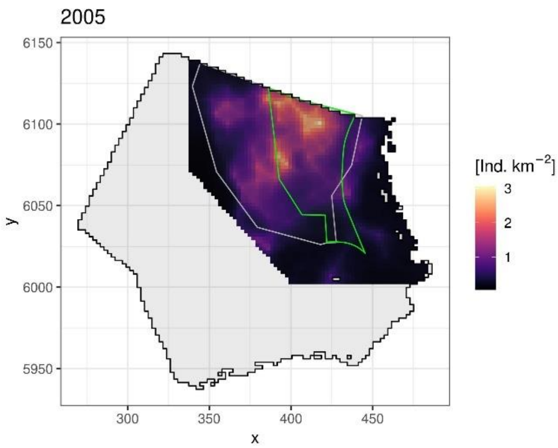
A.1.4 Results from spatio-temporal model

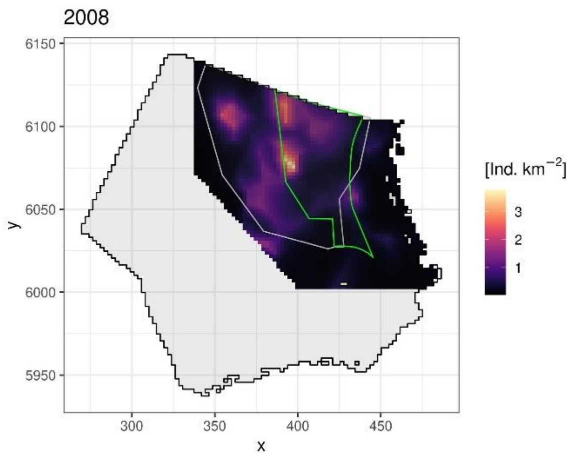


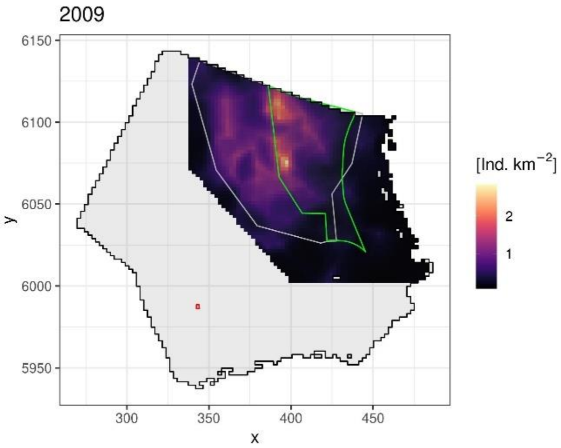


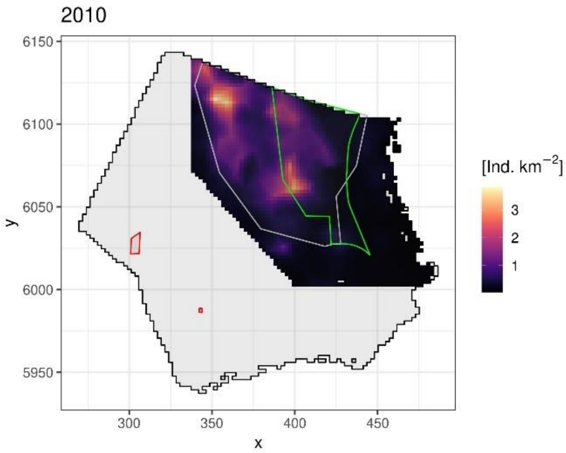


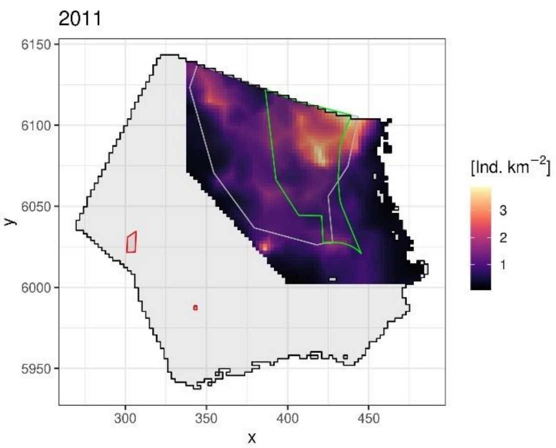


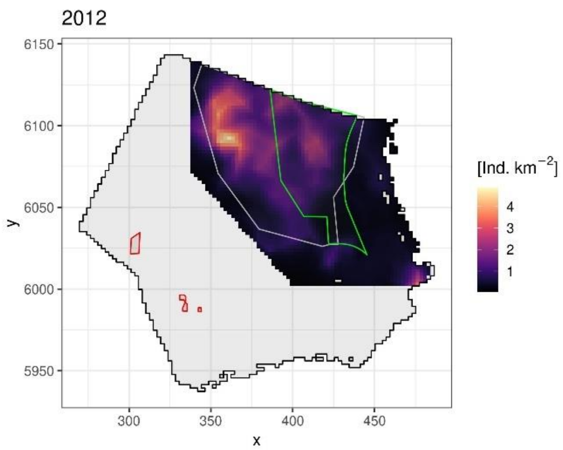


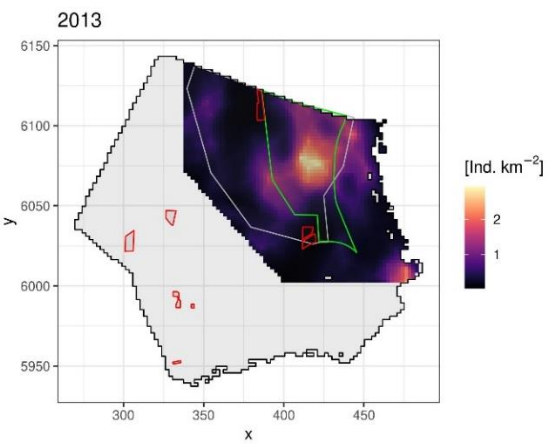


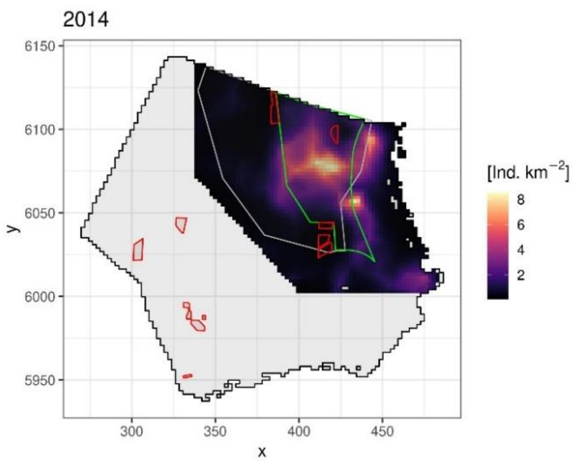

2009
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
2
1

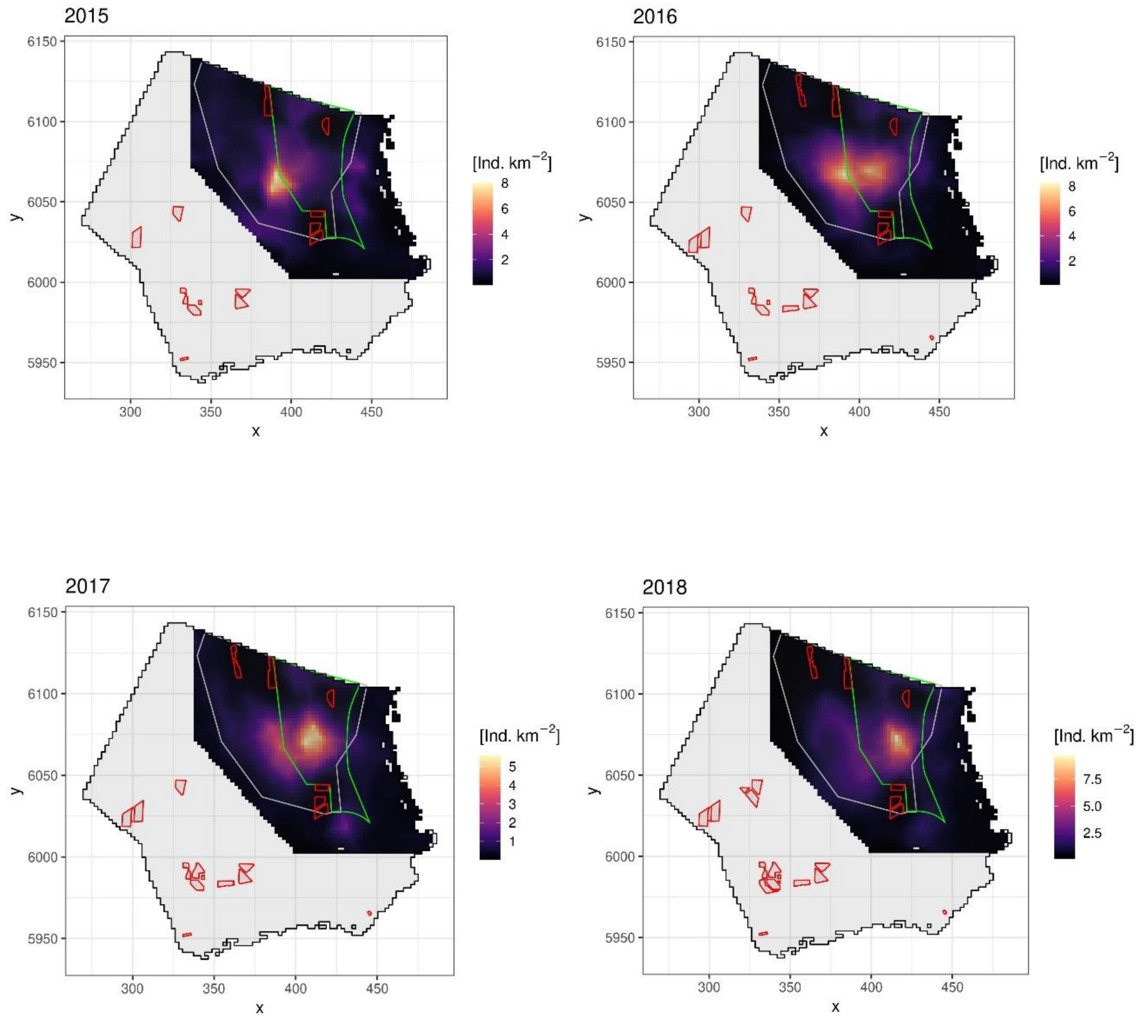

2010
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
3
2
1


2011
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
3
2
1


2012
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
4
3
2
1


2013
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
2
1


2014
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
8
6
4
2



2015
2016
2017
2018
6150
6100
6050
6000
5950
300
350
400
450
x
y
[Ind. km^{-2}]
8
6
4
2
5
3
1
7.5
5.0
2.5

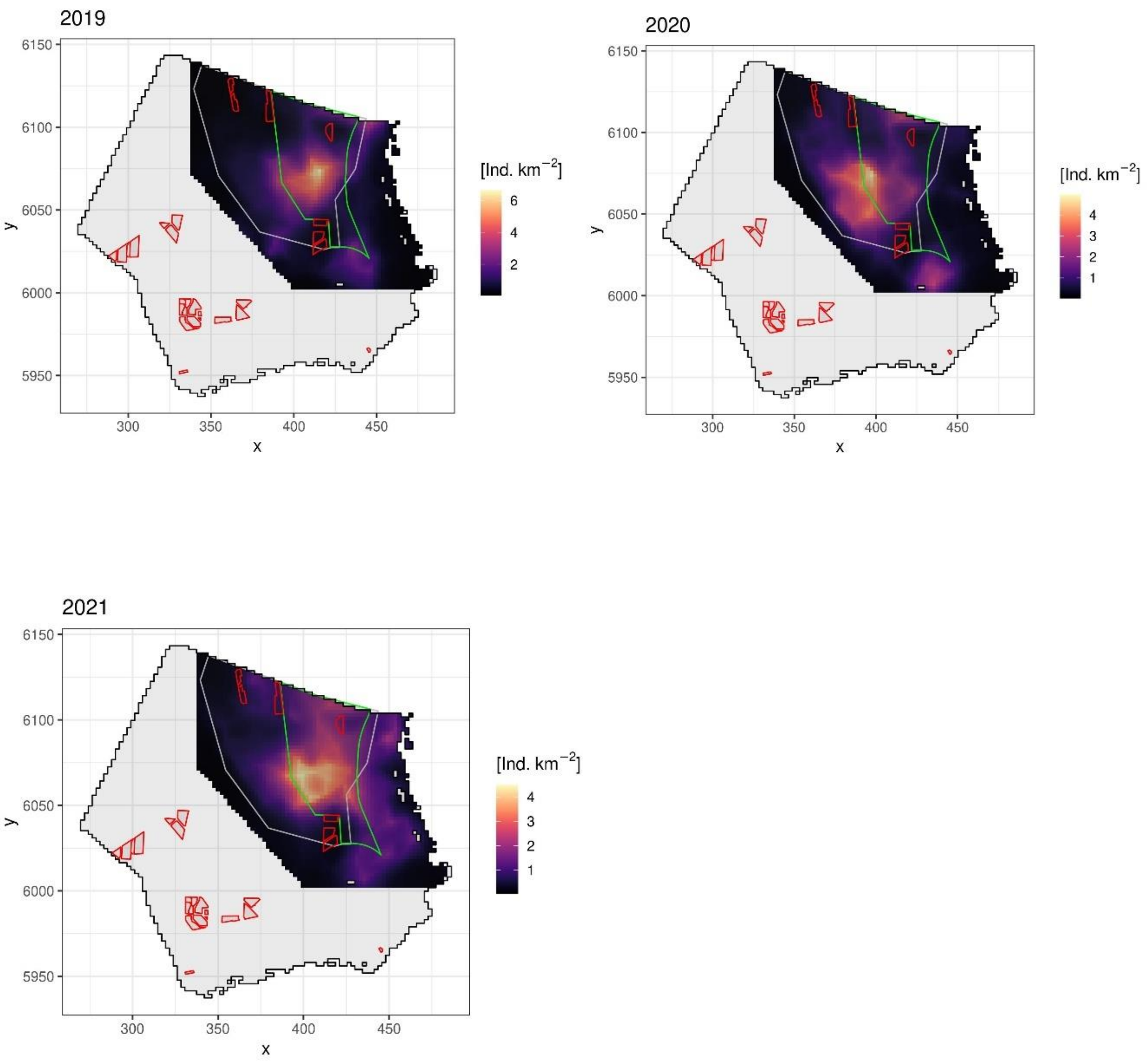
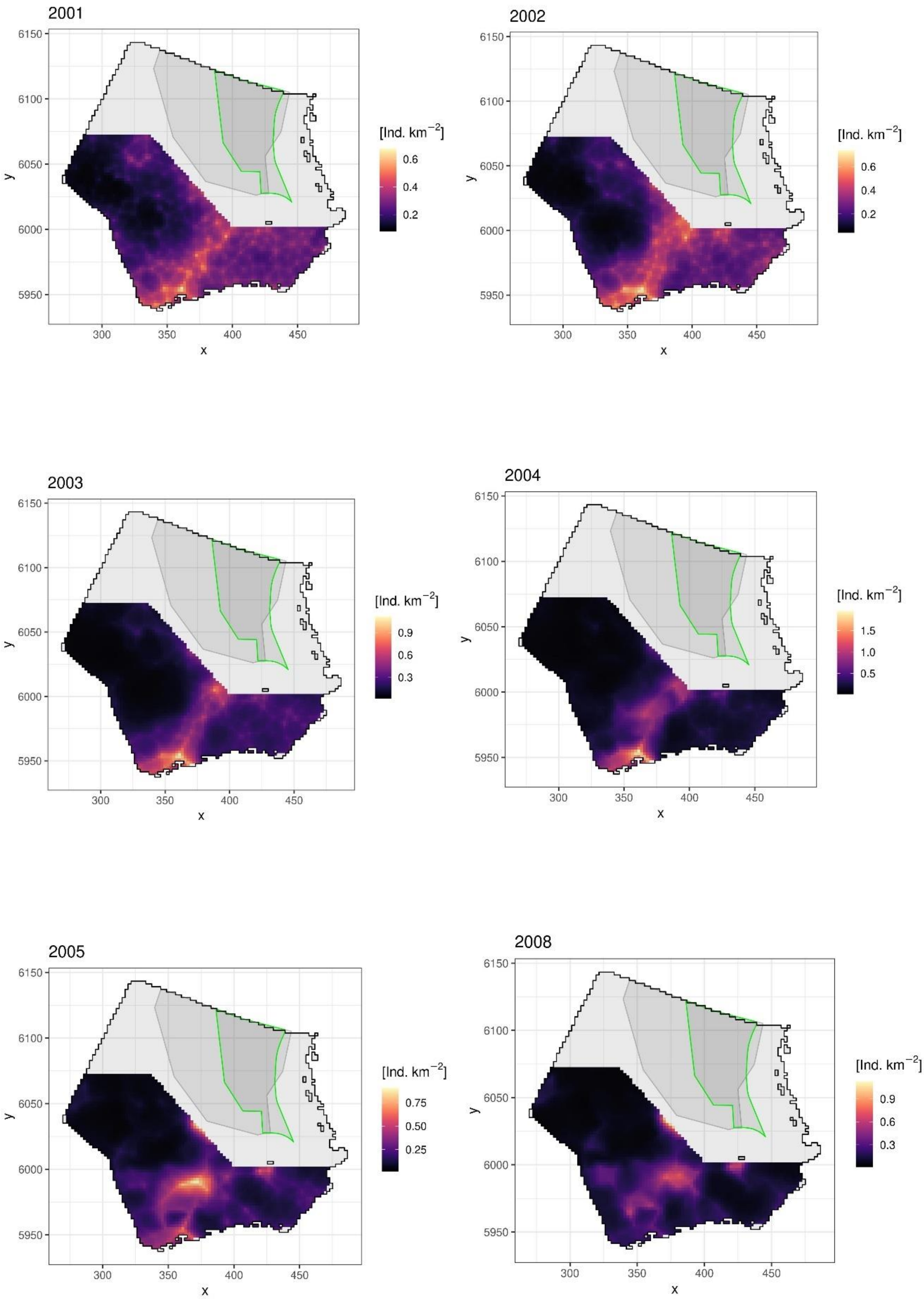
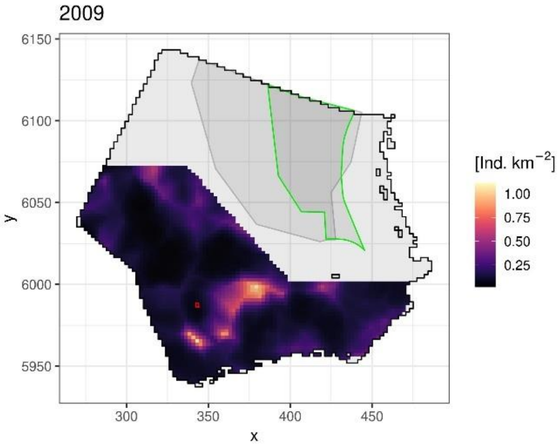
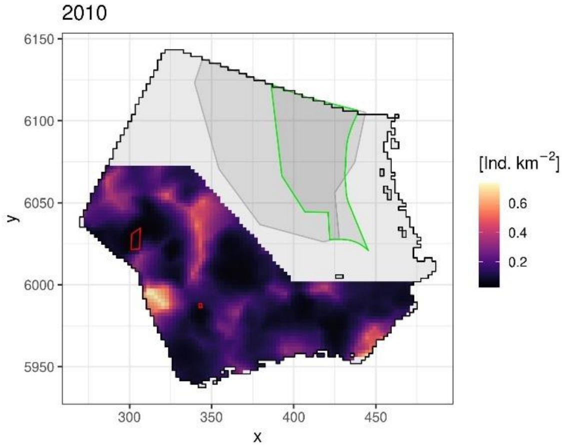
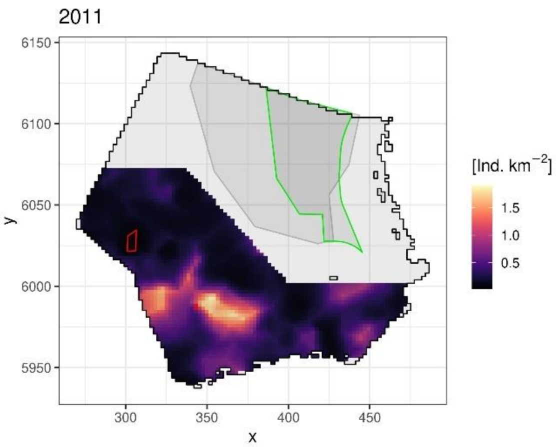


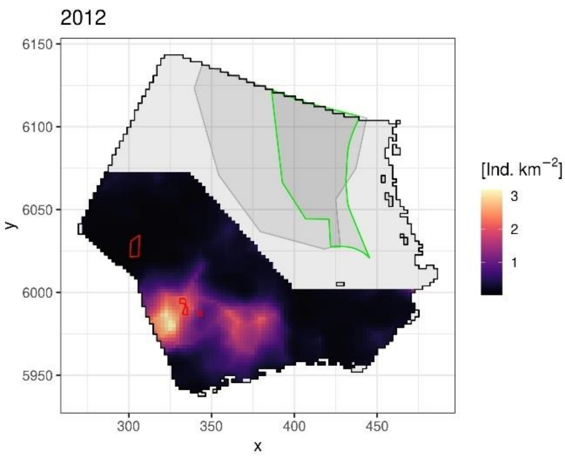
Figure A- 3 Predicted densities for spring for the northern study area. Note varying scales for each phase/year. Red borders indicate wind farms under construction or in operation. Green line depicts border of SPA "Eastern German Bight", white line depicts main concentration area for divers as defined by BMU (2009).

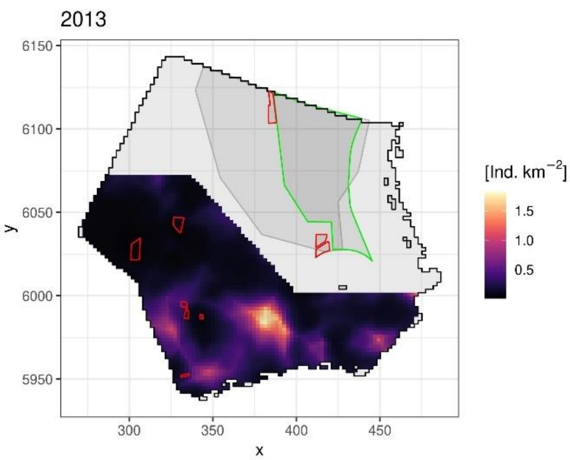

2001
[Ind. km^{-2}]
0.6
0.4
0.2
2002
[Ind. km^{-2}]
0.6
0.4
0.2
2003
[Ind. km^{-2}]
0.9
0.6
0.3
2004
[Ind. km^{-2}]
1.5
1.0
0.5
2005
[Ind. km^{-2}]
0.75
0.50
0.25
2008
[Ind. km^{-2}]
0.9
0.6
0.3
6150
6100
6050
6000
5950
y
300
350
400
450
x

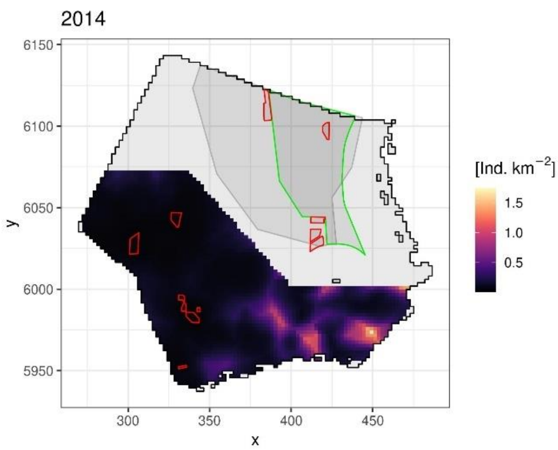

2009
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
1.00
0.75
0.50
0.25

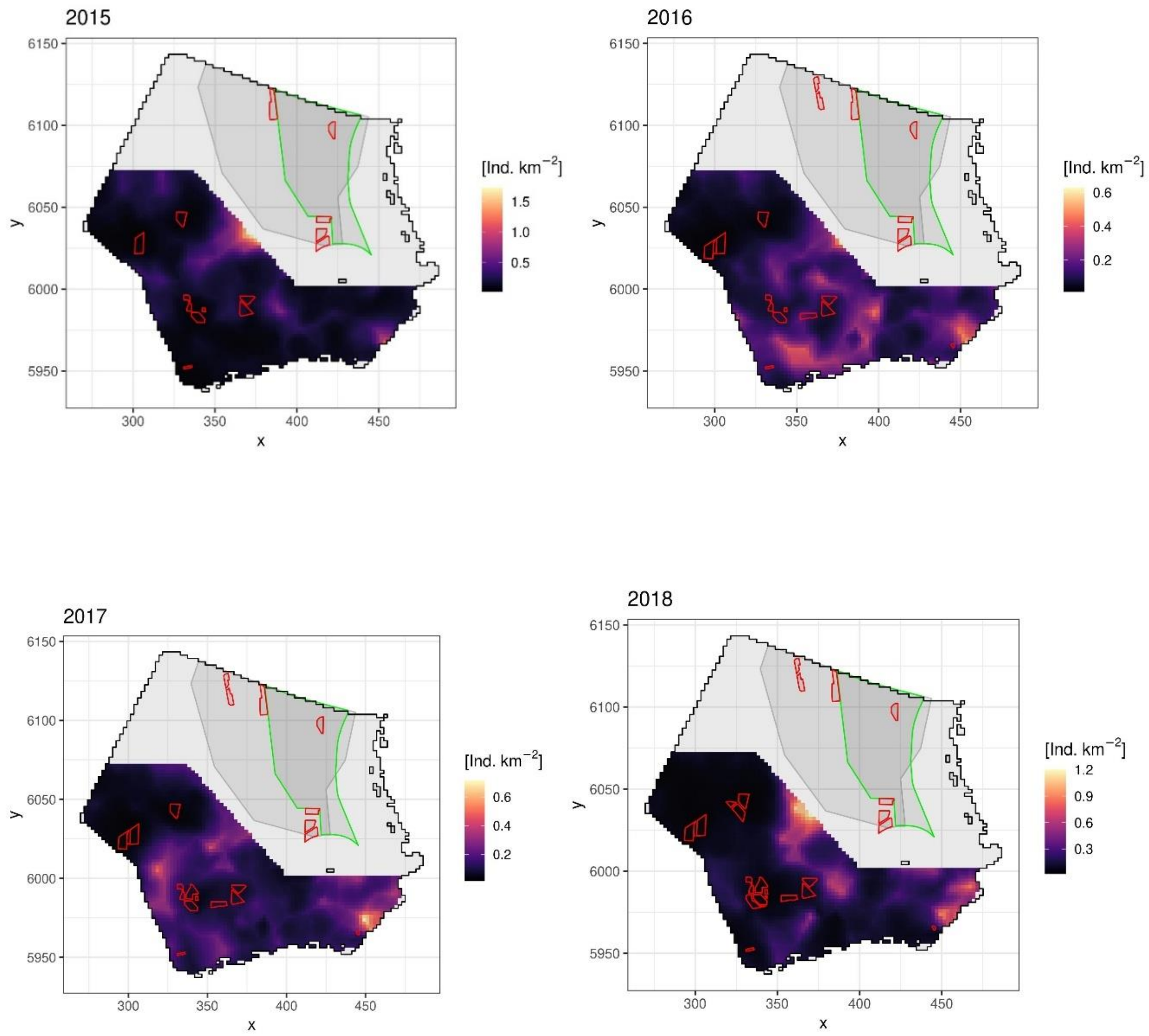

2010
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
0.6
0.4
0.2


2011
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
1.5
1.0
0.5


2012
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
3
2
1


2013
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
1.5
1.0
0.5


2014
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
1.5
1.0
0.5


2015
2016
2017
2018
6150
6100
6050
6000
5950
y
300
350
400
450
x
[Ind. km^{-2}]
1.5
1.0
0.5
0.6
0.4
0.2
1.2
0.9
0.3

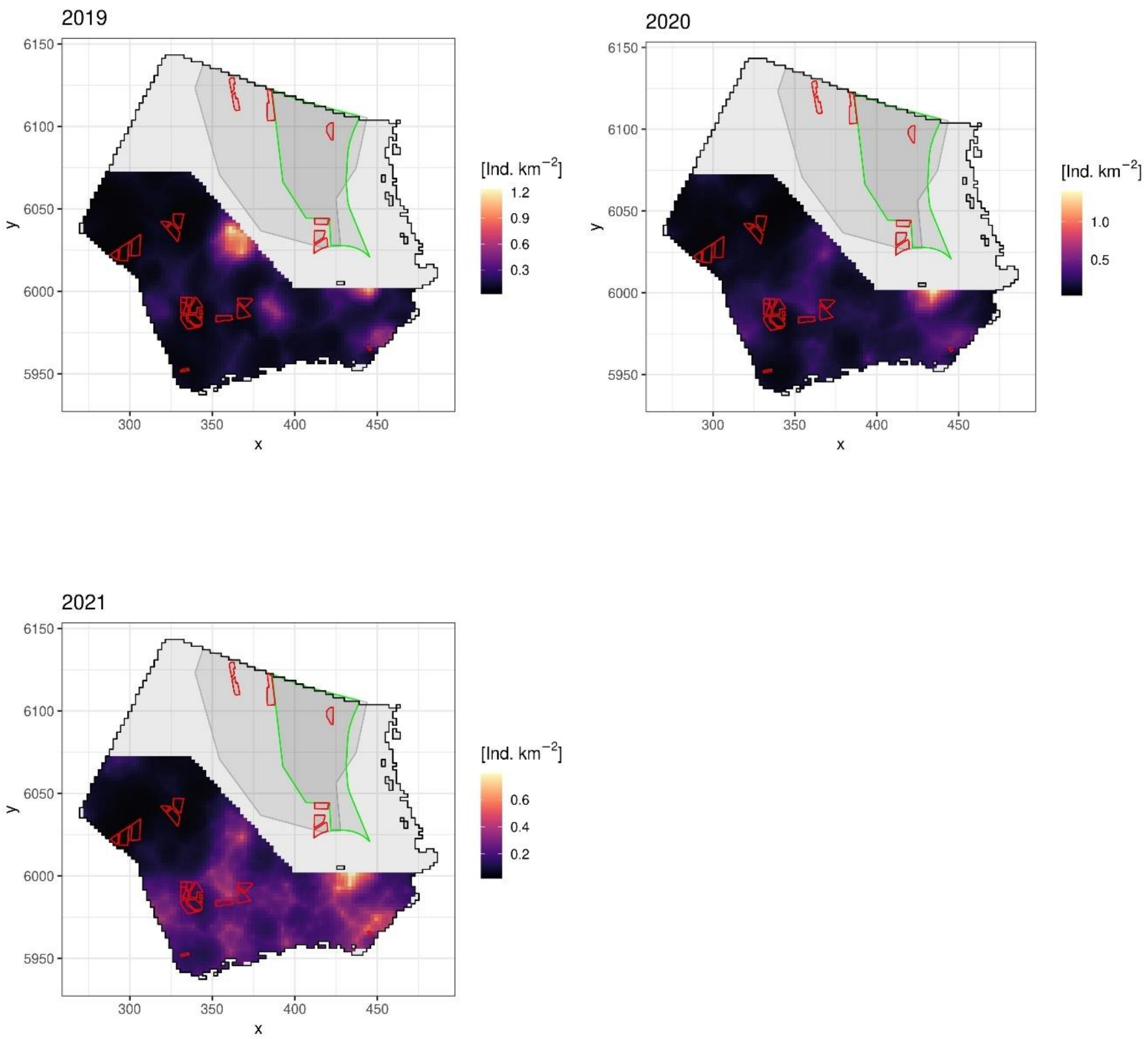


Figure A- 4 *Predicted densities for spring for the southern study area. Note varying scales for each phase/year. Red borders indicate wind farms under construction or in operation. Green line depicts border of SPA "Eastern German Bight", grey line depicts main concentration area for divers as defined by BMU (2009).*