Avoidance of offshore wind farms and movements by Sandwich Terns from pre- to post-breeding

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Summary

Accurate assessment of the impact of offshore wind farms (OWF) on seabirds is critical to their conservation. An important parameter in this assessment is the macro-avoidance rate, i.e., the proportion of birds that avoid entering an OWF. Recently, van Bemmelen et al. (2024) reported on the macro-avoidance rate of OWFs by Sandwich Terns based on integrated Step Selection Functions (iSSFs) using GPS-tracking data from the breeding season. Here, we extend that study with data collected during the pre- and post-breeding periods. We first describe the movements of the tagged terns, with a particular focus on the pre- and post-breeding periods. Most movements were restricted to 25 km from shore and in April-May these movement were primarily off the Belgian and Dutch west coasts. We also quantified flight speeds, which averaged at 33 km/h, in line several previous studies. With regard to macro-avoidance rates, we found similar values as van Bemmelen et al. (2024), with weak evidence for slightly higher avoidance rates only in April-May compared to later months. Furthermore, OWF-level effects were also in agreement with van Bemmelen et al. (2024), some estimates were improved in accuracy and estimates for several other OWFs could be added. Considering that during the April-May movements venturing further than 25 km offshore were common and macro-avoidance rates were estimated to be higher than in other periods, this period may be the time when Sandwich Terns are most vulnerable to displacement by offshore wind farm developments.

Nederlandse samenvatting

Het nauwkeurig bepalen van het effect van windparken op zee (*offshore wind farms*, OWFs) op zeevogels is belangrijk voor het behoud van zeevogels. Een belangrijke parameter daarin is de zogenaamde *macro-avoidance rate*, de proportie vogels die het windpark als geheel vermijdt. Recent rapporteerde van Bemmelen *et al.* (2024) macro-avoidance rates van OWFs door grote sterns *Thalasseus sandvicensis*, op grond van *integrated Step Selection Functions* (iSSFs) en GPS-zendergegevens verzameld in het broedseizoen. iSSFs zijn geavanceerde statistische modellen waarmee habitatselectie kan worden geschat waarbij tegelijkertijd rekening wordt gehouden met hoe de dieren normaalgesproken bewegen. Hier breiden we deze studie uit met data verzameld in de perioden vóór en ná het broedseizoen. Eerst beschrijven we de bewegingen van de gezenderde sterns, met bijzondere aandacht voor de perioden vóór en ná het broedseizoen. De meeste bewegingen beperkten zicht to 25 km van de kust en in april-mei waren ze vooral present langs de Belgische en Nederlandse westkusten. We kwantificeerden ook de vliegsnelheid, met als gemiddelde 33 km/u, wat overeenkomst met eerdere studies. Wat betreft *macro-avoidance rates* vonden we vergelijkbare waarden als van Bemmelen *et al.* (2024), met enig bewijs voor wat hogere waaden in april-mei in vergelijking met latere maanden. Macro-avoidance rates op het niveau van individuele windparken waren ook in overeenstemming met van Bemmelen *et al.* (2024), waarbij sommige schattingen nu preciezer waren (minder onzekerheid) en er konden schattingen voor een aantal extra windparken toegevoegd worden. Aangezien in april-mei de grote sterns zich vaker verder dan 25 km buiten de kust bevonden en de schattingen van macro-avoidance rates dan iets hoger zijn dan in andere perioden, zou deze periode de tijd van het jaar kunnen zijn wanneer grote sterns het meest kwetsbaar zijn voor het uitwijken van windmolenparken op zee.

Contents

1 Introduction

Offshore wind farms (OWFs) can impact seabirds through increased mortality rates following collisions or via habitat loss. An important parameter used in calculations of the effects of OWFs on birds, is the degree to which they avoid entering the OWF area: the macro-avoidance rate. This parameter is, however, difficult to robustly estimate given the logistic and methodological difficulties, and hence are lacking for many seabird species (Furness et al. 2013).

In an earlier study, we estimated the macro-avoidance rate of OWF for Sandwich Terns *Thalasseus sandvicensis* breeding in the United Kingdom and the Netherlands, arriving at an estimate of 0.54 for OWFs near a Dutch colony and 0.41 for the OWFs near a British colony (van Bemmelen et al. 2024). These estimates were derived from an analysis of GPS-tracking data collected and covering the breeding period; when birds were behaving as central-place foragers, i.e., regularly returning to the colony. During the pre- and post-breeding periods, Sandwich Terns extensively visit other colonies around the North Sea (van Bemmelen et al. in prep) and thus may also come within reach of several other OWFs that are normally not within the home-range of breeding terns.

In this study, we extend the study of van Bemmelen et al. (2024) with data collected during the pre- and post-breeding periods. Again, we used integrated Step Selection Models (iSSFs) to estimate macro-avoidance rates of 1) OWFs in general, 2) per period and 3) per OWF.

In addition to macro-avoidance rates, we provide an analysis of several other aspects relevant to assessing the impact of OWFs on Sandwich Terns. We describe the spatial behaviour throughout the time the terns are in the southern North Sea. Specifically, we study how far from land terns usually venture. Finally, we present an analysis of flight speeds, an important parameter in collision rate modelling.

2 Materials and methods

2.1 Study species

Sandwich Terns breed along the coasts of northwestern Europe, the Mediterranean Sea, the Black Sea and the Caspian Sea. The species typically breeds in few but often large colonies, which can show substantial annual changes in size and location, as the species has low breeding site fidelity (Courtens *et al.* 2022). Sandwich Terns forage (almost) exclusively at sea, where they target pelagic fish. Foraging trips during breeding range to about 40 km from the colony Thaxter *et al.* (2024), but outside the breeding period, the terns are known to prospect colonies across a very large area (up to 850 km; Fijn et al. (2014)), basically covering colonies across the entire North Sea basin.

2.2 Device deployment

Adult Sandwich Terns were captured between 2019 and 2021 at three locations: 1) Scolt Head, Norfolk, United Kingdom (52°59'N 0°40'E), 2) Slijkplaat, Haringvliet, with colonies either at Scheelhoek (51°49'N 4°04'E) or 5 km to the east at the Slijkplaat, the Netherlands (51°48'N 04°09'E) and 3) De Putten, Camperduin, the Netherlands (52°44'N 4°39'E). Adults were captured on the nest using self-triggered walk-in cages.

We used Ecotone GPS-UHF loggers (Ecotone, model PICA, ~4.5 g, 35 × 12 × 8 mm) with solar panels. The loggers in the UK in 2019 were fitted using glue-mounting. The glue-methodology followed that described by Seward et al. (2021). Those deployed in the Netherlands were attached using a full body harness constructed from fishing elastic (Preston Innovations Slip Elastic, diameter: 1.4−2.2 mm), which disintegrated over *ca.* 1.5 months (Fijn *et al.* 2024b), or, in 2020 (for 12 birds) and in 2021 (for all 50 birds), from 2 mm wide Teflon, which is relatively permanent. The combined weight of the logger, harness and rings was 6.3 g, which represented 2.3 to 2.8% of the body mass, thus staying below the generally accepted limit of 3% (Phillips *et al.* 2003, Vandenabeele 2013). GPS loggers automatically transmitted the tracking data to base stations positioned at each colony. GPS loggers were pre-set to record positions between 5:00 and 21:00 local time, taking positions at intervals of 5, 10 or 15 min, depending on year, location and the battery voltage. When battery voltage dropped below 3.7V, loggers switched to taking positions every 60 min. This happened particularly among birds with permanent harnesses, which experienced decreasing light conditions later in the season. In addition, we pre-set some of the loggers to ensure that the entire non-breeding period, including the following pre-breeding season, would be recorded without damaging the logger by draining the battery.

As all birds were fitted with temporary harnesses or glue-mounts in 2019, none of these collected data well into the post-breeding period or from the pre-breeding period in 2020. The first birds were fitted with permanent harnesses in 2020, the first post-breeding data was thus collected in 2020 and the first pre-breeding data in 2021. Birds tagged in 2021 using permanent harnesses then collected post-breeding data in 2021 and pre-breeding data in 2022. In 2022, an outbreak of HPAI caused high mortality among the Sandwich Tern population of northwestern Europe (Rijks *et al.* 2022, Knief *et al.* 2024), and also apparently killed many of the tagged individuals, reducing the number of tagged birds during the season, with few data collected in July and August-October. In 2023, only two individuals were detected by our base stations, which collected some post-breeding data in 2022 and pre-breeding data in 2023.

2.3 Spatial behaviour and flight speeds

Using the GPS-tracking data regularized at 60-minute data intervals (see below), we show which areas are used by Sandwich Terns in the southern North Sea per period. For the analysis of flight speeds, we use speeds recorded by the logger (instead of speeds calculated from positions), in line with Fijn and Gyimesi (2018). The speed recorded by the logger is based on three subsequent positions taken in a short interval and represent thereby the 'instantaneous speed'. The speed is logged as knots and were multiplied by 1.852 to arrive at km/h. Extreme speeds, exceeding the maximum speed found by Fijn and Gyimesi (2018) of 100 km/h, were exluded, although they had little effect on the mean and quantile range.

2.4 Macro-avoidance rates: statistical analysis

In line van Bemmelen *et al.* (2024), we deployed integrated Step Selection Models (iSSFs) to estimate macro-avoidance rates. To be able to compare our results with those from van Bemmelen *et al.* (2024) we resampled the data to 10-minute intervals. In addition, to increase the sample size for the pre- and post-breeding periods, we also resampled the data to 60-minute intervals.

In the absence of direct observation of breeding status, we choose to divide the data into periods to study temporal patterns in macro-avoidance. Based on the distribution of the data (see below), four periods were defined: 1) April-May, 2) June, 3) July and 4) August-October. The pre-breeding period is covered by April-May, which will include most of the incubation period. June covers the last parts of incubation and chick-rearing period. July covers the late chick-rearing period and the time after fledging. August-October will likely include data from parents with fledged offspring, as well as the post-breeding period.

As a rough indication of seasonal patterns of overlap in distribution of Sandwich Terns with OWFs, we assessed the number of positions within each OWFs per period and the percentage they make up of all positions. This also indicates which OWFs outside the OWFs studied by van Bemmelen *et al.* (2024) were encountered by Sandwich Terns, and in which period.

Per sampling regime (10 or 60 minutes), three iSSFs were fitted. iSSFs included the available (coded as 0) and used (coded as 1) steps as the response variable. The first iSSF included a categorical fixed effect with with two levels indicating whether a position was inside an OWF (base level) or outside OWFs. In the second iSSF, period and the interaction between the OWF-effect and period were included as fixed effect, to evaluate whether avoidance rates differed between periods. The third model included a categorical fixed effect with 51 levels: outside any OWFs as the base level and the 50 other levels for OWFs that held at least 50 steps with any available position in that OWF. In all models, step length (sl, in km), the log of step length and the cosinus of the turning angle (ta) were included as fixed effects, as including these tends to reduce bias in parameter estimation (Forester *et al.* 2009, Avgar *et al.* 2016). Step ID s was included as a random intercept u_s, with the variance of the random intercept for step ID fixed at 10^6 (Muff *et al.* 2019), which renders the likelihood of this model equivalent to a conditional logistic regression model (Aarts *et al.* 2012, Fithian and Hastie 2013). For the OWF-effects, random slopes u_{1-4} were included per individual i, with penalized complexity priors with scale parameter 3 and probability parameter 0.05 for their precisions. Models were fitted as Poisson models using Integrated Nested Laplace Approximation as implemented in the `R-INLA package` version 24.02.09 (Lindgren and Rue 2015). All calculations were performed in `R` version 4.3.2 (R Core Team 2023). Estimation at the level of OWFs were considered to have failed if they resulted in an avoidance rate of 0 or 1 with credible intervals spanning extremely low values up to 1. Bayesian p-values for comparisons among periods and between periods and the overall estimate of macro-avoidance, we took 1000 posterior samples and quantified how often the difference between two parameters was smaller than 0.

3 Results

3.1 Sample size

The 10-minute interval data used for the iSSFs comprised of 7517 ‘used’ positions of 98 individuals. The 60-minute interval data comprised of 3816 ‘used’ positions of 111 individuals.

The samples are not equally distributed over time, with most data collected in June and July, and no 10-minute data remaining for April and October (figure 3.1). The datasets for 10-minute and 60-minute intervals also differs in spatial distribution: the additional 60-minute data in the pre- and post-breeding periods is mainly from the northern Wadden Sea islands of the Netherlands, Germany and Denmark. It also includes more data from tracks covering the area in the southern North Sea between eastern England and Belgium/the Netherlands (figure 3.2).

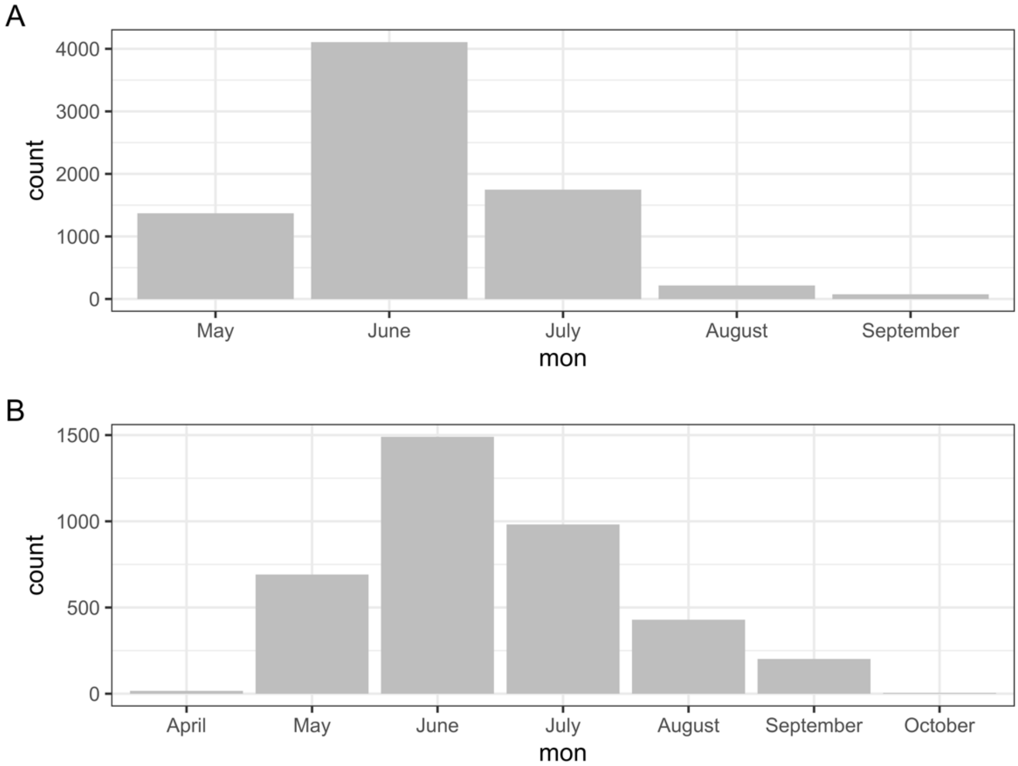

Figure 3.1 Temporal distribution of data per month for A. 10-minute data and B. 60-minute data.

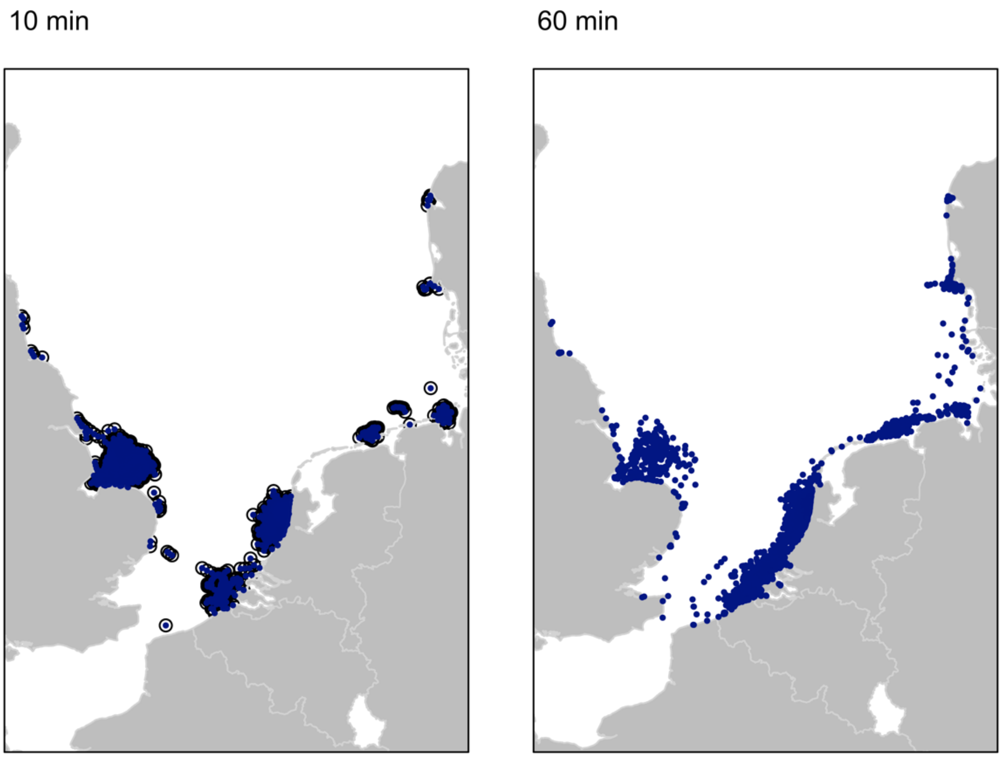

Figure 3.2 Distribution of 10-minute interval data (left) and 60-minute interval data (right).

3.2 Distribution throughout the time in the breeding area

The distribution of the tagged Sandwich Terns mainly reflects the locations of colonies where they were tagged, particularly in May and June (figure 3.3). In July 2019, loggers deployed in the UK had fallen off but, in the Netherlands, a few birds lingered around De Putten, where they were tagged earlier in the season. In 2020, birds tagged at De Putten and Haringvliet did not venture far from these colonies until after breeding in August-October, when some birds went to the German Wadden Sea islands. In 2021, birds tagged at De Putten and Haringvliet in 2020 (n = 2) and 2021 (n = 50) stayed close to the colonies in May and June. From July into August-October, individuals started spreading in all directions: to Norfolk, UK, to Belgium and northwards to the Danish Wadden Sea. In the pre-breeding period of 2022, many birds spent considerable time off the Dutch and Belgian westcoast as well as the Wadden Sea coast of the Netherlands and Germany. In June, thus earlier than in 2021, birds started spreading to, e.g., Norfolk and Denmark. The number of working tags declined greatly following the spread of HPAI, with few remaining in July. These birds were still lingering off the Dutch westcoast, Norfolk and Denmark, which remained more or less the same in August-October. The two remaining individuals in 2023 spent time off the Belgian and Dutch westcoasts in April/May, while one ventured across the North Sea to Norfolk in June. The last few positions recorded were from the Zeebrugge area, Belgium, in July.

During all years and periods, Sandwich Terns mostly stayed within 25 km from land. Positions further offshore mainly occurred in April/May, with proportionally less in other periods (figure 3.4A). Offshore positions in April/May shows mostly occurred off the coasts of Belgium and Zeeland, including trips across the North Sea between Belgium/the Netherlands and eastern England. During June, offshore positions occurred off Scolt Head, Norfolk, where birds made many long foraging trips. Off De Putten, however, trips venturing father than 25 km were apparently less common, although a band of positions can be seen. Finally, some offshore positions were recorded off Germany and Denmark, mainly in August-October (figure 3.4B).

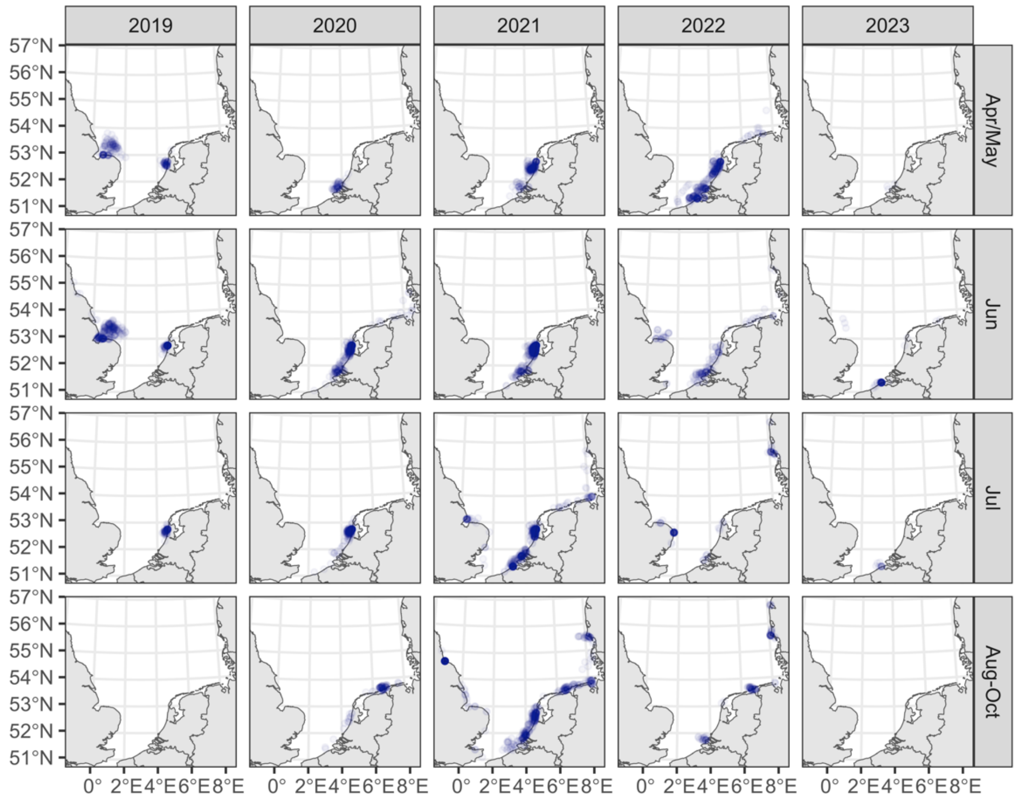

Figure 3.3 *Spatial distribution of GPS-positions in the years 2019-2023 in the four periods. Post-breeding data (i.e. from about late July) was collected from 2020 onwards; the first pre-breeding data thus collected in 2021.*

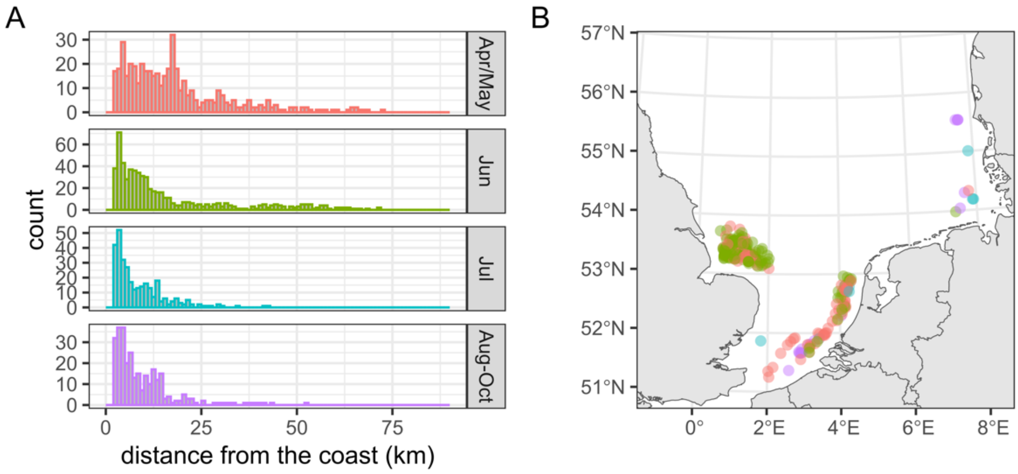

Figure 3.4 *A. Distance to the coast for all positions using the 60-minute data compared between periods, using only data at distances greater than 2.5 km from the coast, to allow detail to be seen at larger distances. B. Distribution of positions further than 25 k.*

3.3 Flight speeds

The distribution of speeds is bimodal, with a large peak close to zero, when birds were stationary or moving only small distances, and another peak between 10-25 km/h. The 'valley' between these peaks is at about 10 km/h. Excluding speeds below 10 km/h, flight speeds were on average 33.6 km/h (sd = 12.7 km/h, 95% CI = 12.4 - 61.1 km/h, n = 111895).

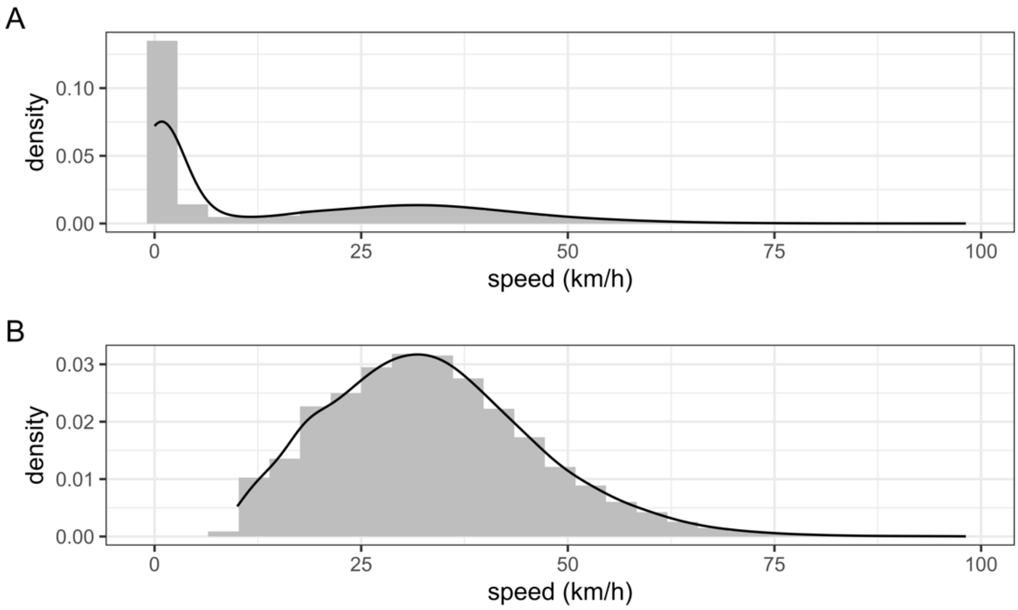

Figure 3.5 *Distribution of speeds of Sandwich Terns GPS-tracked during 2019-2023. In A, all data is shown, in B, only speeds higher than 5 km/h are shown to indicate flight speeds. Black lines show density curves.*

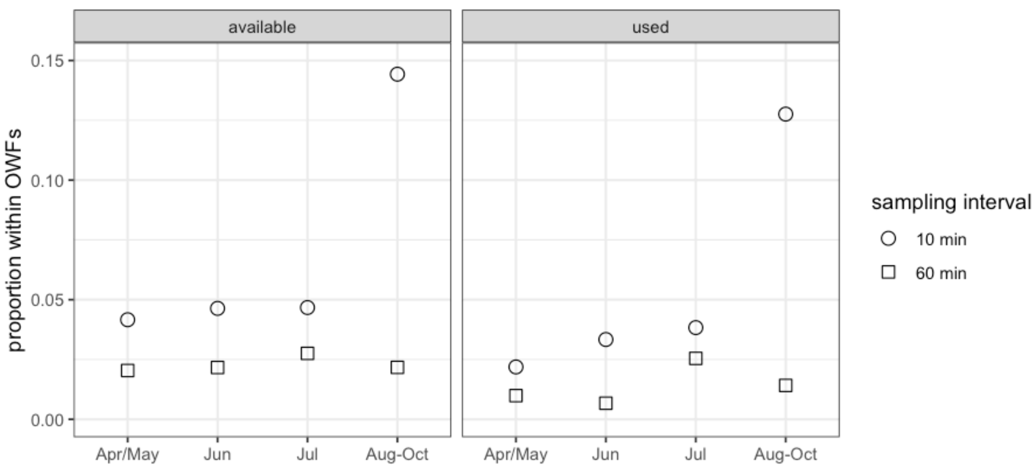

Figure 3.6 *Proportion of steps ending within OWFs for available (random) steps and used steps, for both sampling intervals, per period.*

3.4 Overlap with OWFs

Overall, the proportion of used steps ending within OWFs was small (0.22% % in 10-minute data, 0.16% in 60-minute data), regardless of sampling interval or period. The only exception is August-October, when about 12.8% of the used steps at a sampling interval of 10 minutes ended within OWF perimeters (figure 3.6). Many OWFs, however, did not have any used steps within their perimeters, although these OWFs were within reach as available steps *did* end within their perimeters (figure 3.7).

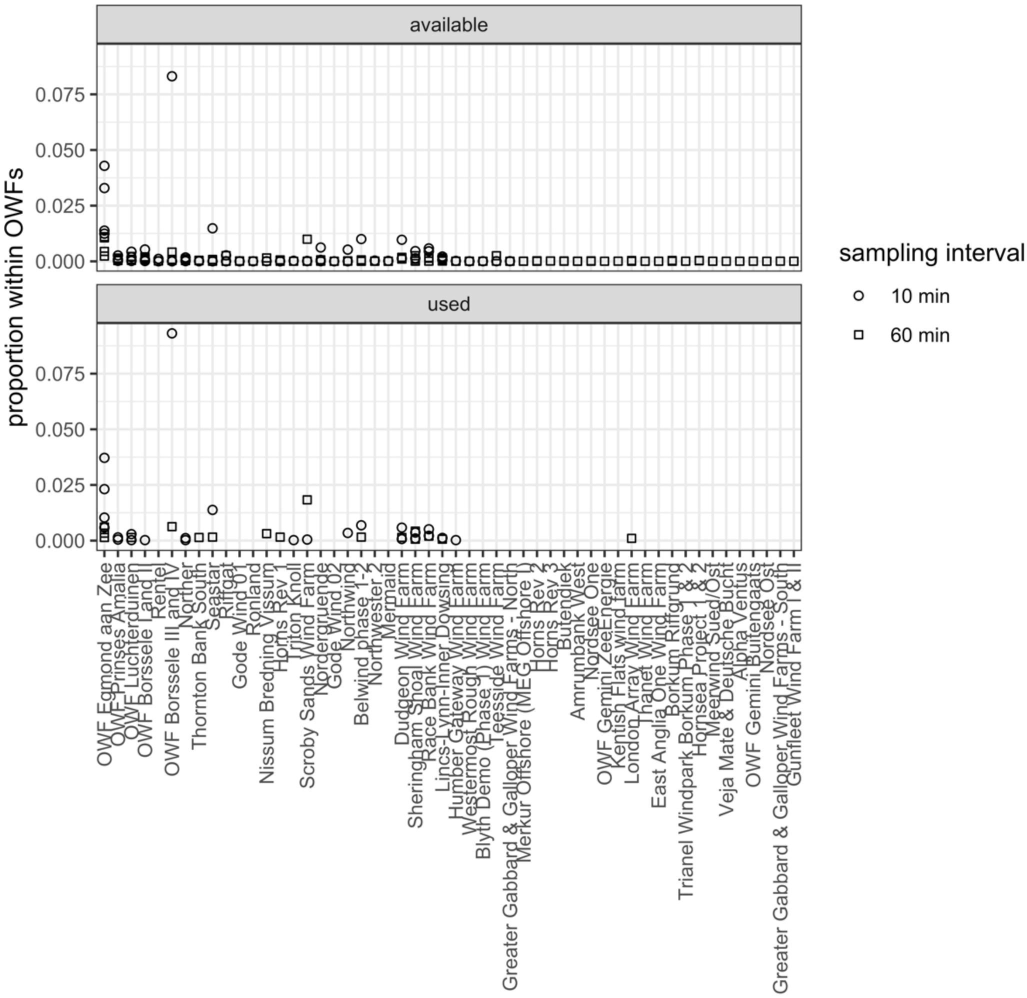

Figure 3.7 *Proportion of steps ending within OWFs, for available (random) steps and used steps, for both sampling intervals, per OWF. Note that many OWFs had available steps within them, but no used steps.*

3.5 Macro-avoidance rates

Using all 10-minute data, macro-avoidance rate was estimated at 0.53 (95% CrI = 0.44 - 0.62), thus equivalent to the estimates from van van Bemmelen *et al.* (2024) that were based on a (large) subset of the data (figure 3.8). As van van Bemmelen *et al.* (2024) used only data sampled at 10-minute intervals, no comparison can be made with our estimates for 60-minute data. Nevertheless, the general avoidance rate estimated from 60-minute data is similar but slightly higher to that of 10-minute data: 0.72 (95% CrI = 0.54 - 0.84) (figure 3.8).

Avoidance rates varied only slightly and mostly non-significantly between the four periods (April-May, June, July, August-October), for both 10-minute and 60-minute data (figure 3.8). For 10-minute data, only April-May seems to stand out with a marginally higher avoidance rate than the other periods (β_{MAY} = 0.67, 95% CrI = 0.51 - 0.78) , $p_{MAYvsJUN}$ = 0.053, $p_{MAYvsJUL}$ = 0.053, $p_{MAYvsAUG}$ = 0.133), but only marginally higher than the overall estimate ($p_{MAYvsOVERALL}$ = 0.069). Other periods did not differ from the overall estimate or from other periods except April-May. For 60-minute data, avoidance rates in April-May were not substantially higher than the overall estimate ($p_{MAYvsOVERALL}$ = 0.425), and only marginal from June and July, but not August-October (β_{MAY} = 0.69, 95% CrI = 0.23 - 0.88, $p_{MAYvsJUN}$ = 0.128, $p_{MAYvsJUL}$ = 0.128, $p_{MAYvsAUG}$ = 0.441). Overall, however, 60-minute data resulted in higher estimates than 10-minute intervals, albeit with larger uncertainty.

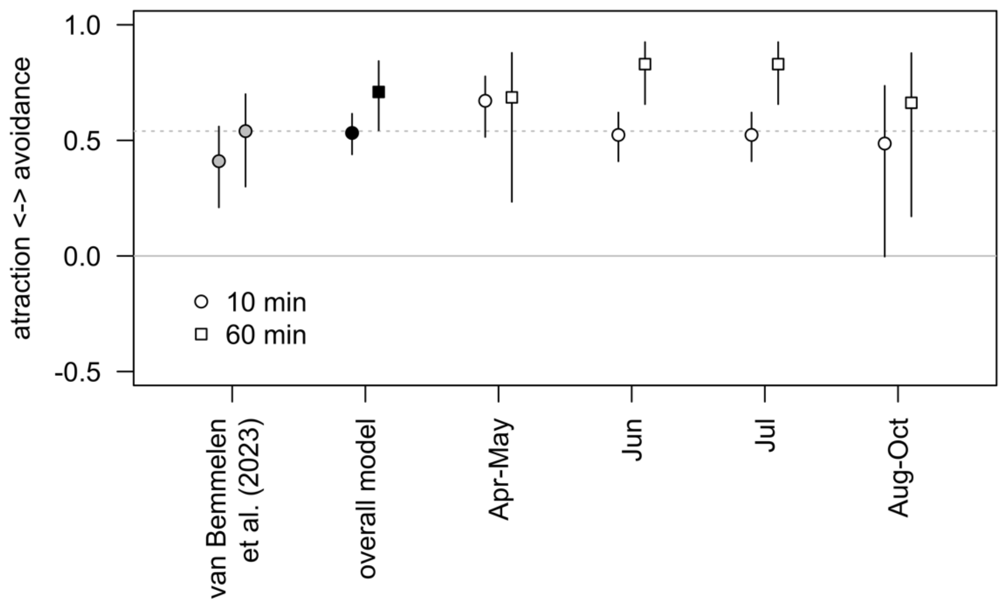

Figure 3.8 *Avoidance rates (positive values) or attraction rates (negative values) based on a subset of the data, as published in van Bemmelen et al (2024) (grey dots), an overall model including all data (black dot), and a model including period as a fixed effect (white dots), showing generally similar avoidance rates. The two estimates from van Bemmelen et al (2024) are for OWFs near the Scolt Head (left) and De Putten (right) colonies, respectively.*

3.6 OWF-specific macro-avoidance

Models failed to estimate macro-avoidance for 42 out of 50 OWFs included in the model (80%), as too few positions were collected near these OWFs and within the perimeters of these OWFs. For the remaining 10 OWFs, estimates varied substantially and were associated with generally very large credible intervals (figure 3.9).

Estimates for OWFs included those also presented in van Bemmelen *et al.* (2024). For the Netherlands, these were OWF Egmond aan Zee, OWF Prinses Amalia and OWF Luchterduinen. For the United Kingdom, these were Sheringham Shoal Wind Farm, Dudgeon Wind Farm, Race Bank Wind Farm and the aggregation of Lincs, Lynn and Inner Dowsing wind farms. Estimates for additional wind farms not included in van Bemmelen *et al.* (2024) are Norther (Belgium), OWF Borssele I and II and OWF Borssele III and IV (figure 3.9). For those already presented by van Bemmelen et al. (2024), estimates did not always correspond for OWFs with relatively small sample sizes. These estimates have gained in precision. For example, avoidance of Dudgeon was estimated by van Bemmelen *et al.* (2024) as relatively low, with large credible intervals, and is now estimated at 0.60 (95% CrI = 0.18 - 0.81), thus similar to other OWFs and the overall estimates. Also, the estimate for OWF Luchterduinen is now more similar to other OWFs: 0.92 by van Bemmelen *et al.* (2024) with wide credible intervals, now 0.65 (95% CrI = 0.14 - 0.86). Typically, OWFs with larger sample sizes were similar.

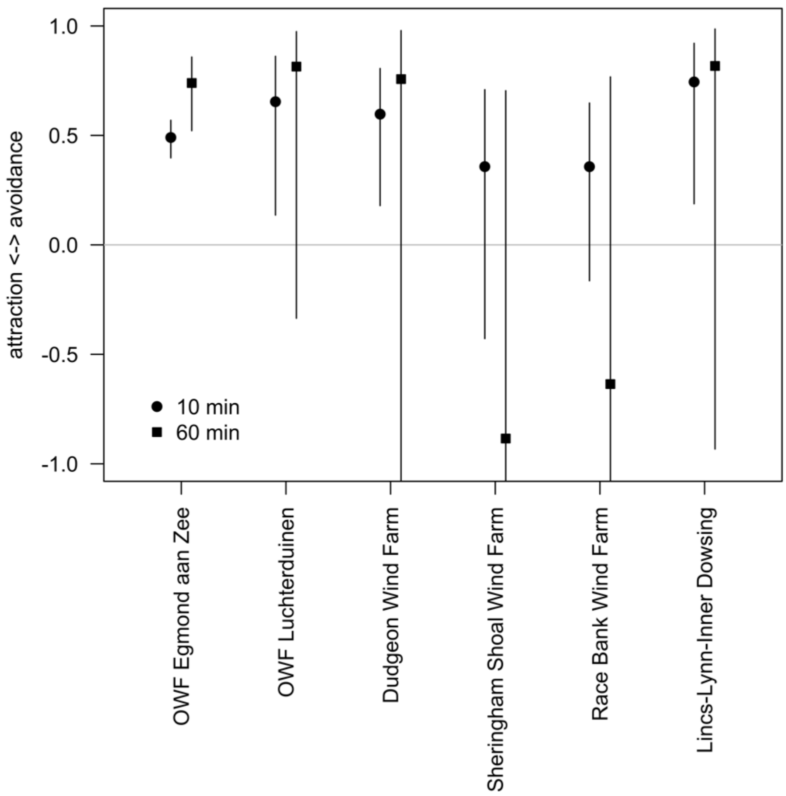

Figure 3.9 Estimates of macro-avoidance at the level of OWFs.

4 Discussion

We successfully collected GPS-tracking data of Sandwich Terns for not only the breeding period, but also the pre- and post-breeding periods. Such data have not been collected before and provided a unique opportunity to study movement behaviour throughout the time the birds are in the breeding area but not breeding. In this study, we described the general movements in the North Sea area, quantified flight speeds and finally estimated avoidance rates.

4.1 Movements

The tracking data confirms that Sandwich Terns are very mobile, performing extensive movements throughout the North Sea, particularly so in the post-breeding period, when individuals routinely moved from Dutch colonies northwards. Northbound post-breeding periods have also been described using colour-ring data (Fijn et al. 2014, Fijn et al. 2024a). Besides individuals moving north in the post-breeding period, many individuals congregated along the west coasts of Belgium and the Netherlands as well. This repeated in the pre-breeding season of 2022, when birds were again spread across a long stretch of coast from Belgium to the German Wadden Sea.

Most movements were within 25 km from shore. During breeding, offshore movements venturing further than 25 km offshore were common among birds breeding at Scolt Head, Norfolk UK, but less common among birds breeding in the Dutch colonies, such as at De Putten. Outside the breeding period, extensive offshore movements occurred during the pre-breeding period, with most data in 2022, when many tagged birds moved off the Belgian and and Dutch west coasts. Some birds were also recorded to move across the southern North Sea between Belgium/the Netherlands and eastern England, in fast directed flights. Also during the aerial surveys within the MWTL-monitoring program, a more offshore distribution of Sandwich Terns in April and August compared to June has been noted (e.g., van Bemmelen et al. 2022, 2023, 2024).

4.2 Flight speeds

The average flight speed calculated in our study arrives at a similar speed (33.6 km/h, 95% quantile range = 12.4 - 61.1 km/h) as reported by Fijn and Gyimesi (2018) in an earlier study using a smaller sample of GPS-tracks. Fijn and Gyimesi (2018) distinguished between foraging, outbound as well as inbound flights and reported averages of 29.9 km/h, 36.9 km/h and 44.4 km/h, respectively. Also other studies report similar speeds to what we found: average speeds of 33.1 km/h with head wind and 51.1 km/h with tail winds were reported for birds in transit flights by one study (Wakeling and Hodgson 1992) and 34.0 km/h and 39.0 km/h were reported for two colonies by another (Perrow et al. 2010). Our estimates of flight speeds could thus be further refined for specific circumstances: behaviour and wind direction.

4.3 Macro-avoidance

The macro-avoidance rate of offshore wind farms by Sandwich Terns, as estimated in our study, does not show substantial temporal patterns throughout the time that the terns are in the breeding area. The only potential exception is April-May, when marginally higher avoidance rates were found.

The overall estimates of macro-avoidance and the OWF-specific estimates generally match well with those from van Bemmelen et al. (2024), which is no surprise given the large overlap in used data. Interestingly, our study resulted in more precise estimates for some OWFs for which van Bemmelen et al. (2024) had little data. Furthermore, estimates for several OWFs close to the Belgian/Dutch border could be added. Many OWF-level macro-avoidance rates could not be estimated, partly because no or very few used steps ended within their perimeter, despite some – but usually also very few – available (random) steps ending within their perimeter. The only way to overcome this is to collect more data of terns that visit the vicinity of these wind farms.

In line with the study of van Bemmelen et al. (2024), our analyses were mainly based on GPS-tracking data sampled at 10-minute intervals. However, as much of our tracking data from the pre- and post-breeding periods concerned data sampled at 60-minute intervals, we also fitted models using 60-minute interval data. Macro-avoidance rates estimated from 60-minute data were generally slightly higher. This may be explained by the larger steps in 60-minute interval data, which will result in more 'steps' being included in the analysis, also from much considerable distances from the OWF where the probability of ending within a OWF by chance becomes very small. We suspect that 10-minute interval data, with concomitant smaller step lengths than the 60-minute data, better represents behavioural responses of Sandwich Terns to OWFs.

Considering that during the April-May movements venturing further than 25 km offshore were common and macro-avoidance rates were estimated to be higher than in other periods, this period may be the time when Sandwich Terns are most vulnerable to displacement by offshore wind farms.

5 Acknowlegdements

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