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# Offshore wind farm prospects and bird migration: Can a protected species be considered adequately?

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A B S T R A C T

Offshore wind farms (OWFs) pose a potential threat to migratory birds, either as a barrier or as a result of lethal collisions. We aimed to demonstrate the temporal and spatial frames for potential mitigation measures for a rare and protected species. We analysed 74 autumn migration tracks for 65 GPS-tagged Caspian terns (*Hydroprogne caspia*) through an area with operating and planned OWFs. On their way to their West African wintering grounds, Caspian terns breeding in Sweden crossed the Baltic Sea between Sweden and Germany in a narrow corridor, from mid-July to the end of August, during the day and at night, with crossings taking 1.5–3.5 h. Most of the tracks passed within > 10 km of existing OWFs, but 19% of birds passed within < 1 km or even crossed OWFs. However, implementation of the current planning scenario means that 77% of the tracks would cross OWFs, and > 9% of the core kernel home range (25% kernel) would overlap with OWF sites. This future scenario would therefore pose a major obstacle for migrating Caspian terns. A mitigation concept tailored to this regionally near-threatened species would need to consider the relatively large migration window of Caspian terns, presenting an economic challenge. However, the migration corridor remains consistent from year to year, allowing affected sea areas to be considered. A harmonized marine spatial planning strategy across national borders will be the best means of minimising the adverse ecological effects of OWFs.

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## 1. Introduction

Offshore wind farms (OWFs) play a major role in the expansion of renewable energies as a countermeasure to global climate change; however, the expansion of offshore wind energy generation also affects marine ecosystems in various ways (Lindeboom et al., 2011; Daewel et al., 2022; Galparsoro et al., 2022). Seabirds might be affected by the loss of habitats due to avoidance and displacement (Dierschke et al., 2016; Peschko et al., 2020; Garthe et al., 2023), even inside marine protected areas (Garthe et al., 2025). Moreover, migration routes across the sea between breeding and wintering areas can be affected for both seabirds and terrestrial birds (Hüppop et al., 2019). On one hand (depending on species-specific avoidance behaviours and prevailing circumstances, such as weather), birds may carry out evasive movements, i.e. they may fly around or over wind turbines or entire OWFs (Desholm and Kahlert, 2005; Plonczkier and Simms, 2012), leading to higher energy consumption (Masden et al., 2010), while on the other hand, birds crossing OWFs run the risk of potentially lethal collisions with turbines (Hüppop et al., 2019).

Environmental impact assessments carried out in the course of licensing procedures for OWFs often consider the impact of a single wind farm on bird migration in isolation, even though birds may encounter several wind farms when migrating over marine areas (Masden et al., 2010). Cumulative assessments are therefore necessary to assess the impact of wind energy on bird populations migrating over the sea. Furthermore, impacts on bird migration are often considered across all species rather than being species-specific, at least partly because radar observations of bird migration do not usually allow statements to be made for individual bird species (Hüppop et al., 2006; Fijn et al., 2015). However, threatened species with relatively small population sizes also migrate over the sea, highlighting the need for risk analyses at the species level. The development of telemetry allows individual flight paths to be tracked during migration: birds equipped with GPS data loggers, providing high spatial- and temporal-resolution data, can show how bird flights proceed in relation to existing and planned OWFs (Thaxter and Perrow, 2019; Schwemmer et al., 2022; 2023).

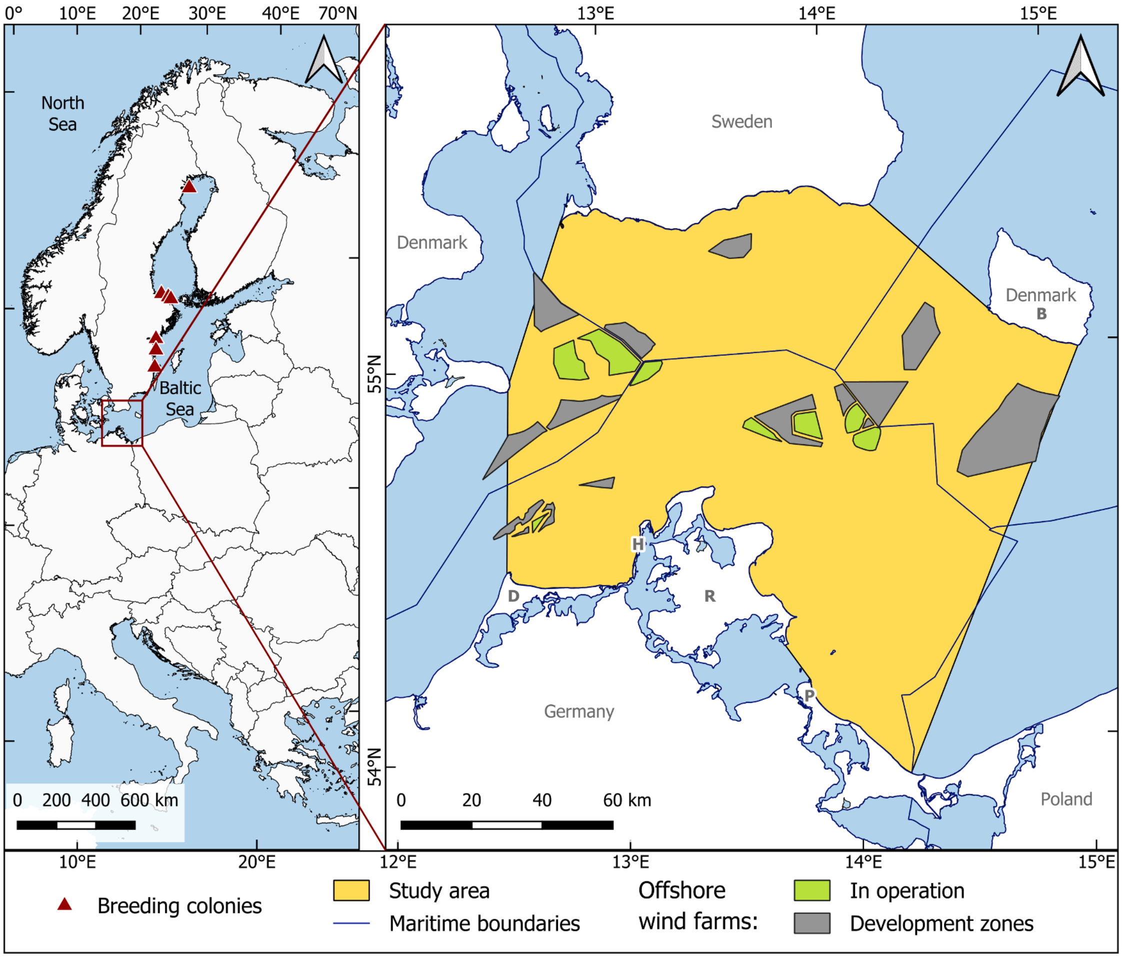


**Fig. 1.** Left: Study area in the Baltic Sea between Sweden, Denmark, and Germany. Breeding colonies (red triangles; n = 11) of tagged Caspian terns along the Swedish coastline (not all colony positions shown due to spatial proximity). Right: Study area (yellow) showing offshore wind farms in operation (green) and development zones by early 2025 (grey). For names, locations and data sources on operational windfarms and development zones, including their sizes and status, see Supplementary Fig. S1 and Table S2. B, Bornholm; D, Darß; H, Hiddensee; P, Peenemünder Haken; R, Rügen.

Telemetry data can be used to identify hotspots in broad-front bird migration (Schwemmer et al., 2022) and to assess the spatio-temporal migration patterns of birds in migration corridors. In this study, we used telemetry data to shed light on the flight paths of individuals of a regionally endangered species in a migration corridor between southern Sweden and northeastern Germany, where several OWFs are already operating and many more are planned (Fig. 1). The maritime area between southern Sweden and Rügen (Germany) allows a relatively short crossing of the Baltic Sea, which is exploited by many bird species, especially those using a mix of soaring, active, and gliding flight (raptors, cranes) (Strandberg et al., 2009; Nowald, 2010; De Koning et al., 2024). The Baltic population of Caspian terns *Hydroprogne caspia* breeds mostly along the Baltic coasts of Sweden and Finland., The vast majority of these birds also cross this sea area on migration from their breeding grounds in Sweden and Finland to their wintering grounds in Central and West Africa (Rueda-Uribe et al., 2021; Byholm et al., 2022). As the only population of Caspian terns in the European Union and accounting for most of the Caspian terns breeding in Europe, this population has been in decline since the 1970s, but has recently started to increase again (Ottosson et al., 2025). However, Baltic Caspian terns are still considered to be "near threatened" (HELCOM, 2025) and are specially protected under the EU Birds Directive, despite increasing on a global scale and treated as Least Concern in the IUCN global Red List. At the very least, this biogeographic population consists of only a relatively small number of individuals (4950–6150 birds in the period 2005–2012; Nagy and Langendoen, 2018).

The sea area between southern Sweden and northeastern Germany is an important passage area for Caspian terns on migration. Detailed knowledge of the exact course of migration is important to inform marine spatial planning in this sector, given the ongoing OWF construction plans by all the Baltic Sea states (Schwemmer et al., 2022). We therefore analysed how the regionally near-threatened tern population is influenced by existing wind farms and how it could be influenced by future planned wind farms. Evidence for overlaps between migration tracks and existing windfarms, the exact timing of migration (phenology and time of day), and ground speed are essential parameters needed to refine the modelling of collision risk (Cook and Masden, 2019; Masden et al., 2021). The current study provides this information, which will serve as a basis for planning possible mitigation measures (e.g. temporary shutdowns) to protect endangered bird species (Marques et al., 2014; Harwood and Perrow, 2019; Schwemmer et al., 2022).

## 2. Methods

### 2.1. Study area

The study area covered the Baltic Sea between southern Sweden and northeastern Germany. The northern boundary extended from Falsterbo in the southwest corner of Sweden, along the Swedish south coast, and further to the southeast corner of the Danish island of Bornholm. In the south, the border was defined from the peninsula Darß along the north coast of the island of Rügen to the German–Polish border (Fig. 1).

### 2.2. OWF data

The number of operational OWFs in the study area increased from two at the beginning of 2017 (Baltic 1, Baltic 2) to five in 2022 (Wikinger, Arkona Becken Südost and Kriegers Flak; Supplementary Table S1). Four of these OWFs are located within the territorial waters or the Exclusive Economic Zone (EEZ) of Germany, whereas Kriegers Flak is located in the Danish EEZ (see Supplementary Fig. S1). At the end of 2022, turbine construction for another OWF started, and many more OWFs are currently being approved or planned in the study area (4C Offshore, 2021) (Fig. 1, Supplementary Table S2).

OWFs were grouped into three distinct categories: in operation, under construction, and development zones. 'In operation' refers to operational OWFs as soon as the installation of all turbines was completed (even if only partially generating power), because of their aforementioned potential barrier effects for birds. 'Under construction' refers to the period between the installation of the first and last wind turbines. Construction phases prior to wind turbine installation, such as subsea exploration and monopile drilling, were thus not explicitly considered, despite potentially negative effects from noise and increased ship traffic. 'Development zones' refer to both approved and planned areas for future OWF developments and were included in the analysis to investigate potential effects in the future.

Notably, the information on existing wind farms and designated development zones is based on comprehensive research across various publicly available data portals conducted at the beginning of 2025 (see Supplementary Table S2 for sources); however, we cannot guarantee the completeness, accuracy, or currentness of the data, given the dynamic nature of spatial planning processes and the influence of shifting political prioritisations. The delineation and status of development zones have therefore been subject to frequent changes, depending on the data source, and may continue to change in the future.

### 2.3. Bird tracking

A total of 183 solar-powered Global Positioning System-Global System for Mobile Communications (GPS-GSM) 3 G devices were deployed on 32 adult and 151 juvenile Caspian terns across seven breeding colonies along the Swedish coast from 2017 to 2022 (n = 177 from Ornitela, Lithuania, weighing 15 g; n = 6 from Ecotone, Poland, weighing 15 g). The devices were attached using leg-loop harnesses using 9 mm tubular Teflon tape (Ecotone, Poland) (Mallory and Anderson, 2008). All terns were weighted prior to tagging to ensure that loggers represented 2.0%–2.7% of the individually measured bird's body mass. Previous work has shown limited negative impact of bio-logging on diving seabirds (Evans et al., 2020) and for tags without external antennae for aerially foraging swifts (Morganti et al., 2017). We used loggers without an external antenna to minimize impact on the terns foraging and flight

(Morganti et al., 2017) and harness material that degrade over time (9 mm Tubular Teflon tape, Ecotone, Poland) such that loggers will be lost. We have observed Caspian terns with colour rings returning without tags to the colonies (own observations) confirming the loss of tags but also successful breeding after logging by use of surveillance cameras in breeding colonies. Tags were lost several years after tagging. Adult birds were caught using walk-in or spring traps set over the nest during the incubation period. Juveniles were caught on the ground shortly before fledging. It was generally difficult to assign juvenile birds to their parents or siblings, but this was not an aim of this study.

The GPS devices recorded time of day, longitude, and latitude coordinates for the bird's location, flight altitude above sea level, instantaneous ground speed (i.e. flight speed over ground), and heading. Both the Ornitela and Ecotone devices recorded these data every 5 min with a battery charge over 75%, every 15 min with 50%–75% battery, every 30 min with 25%–50% battery, and every 2 h with < 25% battery charge. Data transfer was realized by the GSM network every 6 or 24 h (depending on battery levels) for Ornitela devices, and via UHF communication to a base station every 6 h (24 or 48 h at low battery levels) for Ecotone devices.

### *2.4. Selection of migratory tracks and data processing*

All GPS positions recorded from the tagged Caspian terns were visualized in a Geographic Information System using the open-source software QGIS (QGIS.org, 2025). To ensure data consistency, all geographic coordinates were re-projected to the coordinate reference system ETRS89-extended/LAEA Europe (EPSG: 3035). For the purpose of this analysis, all individuals that crossed the entire or part of the defined study area (Fig. 1) during their post-breeding migration were preselected.

For data-quality assessment, the available sea crossings were examined separately for each individual and year (each considered a "track"), given that the temporal resolution of the obtained GPS data varied depending on device type and battery status (see above). Records containing empty or invalid coordinates (i.e. latitude and longitude values of 0), e.g. caused by transmission failures of the data loggers, as well as entries with duplicate time stamps, were removed from the dataset. Subsequently, bird tracks with several missing GPS fixes resulting in large data gaps, e.g., tracks with less than three positions available or temporal gaps of more than 1.5 h within the study area, were omitted from the analysis due to insufficient data availability and positional accuracy.

To retain bird tracks with few gaps relative to the temporal resolution of the input data and further account for differences in sampling regimes, the remaining tracks were interpolated to a uniform interval length of approximately 5 min using generalized additive models implemented in the *mgcv* package (Wood, 2011), available in the open-source software R (R Core Team, 2024). This interpolation provided estimated latitude and longitude positions for all gaps within the defined interpolation interval, while preserving all originally recorded GPS locations. This led to a total of 1176 interpolated GPS fixes within the study area (Table 1).

The start and end points of all tracks were defined to enable individual and seasonal comparisons of departure dates and times, as well as flight durations, of the birds' sea crossings. The start of the crossing corresponded to the first position entering the study area and the end of the crossing corresponded to the last position before leaving the study area and/or before reaching the coastline. For most crossings (66 out of a total of 74 tracks) all positions of the tracks (both original and interpolated) were located completely within the study area. The remaining eight tracks extended partially beyond the defined boundaries but still contained a sufficient number of GPS positions within the study area to be included in further analyses. This occurred if individuals left and re-entered the study area in the middle of a track or arrived at the coast to the west or east of the defined boundaries after crossing the Baltic Sea. For comparability, the last position before reaching the coastline was defined as the track's endpoint in the latter case, despite being located outside the study area. A few remaining resting positions located within the study area were identified by means of their flight speed as well as geographic location on sandbanks near the shoreline and were excluded from the respective tracks. The crossing duration was subsequently calculated as the flight time between the defined start and end points of each sea crossing.

This resulted in a dataset comprising 74 tracks collected between 2017 and 2022 with a total of 2348 GPS positions, including 1176 interpolated locations that were used in the analysis (Table 1). These 74 tracks were obtained from 65 individuals, because four individuals had tracks from several years (2 years, n = 2; 3 years, n = 1; 4 years, n = 1).

**Table 1**
Annual numbers of bird tracks and positions used in this study.

| Year | Age class | No. of tracks | No. of positions (original/interpolated) |
|---|---|---|---|
| 2017 | Adult | 3 | 74 (12/62) |
| | Juvenile | 1 | 27 (8/19) |
| 2018 | Adult | 3 | 83 (40/43) |
| | Juvenile | 17 | 608 (354/254) |
| 2019 | Adult | 4 | 105 (66/39) |
| | Juvenile | 5 | 178 (57/121) |
| 2020 | Adult | 3 | 88 (40/48) |
| | Juvenile | 4 | 150 (61/89) |
| 2021 | Adult | 4 | 115 (37/78) |
| | Juvenile | 10 | 315 (209/106) |
| 2022 | Adult | 7 | 196 (106/90) |
| | Juvenile | 13 | 409 (182/227) |
| **Total** | | **74** | **2348 (1172/1176)** |

## 2.5. Data analyses

### 2.5.1. Movement parameters and phenology

As an important flight characteristic, the birds' ground speed was recorded by the GPS devices along with each geographical position (using the Doppler effect). Only original, non-interpolated positions were included in this analysis. The recorded ground speeds were visualized in a histogram aggregated across all years and individuals, and further analysed at the level of individual bird tracks to gain a better understanding of common patterns as well as individual differences. Three GPS devices did not record ground-speed measurements in 2017 (n = 12 positions), reducing the available sample size to 71 tracks with a total of 1160 positions.

It is also important to assess the phenology to gain a better understanding of the birds' flight behaviour and timing of migration. We accordingly analysed the flight duration and temporal variability in departure times, with regard to both time of day and calendar date, for each individual bird track. Departure times and dates were grouped and visualized in 2-h intervals and 5-day periods (pentads), respectively. For the analysis of departure dates, individuals with multiple crossings in one season (n = 2; 4 tracks) were excluded. Furthermore, sunrise and sunset times were calculated for all recorded geographical locations and time stamps using the R package *suncalc* (Thieurmel and Elmarhraoui, 2022) to assess the proportion of diurnal and nocturnal positions during the terns' sea crossings.

### 2.5.2. Home ranges

To investigate the migration corridors of Caspian terns across the Baltic Sea and their potential exposure to OWFs, we assessed the extent and intensity of areas utilized by the tagged individuals by means of a home-range estimation using the kernel density estimation method with the R package *adehabitatHR* (Calenge, 2024). The utilization distribution (UD) was calculated for all available bird tracks and years combined (n = 74) to achieve an aggregated picture of the birds' space use over time. Additionally, the UD kernels were also calculated separately for each study year (2017–2022) to investigate potential patterns and variations in bird distribution across years and account for changes in OWF development.

The UD kernels were computed on a raster with a grid-cell size of 100 × 100 m, using a bivariate normal kernel function. Oriented at the birds' large-scale movements during migration, several values for the critical smoothing parameter or bandwidth *h* were computed, including the "reference bandwidth" *href* (Calenge, 2023). To balance potential over-smoothing of the birds' space use on one hand and local fragmentation on the other, a smoothing parameter of *h*= 8.000 m, corresponding to approximately 70% of the minimum reference bandwidth *href* (Kie et al., 2010), was selected after repeated trials and visual exploration of the resulting UD kernels. For comparability of the results, a single consistent smoothing factor (fixed kernels), grid-cell size and extent were applied for both the aggregated and yearly analyses. Furthermore, several probability levels (95%, 75%, 50%, and 25% isopleths) were calculated to compare and analyse the utilisation intensities of different areas during migration among the tracked individuals.

### 2.5.3. OWF overlap

To investigate the birds' potential exposure to OWFs, we analysed the spatial overlap between the resulting UD kernels and OWF areas using the function *'Vector Overlay – Clip'* in QGIS (QGIS.org, 2025). On a yearly basis, we first calculated the spatial overlap between the annual UD kernels and only those OWF areas that were operational in the respective years (see Supplementary Table S1). We further estimated the potential spatial exposure under a future maximum OWF scenario, in which all approved or planned areas were assumed to be built. For that purpose, we calculated the spatial overlap between the aggregated UD kernels (2017–2022) and the

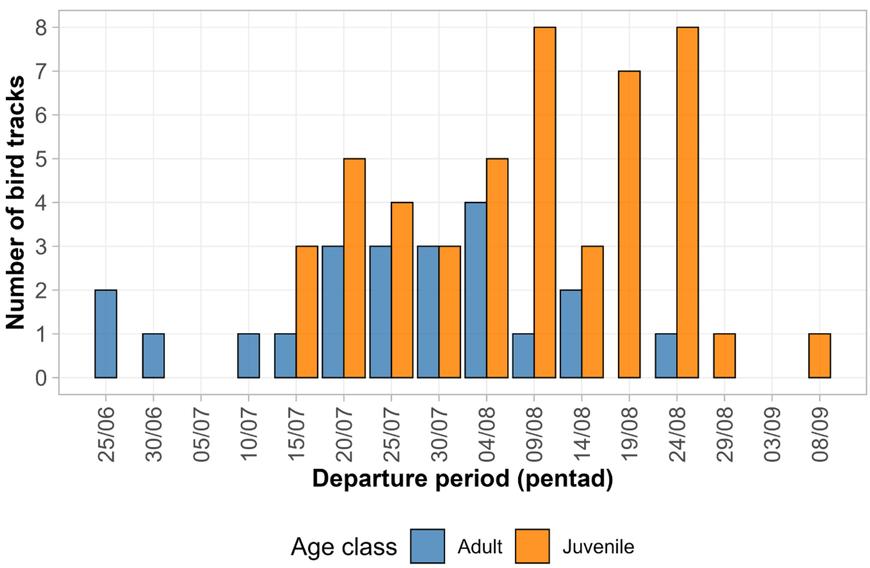


**Fig. 2.** Phenology of Baltic Sea crossings of juvenile and adult Caspian terns during post-breeding migration based on 5-day periods (n = 70). Two individuals with multiple sea crossings in one season were excluded.

OWF areas of all defined categories (see 2.2. OWF data) combined. As of January 2025, this included a total of seven operational OWFs and 14 development zones, with no OWFs under construction at the time of the analysis (see Supplementary Table S2). The resulting overlaps were quantified in absolute terms (total area in km$^2$) as well as relative to the size of the UD kernels (proportion of spatial overlap in %).

### *2.5.4. Distance to offshore wind turbines*

In addition to analysing the spatial overlap between the calculated UD kernels and OWF areas, we assessed the proximity of the birds' flight paths to operational wind turbines, to gain further insights into their migratory routes with respect to potential conflicts with OWFs. The geographical locations of individual wind turbines were obtained from the wind farm dataset compiled for the third Holistic Assessment of the Baltic Sea (HOLAS 3), accessed through the HELCOM Metadata catalogue (HELCOM HOLAS 3 Dataset, 2023). The distance of each position along each bird track to the nearest wind turbine was calculated using the function *'Distance to Nearest Hub'* in QGIS. The minimum distance of each bird track (n = 74) to the nearest offshore wind turbine encountered or passed during migration across the study area was then extracted and displayed graphically. Only wind turbines of operating OWFs during the respective year and migration season were considered.

## 3. Results

### *3.1. Movement parameters and phenology*

Caspian terns crossed the Baltic Sea between southern Sweden and northeastern Germany from late June to late August (adults) and mid-July to early September (first-year birds) during their post-breeding migration (Fig. 2). Young birds are known to usually migrate together with a parent bird (usually the male parent; Byholm et al., 2022). The current analysis only included one case where a tagged adult and a tagged juvenile migrated together; neither parent-offspring nor sibling relationships were confirmed for the other cases, but could not be excluded.

Flights across the study area occurred at nearly all times of day, but approximately half occurred in the morning hours (Fig. 3) and only 34% of all positions were recorded during twilight and at night (defined as the period from sunset to sunrise).

The ground speed mostly varied between 20 and 75 km/h (mean 42.23 ± standard deviation 12.17 km/h; Fig. S2). The crossing of the Baltic Sea in our study area, i.e. from leaving the Swedish coast to arriving at the German coast, usually lasted 1.5–3.5 h (mean 2.58 ± 0.88 h), with very few flights being quicker and some lasting longer (minimum: 1.33 h, maximum: 6.09 h; Fig. 4). The time spent in the study area was thus very short compared with the time spent in other areas visited during the annual cycle (Rueda-Uribe et al., 2021).

### *3.2. Sea crossings and overlap with OWFs*

The sea-crossings are depicted in Fig. 5. Aggregated information from all routes illustrates priorities in space utilisation during post-breeding migration (Fig. 6). The most intensively used routes led from the southeastern corner of Sweden or the southwestern corner of

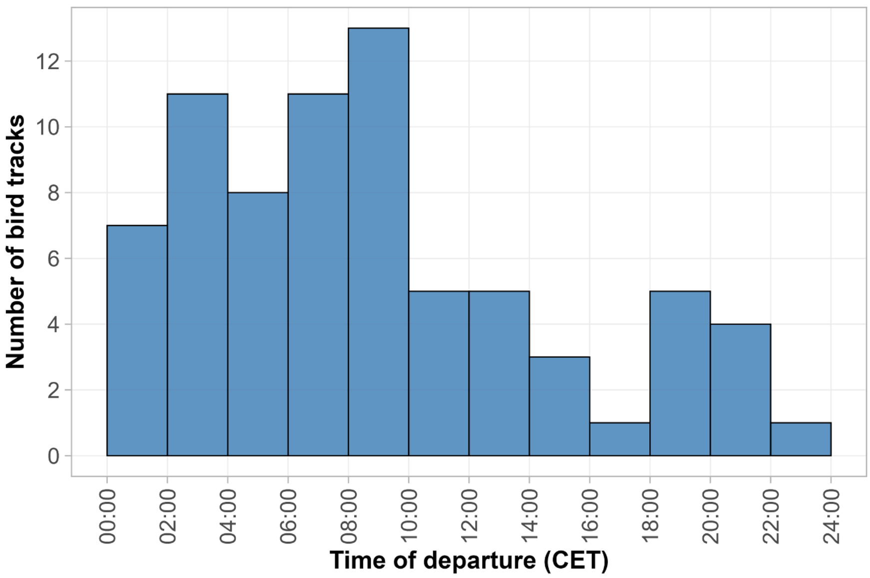


**Fig. 3.** Circadian distribution of Caspian tern migratory flights across the study area (n = 74). Times indicate the start of the sea crossing. During the post-breeding migration season, sunrise and sunset varied by up to 2.25 h.

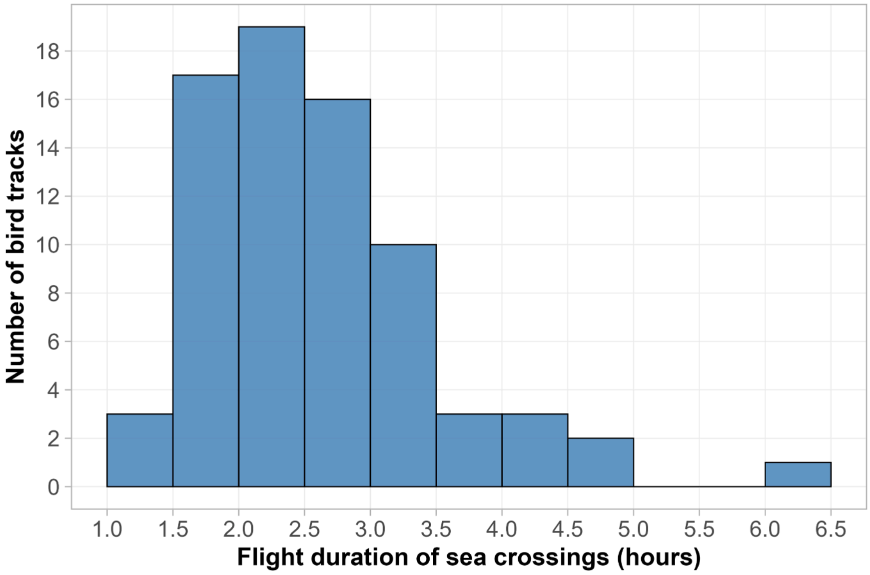


**Fig. 4.** Flight duration for Baltic Sea crossings during post-breeding migration of Caspian terns (n = 74).

Bornholm towards the southwest to the northeastern corner of the island of Rügen, close to important staging sites in the north and the south of the adjacent island, Hiddensee. Some of the birds also migrated from the southeastern corner of Bornholm to the southwest and reached the German coast at another important staging site, the Peenemünder Haken. Comparatively few birds initiated the sea-crossing in the western part of the Swedish south coast. Aggregated information separated by study year shows the persistence of the main route from southeastern Sweden to Rügen in nearly all years, whereas only some minor hotspots may change on an annual but small-scale basis (see Supplementary Fig. S3).

The temporal resolution of the data was insufficient to detect small-scale directional changes of birds in the vicinity of an operational OWF, including avoidance of individual turbines. However, of the 74 tracks considered, most individuals passed an operational OWF at a distance of several kilometres and most at > 10 km distance (Fig. 7). Fourteen birds appeared to pass an OWF at a closer distance (i.e. <1 km), and in 12 cases, a tern flew towards the outer boundary of an OWF and appeared to cross it without performing any large-scale evasive manoeuvres (Fig. 5; years 2021 and 2022, passages of two OWFs in a row counted as one case only). A total of 23 GPS positions (8 original, 15 interpolated) were located in the footprints of operating OWFs. With respect to the future maximum scenario of wind farming in the study area (all approved or planned OWFs assumed to be built), 57 of the tracks (77%) would cross or partly intersect at least one OWF (Fig. 5). In this scenario, > 9% of the core kernel home range (25% kernel) would overlap with foreseen OWF areas (Table 2).

## 4. Discussion

In parallel with extensive plans to expand the use of wind energy at sea, efforts are being made to minimise the impact of this kind of human activity on marine ecosystems (Perrow, 2019). The marine conservation organisation for the Baltic Sea (HELCOM) addresses not only the waterbirds living in the Baltic Sea, but also bird migration across the Baltic Sea. In its Recommendation 34E/1 'Safeguarding important bird habitats and migration routes in the Baltic Sea from negative effects of wind and wave energy production at sea' (adopted in 2013), it recommends to 'avoid that wind energy facilities are situated within major migrating routes of birds' (HELCOM, 2013). Using the example of a bird species that is strictly protected under European law, we analysed the alignment of current and future planned OWFs with the above objective.

Using GPS data loggers, we showed that a large proportion of the Caspian tern population, which migrates from Scandinavia to Central and West Africa after breeding, uses a migration route across the sea area between Sweden and Germany (Rueda-Uribe et al., 2021), through established OWF sites and an area with extensive planning scenarios. At the current stage of development, relatively few individuals approach or fly through OWFs, but future plans for a massive belt of OWFs could present a barrier for migrating birds between Sweden and Germany. Assuming that the sample of birds tagged in the current study was representative of the entire population, this would affect 77% of the terns on this migration route, which is not in line with the HELCOM recommendation. We assume that this proportion is representative of the Swedish breeding population (2022: 783 breeding pairs, own unpublished data); for Finnish birds, no such proportion is known. As the Caspian terns use more or less the same routes during spring migration (Rueda-Uribe et al., 2021), we expect the issues described in this study apply to a passage that takes place twice a year.

Notably, the results of the analyses of the distances between flight tracks and OWFs were constrained by data limitations, such as the positional inaccuracy of wind turbine data and recorded GPS positions. In particular, the performed interpolation of positions to fill gaps and regularize the tracks can only approximate the birds' movements, with no definitive knowledge on their exact positions. The

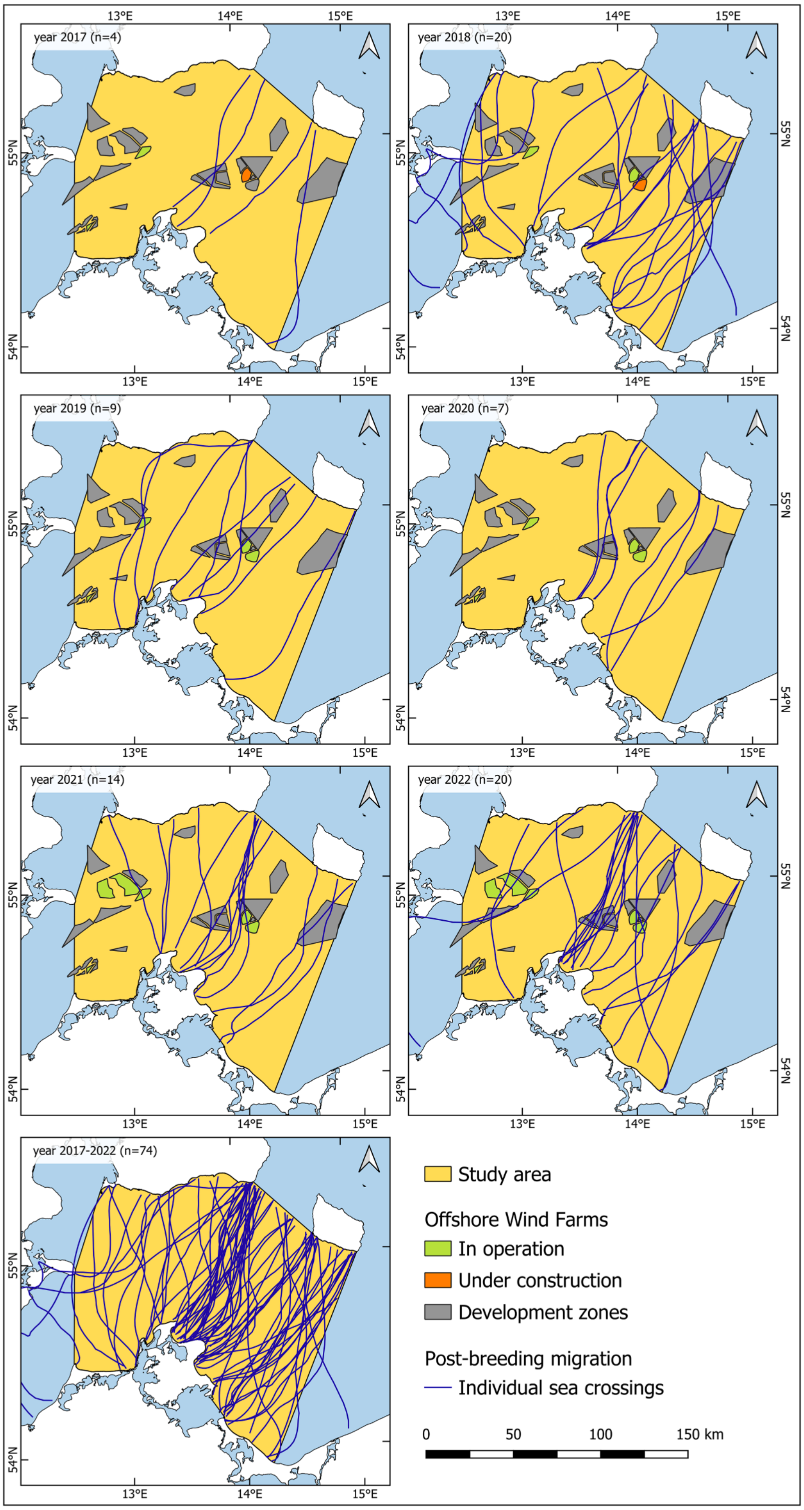


**Fig. 5.** Caspian tern tracks during post-breeding migration in the study area, the Baltic Sea between southern Sweden and northeastern Germany split by study year (first three lines of maps) and overview of all tracks (bottom left map).

calculated minimum distances therefore provide a purely descriptive metric of the tracks and must be interpreted with caution, because they do not allow for conclusions about the birds' behavioural responses towards wind turbines on a micro- or meso-scale, for which higher temporal resolution tracking data would be needed (e.g. Schwemmer et al., 2023). Although the current dataset of tagged

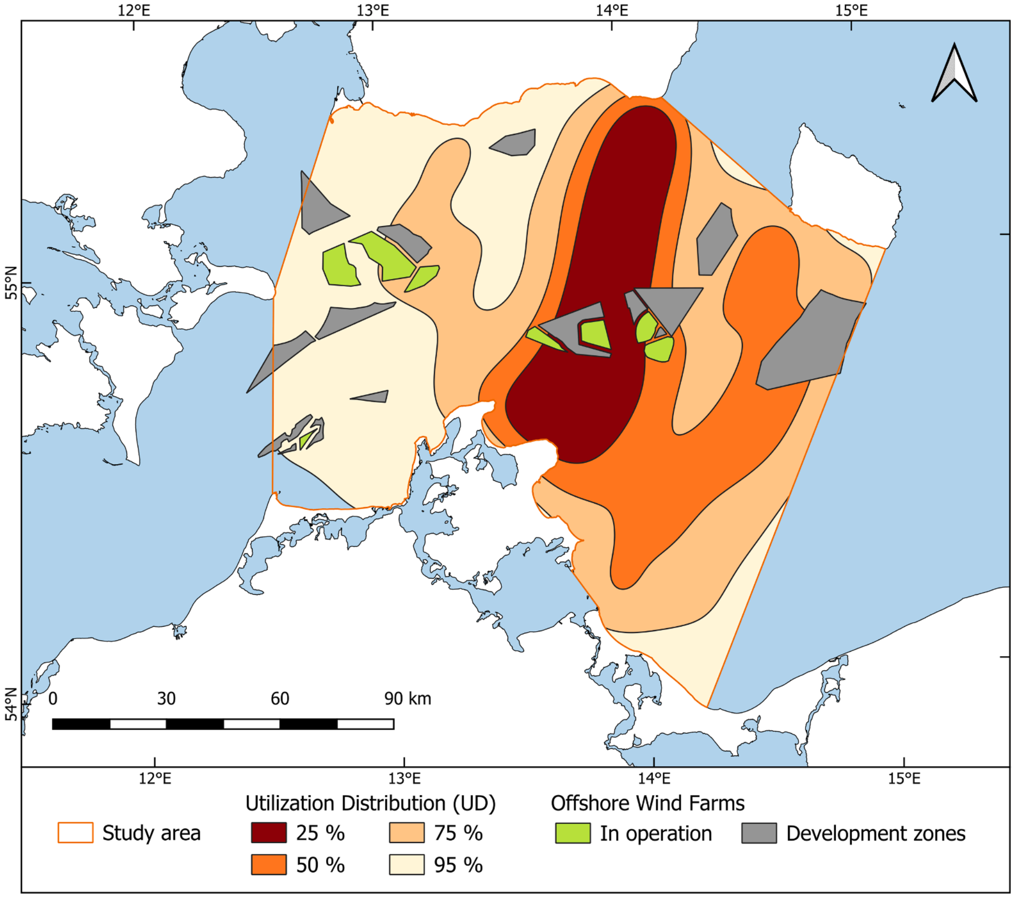


**Fig. 6.** Aggregated home range of Caspian tern post-breeding migration across the study area (orange line) based on all tracked individuals in the years 2017–2022. For home ranges in the individual years, see Supplementary Fig. S3. Offshore wind farms in operation and development zones also shown.

Caspian terns does not yet allow us to assess the individual reactions of birds to individual wind turbines, our findings clearly suggest that they do not show pronounced macro-avoidance of OWFs. This is supported by the relatively straight nature of the recorded tracks, suggesting that many terns are likely to fly through OWFs in the future, rather than taking long detours. Both assumptions must be regarded as having an impact on the birds, which will either be exposed to higher collision risks or will need to spend additional energy resources to avoid the turbines. In this context however, it is important to bear in mind that a high proportion of our tracks were interpolated, which reduces the precision of the potential overlap and prevents the assessment of small-scale evasive movements. Other seabirds show large variation in behaviour when confronted with OWFs, ranging from strong avoidance to attraction (Dierschke et al., 2016). While information is scarce for most other tern species, sandwich terns *Thalasseus sandvicensis* were found to show macro-avoidance of OWFs in the North Sea, i.e. between 41% and > 70% of birds heading towards an OWF avoided to enter the footprint of the OWF (Harwood et al., 2017; van Bemmelen et al., 2024) , especially during commuting flights (Thaxter et al., 2024). However, exceptions were observed, with sandwich (and also common/Arctic tern *Sterna hirundo/paradisaea*) resting on buoys or turbines and foraging close to the base of turbines (Stienen et al., 2024).

In addition to ground speed, the GPS devices also recorded flight altitude of the Caspian terns. Unfortunately, these recordings were not robust enough to determine the exact altitude distribution during migration over the Baltic Sea due to the inclusion of many negative values, which is a common problem with telemetry data (Péron et al., 2020). However, negative values have been suggested to represent flight altitudes close to the water surface (being no systematic measurement errors; Schwemmer et al., 2022), and the altitude data thus indicated that > 75% of the Caspian terns flew at altitudes < 200 m. This means that they were generally exposed to the risk of fatal collisions with either the turbine tower or rotor blades when flying through OWFs. Further modelling is needed to assess the exact collision risks (Cook and Masden, 2019), and the current data on temporal patterns and ground speed will contribute to these models (Fijn and Gyimesi, 2018; Masden et al., 2021).

One possible measure to reduce collisions in OWFs is to temporarily switch off the turbines. With regard to bird migration, shutdowns have been discussed and occasionally practised in situations with strong bird migration at rotor levels (Harwood and Perrow, 2019; Brabant, Degraer, 2023). If an additional or alternative switch-off regime has to be defined for the protection of individual protected species, it would be necessary to define the appropriate daily and seasonal time windows. Although condensed

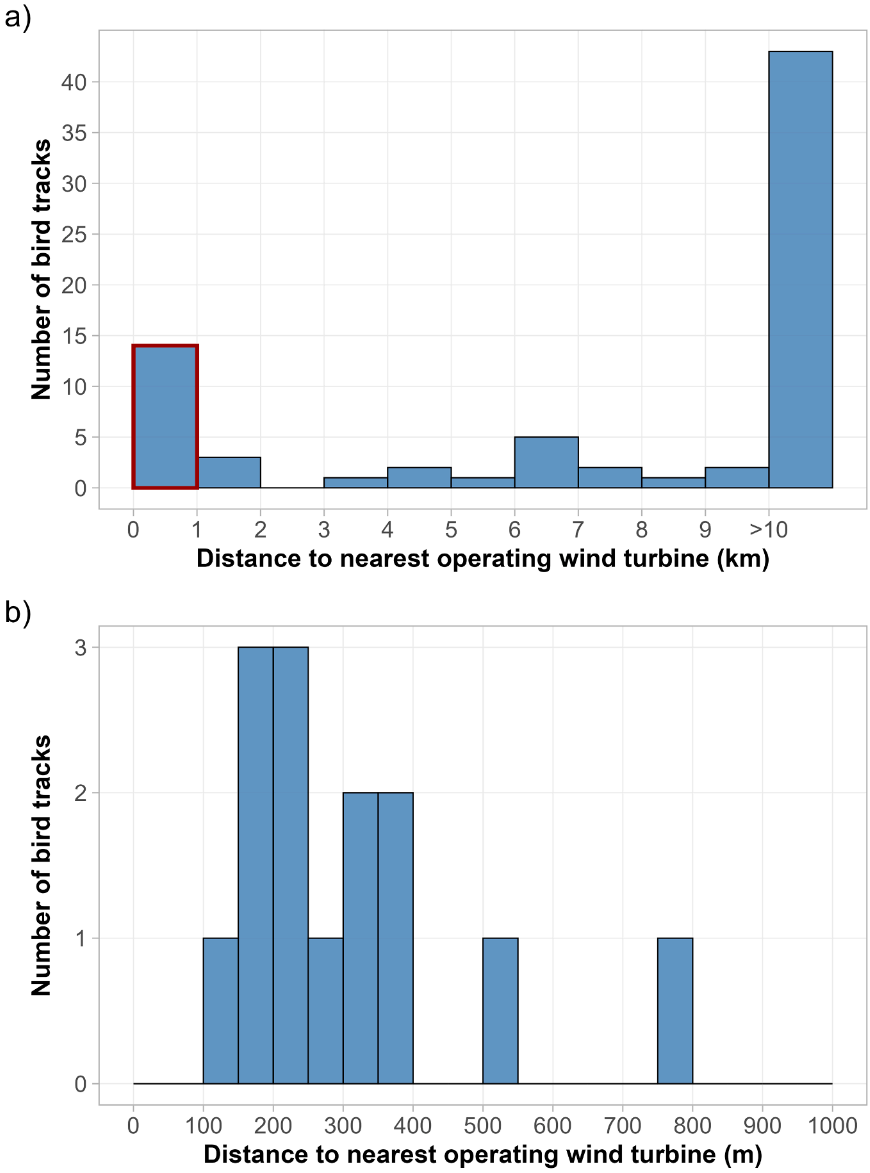


**Fig. 7.** Calculated minimum distances between the flight paths of tagged Caspian terns and nearest operating offshore wind turbines encountered during post-breeding migration between S Sweden and NE Germany: a): Minimum distances of all tracks (n = 74); b): Enlarged view of tracks with minimum distances between 0 and 1000 m (n = 14), corresponding to bar highlighted in red in panel a).

**Table 2**
Spatial overlap between the aggregated home range kernels (2017–2022) and the future maximum OWF scenario (including all categories combined, i.e. OWFs in operation (n = 7) and development zones (n = 14); see also Fig. 6 and Supplementary Fig. S1), in km² and percentage of home range area. For results of the spatial overlap between the annual home range kernels and operating OWFs, see Supplementary Table S3.

| OWF status | 25% UD | 50% UD | 75% UD | 95% UD |
|---|---|---|---|---|
| In operation | 69.22 km² (3.16%) | 137.14 km² (2.46%) | 231.75 km² (2.21%) | 346.91 km² (2.21%) |
| Development zones | 131.00 km² (5.98%) | 410.65 km² (7.35%) | 838.27 km² (8.00%) | 1161.62 km² (7.41%) |
| **Total** | **200.23 km² (9.14%)** | **547.80 km² (9.81%)** | **1070.03 km² (10.21%)** | **1508.52 km² (9.63%)** |

OWF, offshore wind farm; UD, utilization distribution

migration windows across the Baltic Sea have been shown for other migrating bird species (e.g. Schwemmer et al., 2022), the present study showed that Caspian terns had a relatively long seasonal time window, covering the whole of July and August. Specifically, our data showed that autumn migration had already started by the end of June/mid-July, mainly involving adult birds. Given that male adult Caspian terns especially are known to migrate together with their offspring (Byholm et al., 2022), the first migrating adults are likely to be failed breeders, which extends the migration window. Furthermore, the timing of migration is known to be affected by the wind conditions, with birds favouring tailwinds for departure (Åkesson and Hedenström, 2000). This is also likely to impact Caspian tern sea crossings, with suboptimal wind conditions over a longer period of time extending the migration window. Wind conditions also affect flight altitudes (e.g. Krüger and Garthe, 2001; Kahlert et al., 2012), which will in turn affect the collision risk. Although the current flight-altitude data were not precise enough to quantify flight heights precisely, they suggested relatively low altitudes throughout the entire sea crossing, in line with a previous study showing low flight altitudes for Caspian terns across water bodies as a consequence of combined migration and foraging movements (Rueda-Uribe et al., 2022). It can thus be assumed that a large proportion of the migration will take place within the dangerous rotor-swept zone with respect to potential collisions. Finally, Caspian terns migrated across the sea between Sweden and Germany at almost all times of day, including the night (although in lower proportions). Because wind turbines are illuminated at night, nocturnal migration might increase the collision risk due to attraction effects, as shown for other species (Hüppop et al., 2006; Rodríguez et al., 2017; Rebke et al., 2019). It is therefore not possible to plan precautionary shutdowns precisely, but it may be possible to narrow down the timing of migration in relation to weather conditions (which were not the focus of the current study; (Manola et al., 2020; Bradarić et al. 2024). Nevertheless, the required time window for shutting down OWFs in relation to the post-breeding migration of Caspian terns alone would be very broad, and therefore extremely challenging from an economic perspective.

In contrast to the broad timing of migration, our data clearly suggested that Caspian terns wintering in West Africa migrated along a comparatively narrow corridor, touching only a small part of the Baltic Sea. This corridor shows some degree of variation among the years, and therefore the 50% UD of this corridor reflects the area of main migration intensity. This route is also used by some Caspian terns breeding in Finland, while most Finnish (and some Swedish) birds use an alternative route involving a short sea crossing across the Gulf of Finland (Valkama et al., 2014; Rueda-Uribe et al., 2021; 2022). Corridor-like migration across sea areas is in line with findings for other bird species, such as white storks (*Ciconia ciconia*) (Oloo et al., 2018), cranes (*Grus americana*) (Pearse et al., 2018), and geese (Heuer, 2023); however, to the best of our knowledge, the current study provides the first evidence for such a migration pattern in a seabird species. In contrast to most other seabird species, Caspian terns thus appear to choose the shortest routes over the sea, with most then continuing their migration overland rather than following coastlines (Rueda-Uribe et al., 2021; 2022). Large amounts of tracking data are currently being generated (Kays et al., 2022), enabling future research on other bird taxa to determine if other species exhibit similar migratory behaviours.

Our home-range analysis based on tracking data for many individuals clearly identified a condensed area of high migration intensity of Caspian terns that remained stable across the 6 years of the study. This is an important finding in terms of informing marine spatial planning, clearly identifying areas to be excluded from future OWF planning in order to achieve the goal of comprehensive protection of Caspian terns according to the target formulated by (HELCOM, 2013). Being listed in the Annex I of the EU Birds Directive, a precautionary approach to future planning scenario should be adopted, and the hotspot of Caspian tern migration identified in this study provides a valid basis for shaping future spatial planning scenarios.

Transnational planning regarding the spatial arrangement of future OWFs is required with regard to bird migration, to avoid situations such as that described here for Caspian terns. This would be in line with a cross-border, ecosystem-based approach to marine spatial planning as addressed in the Baltic Sea Action Plan, which also highlights the need to signal areas of high nature value and to steer activities away from areas where they can cause serious damage or disturbance (HELCOM, 2021). The bird tracks determined in this study indicate the existence of spatial hotspots in relation to migration routes over the sea. Although the current example of Caspian terns only identifies a very broad temporal window for measures relating precisely to this species, similar analyses need to be repeated for other migratory bird species that have been studied using telemetry. In conjunction with the exact definition of migration seasons and flight altitudes, multi-species sensitivity maps need to be created showing sensitive marine areas in relation to the potential conflict between bird migration and wind energy utilisation. Such analyses will support the development of both targeted mitigation measures for individual species, as well as multi-species protection schemes that are required for highly mobile marine megafauna (Sequeira et al., 2025; VanCompernolle et al., 2025).

## CRediT authorship contribution statement

VD: Writing – original draft, writing – review and editing, conceptualization; KH: Writing – original draft, writing – review and editing, formal analysis, visualization; UL: Data curation, writing – review and editing; SÅ: Funding acquisition, data curation, project administration, writing – review and editing; SG: Writing – review and editing; ML: Formal analysis, writing – review and editing; PS: Conceptualization, methodology, supervision, writing – original draft, writing – review and editing.

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## Declaration of Competing Interest

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

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2026.e04298.

## Data Availability

Data will be made available on request.

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