



Estimating the traffic rates of bats migrating across the North and Baltic Seas to develop efficient mitigation measures at offshore wind energy facilities

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ABSTRACT

Bats migrating across the open seas are at high risk of colliding with offshore wind turbines. Despite recent advances on how to conduct offshore environmental impact assessments for bats, there is still a lack of standardized methods to estimate the extent of offshore bat migration. We here present a method for estimating the number of migrating bats from long-term acoustic monitoring data collected at remote offshore structures like buoys and platforms. As an example, we apply the method to the German Seas, using ultrasound recordings from multiple offshore structures. We show that high bat migration traffic rates of 1500 bats per km and year, related to a 1 km line perpendicular to the general migration direction, occur closer to the shoreline of the German North Sea. In the German Baltic Sea, bat migration rates ranged from 900 to 4600 bats per km and year. These findings underscore the urgent need to protect migrating bats from collisions with rotating rotor blades of offshore wind turbines in German seas and beyond. Our method may also be suitable for assessing the extent of offshore bat migration in other regions. It provides the opportunity to define threshold values at which protective measures through spatial planning and mitigation measures like curtailment schemes during times of intense offshore migration of bats should be taken.

1. Introduction

In an effort to produce relatively cheap electricity from wind energy and to shift from conventional to renewable energy production, wind

turbine facilities are currently being built worldwide. Specially, offshore wind energy production is expanding in Europe (GWEC, 2025). However, this expansion is being carried out with environmental impact assessments (EIA) that do not cover the full potential ecological damage

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(Watson et al., 2025), although it has been known for more than three decades that European bats migrate twice a year on their way between summer and winter habitats across the North and Baltic Sea at night (Ahlén, 1997; Ahlén et al., 2009; Brabant et al., 2021; Bach et al., 2022a, 2022b; Hüppop and Hill, 2016; Hüppop et al., 2019; Lagerveld et al., 2024; Seebens-Hoyer et al., 2022; Skiba, 2007a). Notably, bats migrating offshore have been observed at wind turbines in the North and Baltic Seas, showing that they come close to the rotating blades when passing by or exploring offshore turbines (Ahlén et al., 2009; Brabant et al., 2019; Lagerveld et al., 2014, 2023). Nevertheless, protective measures for bats at offshore wind turbines were rarely implemented, revealing that the protection of bats in offshore wind farms is still in its infancy.

In Europe, efficient mitigation practices to protect bats have been implemented for onshore wind energy facilities. These include optimal siting away from ecologically valuable habitats and the temporary shutdown of turbine operation during periods of high bat activity (Behr et al., 2015; Voigt et al., 2024; Whitby et al., 2024). The necessity for these measures stems from the high protection status of bats in Europe. European bats are strictly protected by various national and international laws such as the Habitats Directive of the European Union (EU; 92/43/EEC) and the Convention on Migratory Species of Wild Animals (CMS) under the UNEP/EUROBATS Agreement (Bonn 1979, London 1991). Despite this, a thorough understanding of how best to survey bats offshore and protect them from collision with offshore wind turbines is still lacking. In a few countries, guidelines provide first recommendations on how to design an EIA for bats in relation to offshore wind turbines (e.g. BSH, 2013), yet it is unknown how to monitor bats on a larger scale when they migrate offshore.

In the current situation, where bats are barely considered during offshore wind energy production, it is crucial to understand the scale of the issue to achieve consensus among stakeholders about implementing adequate protection measures for bats migrating offshore. A fundamental problem is that, by now, it is not possible to verify the number of casualties caused by offshore wind turbines since carcass searches are impossible and imaging methods are still inadequate and not routinely used (Dempsey et al., 2025; Hooker et al., 2025; Sato and Kawaguchi, 2025; Solick and Newman, 2021; Weaver et al., 2025). Until practicable collision monitoring methods are available, it is therefore key to estimate how many individuals migrate across the open sea with available methods and to assess the extent individuals could potentially collide with the rotor blades of offshore wind turbines. Imaging recording methods such as radar or thermal imaging, which are widely used to monitor migrating bird populations at night (e.g. Hüppop et al., 2006; Molis et al., 2019), are currently under development for studying bats offshore (Ballester et al., 2024; Matzner et al., 2020; Solick and Newman, 2021; Weaver et al., 2025). Acoustic methods have already been successfully applied to study offshore bat migration, mostly from offshore structures, and are therefore widely used (Ahlén et al., 2009; Brabant et al., 2019; Hüppop and Hill, 2016; Lagerveld et al., 2023; Peterson et al., 2014; Sjöllema et al., 2014). However, there are still no methods at hand to evaluate particularly acoustic bat data collected offshore as a source for adequate conservation measures in spatial planning and EIAs and for deriving efficient mitigation measures. As a first step, the present study aims to offer a method to estimate the number of bat passes (hereafter referred to as the number of bat individuals) at a given site in the open sea. To this end, we conducted acoustic surveys using the example of the German North and Baltic Seas. Accordingly, the focus of this study is not on estimating the collision risk of bats (number of fatalities) but on estimating the number of bats potentially affected by offshore wind turbines.

We hypothesize that the number of bats migrating across the sea can be estimated by converting the acoustic activity measured at remote offshore structures apart from islands and the coast into bat individuals. By extrapolating to a larger scale, an estimator for bat migration traffic rates can be derived, namely the number of bat passes crossing a 1 km

line per year. This takes into account the detection ranges of ultrasonic devices and species-specific echolocation call characteristics. Based on this, we aim to reduce the disparities between different recording devices and provide an opportunity to compare the results across different geographic regions and different studies. Subsequently, measuring the bat migration traffic rate will enable us to estimate the extent of the potential conflict between offshore bat migration and to facilitate the development of assessment procedures by clarifying thresholds for bat migration traffic rates at which a potential risk is assumed and measures to protect bats should be taken.

2. Materials and methods

The work steps of the method described below are summarized in a flow chart (Fig. 1).

2.1. Acoustic survey

We carried out acoustic bat surveys throughout the spring and autumn migration period at 11 sites in the German North and Baltic Seas between 2016 and 2024 (Figs. 2 and 3). We focused on remote sites away from the mainland and islands to avoid hunting bats, e.g. near the mainland or at stop-over sites at the coast and on islands (see Ahlén et al., 2009; Cryan and Brown, 2007). The ultrasound detectors were mounted at buoys about 3 to 10 m height above sea level, at 10–20 m height above sea level on platforms and at about 40 m height above sea level at the lighthouse.

A yearly calibration ensured consistent sensitivity. The sensitivity was tested and documented daily using a test signal in most cases. The microphones were replaced at least annually (see Supplementary Material 1 for more details about the study sites and equipment). The registered sound files were analysed manually to species or group level following Barataud (2015), Russ (2012) and Skiba (2007b) by using minimum frequency, peak frequency, call length, call intervals and rhythm. Bat activity was documented as minute intervals with bat activity following Miller (2001) (i.e. at least one bat call registered) to eliminate differences between ultrasonic devices in the number of recorded echolocation calls by a passing bat (Disca, 2023; Miller, 2001; Runkel et al., 2021).

2.2. Derivation of individual numbers from data on acoustic activity

We estimated the number of individuals recorded within the spring and autumn migration period from the acoustic activity data (see Supplementary Material 1 for details on the survey periods). In contrast to the situation on land, on islands or near-shore, we argue that the bat activity at remote offshore sites can be converted to individuals for the following reasons. (1) Individuals should only be registered once per migration season, as there are no resident bats present, only migratory bats. Past tracking studies in *P. nathusii* moving across the North and Baltic Sea indicated only movements in a single direction (Bach et al., 2022a; Lagerveld et al., 2024). (2) The temporal pattern of bat activity at remote offshore study sites apart from islands and coasts is very distinct. Compared to sites with local bats or stop-over-sites, extensive hunting, commuting, or other behaviours resulting in multiple activity records per bat individual are absent. During offshore migration, bats usually pass through or stay for short periods of exploration, resulting in relatively few recordings and activity events that are often separated from each other in time (Seebens-Hoyer et al., 2022, see also Bach et al., 2022a; Lagerveld et al., 2024). As a result, the distinct temporal pattern of activity allows activities to be assigned to individuals (see Supplementary Material 2 for an example dataset).

2.2.1. Definition of the separator for individuals and calculation of the number of individuals

To separate between activities likely representing two different

1. Acoustic survey

Collection of acoustic activity data and species identification of calls

2. Derivation of individuals

Assumptions: no resident bats, low activity → distinct temporal patterns

2.1 Definition of the separator for individuals and calculation of the number of individuals

> 20 min without activity → new individual

≤ 20 min → same individual

2.2 Modelling the number of individuals for missing nights

Modelling of unmonitored nights (phenology model): Linear model with negative binomial distribution, explanatory variable: date (8 polynomial terms), random effects: year, site, model estimates individual numbers for unmonitored nights

Assign estimated individuals to species distribution proportional to observed species composition

3. Extrapolation to a 1 km transect

Bat migration traffic rate (per site and species)

= (1000 m/detection distance) * individuals

Calculation of detection distance (per species & detector) based on sound pressure level & frequency (dB SPL, kHz), atmospheric attenuation, microphone direction, flight speed & call interval

Assumptions: rather homogeneous distribution across several kilometres, validation through similar neighbouring sites and absence of simultaneous recordings of multiple bats

4. Mapping of bat migration traffic rates

Transformation of bat migration traffic rates and expert knowledge into bat migration traffic rate maps.

Fig. 1. Flowchart of working steps.

individual bats in a standardized way, we defined a period without bat activity (hereafter called separator). To identify an appropriate separator, we plotted the density distribution of temporal gaps between minutes with bat registrations (Fig. 4). This visual analysis of these graphs showed that the resulting number of individuals is not strongly affected whether we use 5, 10, 15, 20 min or even higher values as

separator (Fig. 4). This is because most time gaps between successive calls from the same species at the same site were either very short (often 0 min, i.e. minute intervals with bat detections follow directly one after the other, indicating a bat passing by) or very long (well above 30 min), while the abundance of intermediate temporal gaps of, e.g., 5, 6, 7, to 20, 21 etc. minutes duration was overall low. Therefore, moderate



Fig. 2. Map of the location of the study sites. Land is coloured in light grey, sea in white. The light grey line represents the border of the territorial seas of the littoral countries. The map base was changed after OpenStreetMap.

variation in the pre-defined threshold gap around 20 min has little impact on the number of events categorised as originating from one or more animals and consequently on the migration traffic rate derived from this.

We selected a 20-min threshold as a conservative estimate because it is more likely that bat migration traffic rates will be underestimated than overestimated, given that it is unlikely for the same bat to return to the same offshore location several minutes later, and considering that we counted several bats co-occurring at the same site within 20 min as a single individual.

Using this separator derived from our data we calculated the number of individuals from our activity data. To test the assumption of separator duration on the calculated bat migration traffic rate, we performed a sensitivity analysis which suggested a high consistency in the outcome of the analysis (see Supplementary Material 3 with bat traffic rate estimates for different separator lengths and detection distances of calls).

2.2.2. Modelling the number of individuals for missing nights

Due to logistic constraints and some temporary failures in the performance of the recording devices, there were unmonitored periods (Fig. 2). To estimate the number of bats missed during such unmonitored periods, we fitted a linear model for the number of bat individuals (total across species) observed per night, assuming a negative binomial data distribution around the estimated mean. This mean was estimated from the date (i.e., night of the year) using 8 polynomials to model the strongly bimodal distribution ('spring and autumn migration'). Year and study site were included as random factors, with random slopes for

all polynomials of date for site, i.e. allowing a separate estimation of the bat phenology per site (hence we call it the "phenology model").

From the phenology model, we estimated the number of bats for each night and site without monitoring (see Supplementary Material 3 for the estimated bats and phenology). This estimate was made regardless of bat species, but the estimated number of missed bats was assigned to species in the same proportions as calculated among the observed bats for that study site and year. This was necessary because we used species-specific detection distances for the extrapolation to one kilometre (see below). The number of observed plus estimated (for unmonitored periods) bat individuals was then used to estimate the bat migration traffic rate per study site and year. From these values, we calculated a mean for the bat counts per study site, including a standard error reflecting among-year variance.

Our extrapolation is an estimate for the number of bats passing at our study sites. While many uncertainties of the calculations cannot be taken into account due to the lack of corresponding data (regarding many aspects of bat echolocation and migration, registration of calls etc.) we can provide a sensitivity analysis regarding some critical assumptions we make. Hence, we used short, mean and long detection distances (see below), and we varied the length of the separator (see Supplementary Material 3 with bat traffic rate estimates for different separator lengths and detection distances of calls).

2.3. Extrapolation to a 1 km transect

The extrapolation of the number of bats recorded at a particular study site to a bat migration traffic rate is facilitated in the offshore environment, because bats tend to occur relatively homogeneously on a geographical scale of several kilometres for the following reasons: (1) Direct observations from land, islands and ships of bats flying at sea showed that they crossed the Seas individually, not in flocks (Ahlen et al., 2009; Boshammer and Bekker, 2008; Seebens-Hoyer et al., 2022; Skiba, 2007a; Walter et al., 2007, see also Solick and Newman, 2021). Accordingly, only 1.4% of all recordings in our study ($N = 4801$) contained echolocation calls of more than one individual of the same species (see Supplementary Material 4 for the number and percentage of records with simultaneously echolocating bats). We would expect a higher proportion, if bats fly in pairs or flocks regularly. (2) Mean bat activities and the number of bat individuals at neighbouring study sites, which were a few kilometres apart from each other, are rather similar (see below). (3) Besides, past bat surveys in the area did not suggest

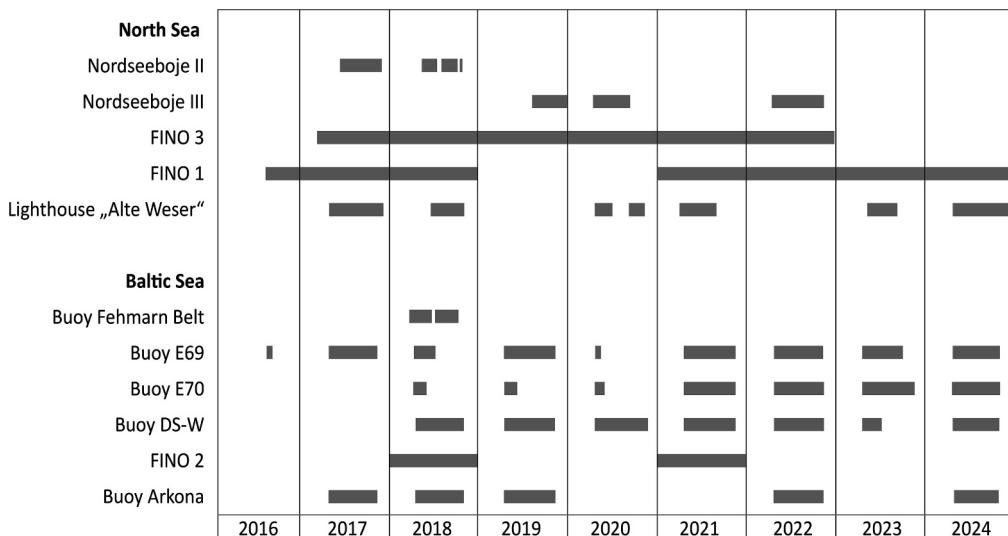


Fig. 3. Recording times at the study sites in the years 2016 to 2024. The grey bars show the periods with recordings of the several years. The North Sea sites are in order of decreasing distance to the coast, the Baltic Sea sites from west to east.

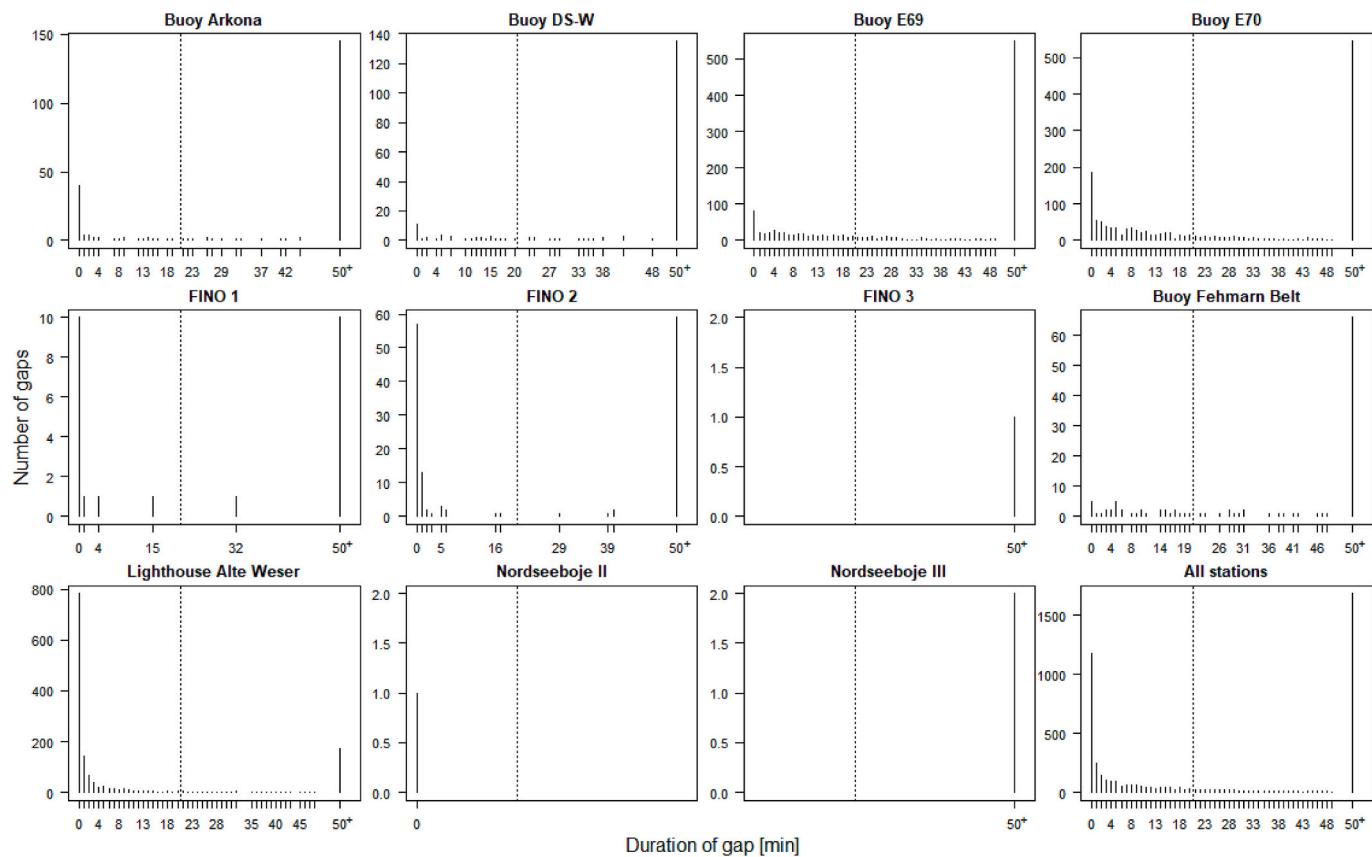


Fig. 4. Observed time gaps between minutes with a registration of a bat of the same species, per study site and across all study sites (last plot). For our analyses, we used a threshold of 20 min or less (left from dotted vertical line) to merge minutes with registrations of individual bats.

condensed migration corridors in the range of a few kilometres or even less (e.g. Ahlén, 1997; Ahlén et al., 2009; Seebens-Hoyer et al., 2022; Skiba, 2007a). We therefore consider it legitimate to extrapolate bat numbers to one kilometre, a dimension also used to estimate the migration traffic rate in migrating nocturnal birds (Lowery Jr., 1951; Bruderer, 1971). Accordingly, we define a line of one kilometre perpendicular to the main migration direction as a reference value. We then calculate the bat migration traffic rate (number of bats crossing within the two migration periods) by extrapolating the total number of individuals recorded within the migration periods and the bat detector detection range (see below) to one kilometre and year.

The range at which bat detectors can reliably detect bat calls is strongly influenced by the sound pressure level (dB SPL) of the calls emitted and the frequency range of these calls. These two factors strongly influence sound propagation in terms of atmospheric and geometric attenuation (Voigt et al., 2021). Atmospheric attenuation is positively correlated with frequency and can reach values from about 0.5 dB / m (e.g. for *Nyctalus noctula*) to more than 1.6 dB / m (e.g. for *Pipistrellus nathusii*), depending mainly on temperature and humidity (de Framond et al., 2023; Goerlitz, 2018; Voigt et al., 2021). The dominant species offshore in the Baltic Sea are the common noctule (*Nyctalus noctula*; range of echolocation call frequencies: 17–22 kHz), Natusius' pipistrelle (*Pipistrellus nathusii*; range: 34–40 kHz), common pipistrelle (*P. pipistrellus*; range: 43–48 kHz) and soprano pipistrelle (*P. pygmaeus*; range 52 kHz - 57 kHz).

Under ideal conditions, acoustic detection is equally reliable within a sphere around the microphone (omnidirectional). In reality, physical constraints make it impossible to detect bats with equal probability within a sphere. Due to the structure to which the microphone is attached and the shielding of the microphone from the harsh weather conditions at sea, some directions are completely blocked from

incoming sound. Therefore, bats calling from these directions will not be recorded. Data from two microphones placed at 4 m height and parallel to the water surface at 180° to each other show that about 20 to 25% of the detected calls were recorded by only one microphone (Pommeranz, H., unpublished results). In addition, a bat flight speed and call intervals affect the detection probability.

We estimated the detection distances of the different detector systems used for the three species Natusius' pipistrelle, common pipistrelle and common noctule, taking into account the factors mentioned above. We assumed that bats approached the microphones from the front and that flight trajectories passed straight through the vertical plane of the microphone. We also assumed that calls are propagating in a wide beam in front of the bat (see Supplementary Material 5 for an illustration of the assumed detection area, Fig. S6). The sound pressure level of bat calls decreases by 3 to 6 dB SPL at a 45° deviation from the main axis, and decreases by at least 12 dB SPL behind the animal (Jakobsen et al., 2013; Ratcliffe and Jakobsen, 2018). We assumed typical temperature and relative humidity conditions for range calculations; thus, overestimating potentially our detection range in very humid conditions. Most of the microphones were installed slightly recessed in a tube, which was inclined downwards at 45°. The recessed installation of the microphone reduced the aperture angle of the microphone from 180° to about 120°. We assumed that the bat travels within detection range for at least the call interval of two adjacent calls to be registered with its current flight speed. In Europe, migrating Natusius' pipistrelles have been observed to skip echolocation calls every second or third wing stroke, particularly when flying at more than 10 m altitude during migration (Jakobsen, L. and Voigt, C.C., unpublished results). This skipping of echolocation reduces the probability of bats being recorded acoustically if not taken into account. For calculating the detection distances we used the migration call intervals (which differ from foraging by being longer) of this

unpublished data. The actual range was calculated for exactly the situation of two calls within range, to allow for that one call could be skipped (either incidentally or due to calling to another direction).

For a *Nathusius' pipistrelle* bat flying at a speed of 7 m/s (Troxell et al., 2019; Bach et al., 2022a) and a call interval of 250 ms this results in a lateral detection distance reduced by about 1/4 compared to the 180° aperture angle. Depending on the detector this results in a detection distance of $\frac{3}{4} * 16 \text{ m} = 12 \text{ m}$ to $\frac{3}{4} * 22 \text{ m} = 16.5 \text{ m}$ to each lateral side of the microphone (see Supplementary Material 5 for an illustration of the assumed detection area, Fig. S7). This means that a „stripe“ with a width of 24 m or 33 m will be covered by a single bat detector. Similar estimates were obtained analogously for bats with higher frequency calls, namely common pipistrelles and soprano pipistrelles. For common noctule bats a flight speed of 10 m/s and call interval of 750 ms results in a detection stripe of 57 m to 69 m depending on the detector.

Using the mean detection distances for each species as presented in Table 1 we calculated the mean bat migration traffic rate as follows (example for Batcorder):

$$1000 \text{ m} / 26.3 \text{ m detection distance} * [\text{Nathusius' pipistrelle individuals} + \text{individuals of other species}] + 1000 \text{ m} / 56.3 \text{ detection distance} * [\text{greater noctule individuals}] + 1000 \text{ m} / 24.0 \text{ m detection distance} * [\text{common pipistrelle individuals}] = \text{bat migration traffic rate}.$$

We used the open-source software R (version 4.4.3; R Core Team, 2025) for statistical analyses and graphics. The phenology model was fitted using package brms (2.22.0; Bürkner, 2021).

2.4. Mapping of bat migration traffic rates

Additionally, the bat migration traffic rates were transformed into bat migration traffic rate maps of the German waters in the German Bight and the Southwestern Baltic Sea. These maps are to be understood as expert maps in the way, that our estimated bat migration traffic rates were interpreted in light of additional own survey data only covering some nights or weeks from additional study sites, survey data from the grey literature (e.g. EIAs), personal communicated observations and anecdotal observations from others.

3. Results

In the North Sea, the bat migration traffic rate decreases with distance from the coast, with high bat migration traffic rates (1500 bats per km and year) in the territorial waters closer to the coast at the lighthouse „Alte Weser“ (Table 2, Fig. 5) to low bat migration traffic rates (less than 100 bats per km and year) at great distance to the coastline (FINO 3, Nordseeboje III, Nordseeboje II).

In the Baltic Sea, mean bat migration traffic rates are generally higher, ranging between 900 and 4600 bats per km and year. The highest bat migration traffic rate of around 3500–4600 bats per km and year are found in the western parts, high bat migration traffic rates of around 1000 occur in the eastern parts (see Table 2, Fig. 6).

Table 1

Minimal (i.e. short), mean and maximum (i.e. long) estimated detection distances of different bat detectors and species.

Recorder	Species	Detection distance (m)		
		short	mean	long
Batcorder, Anabat	<i>P. nathusii</i> , other species ¹⁾	24.0	26.3	28.5
	<i>Nyctalus</i>	48.0	56.3	64.5
	<i>P. pipistrellus</i> , <i>P. pygmaeus</i>	21.8	24.0	26.3
	<i>P. nathusii</i> , other species ¹⁾	28.5	31.5	34.5
Avisoft	<i>Nyctalus</i>	57.0	68.3	76.5
	<i>P. pipistrellus</i> , <i>P. pygmaeus</i>	26.3	29.3	32.3

¹ *Myotis daubentonii*, *M. sp.*, *Vespertilio murinus*, *Eptesicus serotinus*.

Table 2

Estimated bat migration traffic rates (and standard error for among-year uncertainty; values above 100 rounded to 10, values below 100 rounded to 1) per study site using a 20-min separator to identify bat individuals and mean detection distances of calls. N years = the number of years of data collection. “Großtonne Fehmarn Belt” has no standard error as there was only one year in the data.

study site (N years)	bat migration traffic rate (estimated number of bats per km within the two migration periods of a year)	Standard error
<i>North Sea (in order of decreasing distance to the coast)</i>		
Nordseeboje II (2)	67	16
Nordseeboje III (3)	42	42
FINO 3 (5)	16	11
FINO 1 (4)	78	33
Lighthouse “Alte Weser” (6)	1510	350
<i>Baltic Sea (from west to east)</i>		
Buoy Fehmarn Belt (1)	3600	–
Buoy E69 (9)	3550	590
Buoy E70 (7)	4590	1200
Buoy DS-W (7)	920	140
FINO 2 (2)	960	160
Buoy Arkona (5)	1200	130

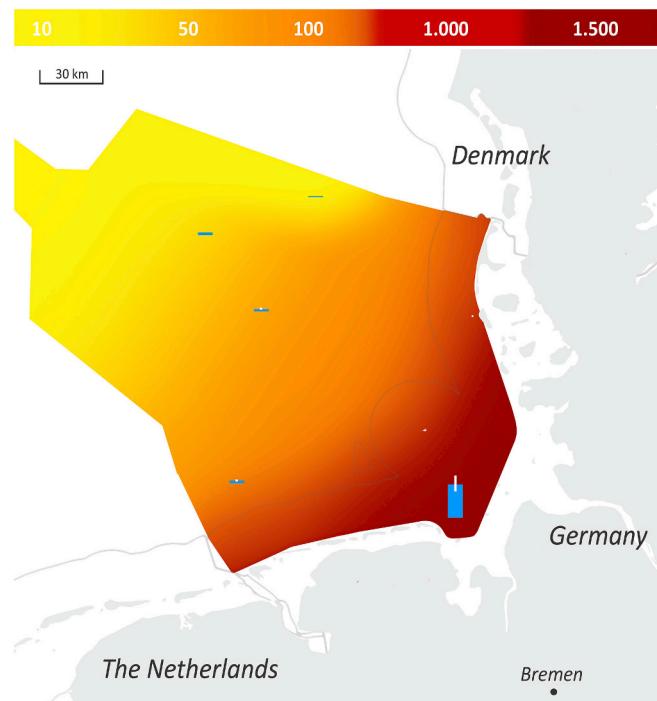


Fig. 5. Map of the annual bat migration traffic rates (n of individuals along a 1-km strip per year) in the German North Sea. The land is coloured in light grey, the sea in white, the grey line represents the 12 nautical mile limits of the countries. The columns depict bat migration traffic rates at the study sites with standard error for among-year uncertainty (see Table 2), the colour of the German Sea indicates the extrapolated bat migration traffic rates from low (yellow) to high (red). The map base was changed after OpenStreetMap.

4. Discussion

Based on large-scale, multi-year acoustic recordings of bats migrating low above sea level at selected structures in the German North and Baltic Seas, we developed a method for estimating the number of individuals and the traffic rate of offshore migrating bats. Our estimates for bat migration traffic rates suggest that the extent of offshore bat

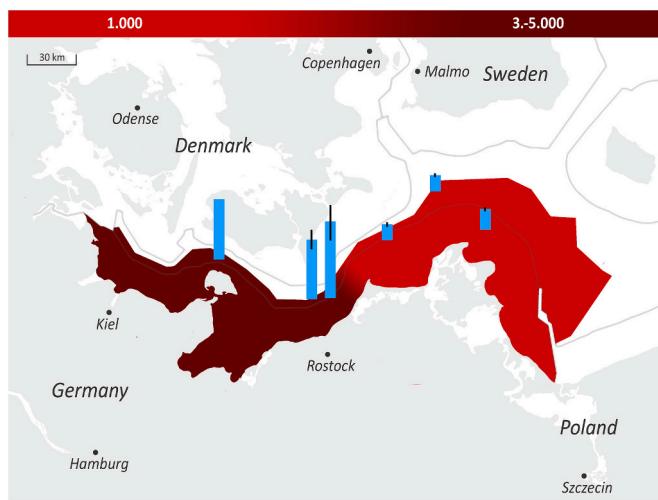


Fig. 6. Map of the bat migration traffic rates (n of individuals along a 1-km strip per year) in the German Baltic Sea. The land is coloured in light grey, the sea in white, the grey line represents the 12 nautical mile limits of the countries. The columns depict traffic rates at the study sites with standard error for the among-year uncertainty (see Table 2), the colour of the German Sea indicates the extrapolated migration traffic rates from high (red) to very high (dark red). The map base was changed after OpenStreetMap.

migration is considerable and ranges from up to 1500 bats per km and year in the German North Sea to up to 4600 bats per km and year in the German Baltic Sea. The km distance relates to a 1 km line perpendicular to the general migration direction.

We expect the potential risk of bat collisions with offshore wind turbines increases with increasing bat migration traffic rate, and that there is an urgent need for action to protect bats in accordance with national and international law and agreements. Therefore, our findings have strong implications for the operation of offshore wind turbines during nights of bat migration.

4.1. Bat migration traffic rates and distribution in the German Seas

Our study provides a comprehensive database to describe and assess the occurrence of migratory bats in the German North and Baltic Seas. Our observation of bats occurring in large numbers in both the German North and Baltic Sea confirms earlier studies with a more qualitative approach (Ahlén et al., 2009; Hüppop and Hill, 2016; Seebens-Hoyer et al., 2022; Skiba, 2007a).

The observed bat migration traffic rates in the German North Sea, ranging from around 100 bats per km and year in the EEZ (maritime zone beyond the 12 nautical mile limit) to 1500 bats in the territorial sea, suggests the existence of a bat migration traffic rate gradient perpendicular to the coastline. This is supported by the slightly higher bat migration traffic rates found at FINO 1 and consistent with findings from the Wadden Sea islands (e.g. Bach et al., 2022b; Reimers, 1999) and random observations from remote offshore structures and boats (Skiba, 2007a; Walter et al., 2007). It is possible that bats moving along the coastline follow migratory insects (see Rydell et al., 2010) that are drifted to the sea as it was observed in the Baltic Sea (Ahlén et al., 2009), or simply shorten the travel distance by flying across the German Bight (Bach et al., 2022a; Lagerveld et al., 2024; Seebens-Hoyer et al., 2022). Occasionally, bats may also be drifted offshore by strong winds (Hüppop and Hill, 2016), however, we consider this to be the exception, as we do not find correlations between bat activity and strong winds at our survey sites.

Still, it must be considered that there are only a few sample sites in the outer zone of the German North Sea. We consider the consistency in our data set over the many years of our study period, and when

compared to data from past studies (Hüppop and Hill, 2016; Seebens-Hoyer et al., 2022; Skiba, 2007a), as an indication that the overall small number of sampling sites is tolerable. Nonetheless, we acknowledge that our understanding of offshore bat migration in the German North Sea could be improved by adding further study sites. A higher density of sampling sites might be advisable especially for marine zones between larger land bodies, such as the Channel region, because of an uneven distribution of bat migration traffic rates (Lagerveld et al., 2023).

In the German Baltic Sea, estimates are less variable but higher, ranging from 900 bats per km and year in eastern areas, where the land masses are further apart, to as many as 4600 bats in the western areas, where the land masses are closer together. In our opinion, this is not surprising as for migrating bats the Baltic Sea is on their direct route from the summer habitats in Fennoscandia and the Baltic countries to the winter habitats in the south-west. In contrast, the German North Sea can easily be bypassed along the coast and the Wadden Sea islands. The observed pattern of the bat migration traffic rate in the German Baltic is in line with the notion that bats in general prefer to cross the sea where land masses are nearest to each other (e.g. Hedenström, 2009). Additional study sites would allow further testing of this assumption. Nevertheless, the German Baltic Sea area is sufficiently well covered by survey sites to demonstrate with certainty its importance for bat migration. We consider the principle findings and orders of magnitudes of bat migration traffic rates to be applicable for the following reasons: (1) the complete migration periods of most sites have been recorded over several years and (2) the estimates are consistent with observations from the German Baltic Sea islands (Seebens et al., 2013) and from the German and Scandinavian Baltic Sea (Ahlén et al., 2009; Bach et al., 2017; Rydell et al., 2014; Seebens et al., 2013; Seebens-Hoyer et al., 2022; Walter et al., 2007).

We consider it likely that the potential for bat fatalities at offshore wind turbines is higher in the Baltic Sea than in the North Sea. For the German North Sea, we see a relatively low potential for conflicts with wind turbines sited at large distances of 24 nautical miles or more from the coast. In contrast, we rate the potential for conflicts with wind energy production closer than 24 nautical miles from the coast and especially nearshore to be much higher (e.g. Bach et al., 2022b; Hüppop and Hill, 2016). From other parts of the North Sea, e.g. where two landmasses are closer to each other (southwestern part of the North Sea, Skagerrak) the situation is quite different. From the area between The Netherland or Belgium and UK high numbers of migrating bats have been reported (Brabant et al., 2019, 2021; Lagerveld et al., 2014, 2021, 2024), resulting in a higher probability for conflicts with wind energy production. As the potential for bat fatalities is highest in the western part of the German Baltic Sea, we recommend avoiding these areas for future wind energy development. For offshore areas with high bat activity (eastern German Baltic Sea and territorial sea of the North Sea), we call for the establishment of efficient mitigation schemes, such as curtailing the operation of wind turbines at times of high migration activity.

4.2. Limitations of the methodological approach

Several factors introduce uncertainty into our methodological approach. In the following, we will discuss assumptions underlying (1) length of the separator, (2) the recording technique, (3) structural features at recording sites, and (4) variation in the behaviour of migrating bats.

4.2.1. Length of the separator

We assumed that acoustic recordings of bats separated by maximally 20 min of silence originated from the same individual. If such acoustic recordings are from different individuals, e.g. if different bats pass within only five-minutes, we underestimate the bat migration traffic rates. Therefore, our estimates of bat migration traffic rates may be conservative since they are likely underestimated.

4.2.2. Recording technique

Our extrapolation builds on specific detection ranges for ultrasonic detectors estimated for ideal conditions. We calculated the atmospheric attenuation of echolocation calls using typical ambient conditions observed at mainland sites. As conditions were more humid and colder offshore, we likely overestimated the detection ranges and, thereby, underestimated the bat migration traffic rates, adding to our conservative approach in estimating offshore bat migration activity. Furthermore, we assumed relatively wide angles of sound emission for migrating bats and that bats are detectable even when they do not fly directly towards the microphone. These assumptions were made for the reason of simplicity, but we consider it more likely that bats migrating at high speed have narrow sonar beams. This would lower the probability of ultrasonic detectors detecting bats offshore during migration, adding to the possible underestimation of bat numbers. Nevertheless, the detection ranges used in our model are analogous to those observed at onshore wind turbines (Weber et al., 2018; Voigt et al., 2021) and are, therefore, likely to be reasonable estimators, despite lower accuracy. We also acknowledge additional factors that introduced uncertainty in our estimates, like the exact position and orientation of the microphones at spinning buoys, or potentially longer call intervals, which as well lead to underestimation of the true number passing by the detector.

4.2.3. Offshore structures and ALAN

Possibly, bats migrating offshore respond to the offshore structures to which we attached the ultrasonic equipment, namely that the structure itself or its illumination with artificial light at night (ALAN) attracts or displaces bats. The offshore structures involved in the study differ substantially in terms of size and structure, from approximately 4 m high buoys to structured platforms with a 100 m high lattice mast. All offshore structures involved in our study are lit, except for the DS-W buoy. The other buoys carry green (E69, E70) or red-white (Arkona) navigation lights. The masts of the platforms have red position lights. They are situated in or close to lit offshore wind farms. Finally, the lighthouse at which we also obtained some recordings has a much brighter light compared to all the other lights.

To date, no empirical data on the long-distance effect of the size and structuredness of offshore structures or ALAN on offshore migrating bats is available (see also Hüppop and Hill, 2016; Walsh et al., 2025). For bats migrating along the coast, attraction to ALAN is described to some extend (Voigt et al., 2017; Voigt et al., 2018). On the other hand, light avoidance is a known phenomenon for some bat species, especially light at high intensities. Attraction to structures like wind turbines on land has been described repeatedly (Cryan et al., 2014; Lintott et al., 2016). However, avoidance by bats over large spatial scales has also been found in, e.g., common noctule bats at coastal sites (Reusch et al., 2022). Hence, the available information regarding attraction or avoidance of structures is somewhat inconsistent and may vary across aerial-hawking species. In our data, we do not find strong differences in the bat migration traffic rates at nearby study sites of very different structures, e.g. between the unlit buoy DS-W and the lit FINO 2. Also, we do not find differences in the number of bats between the unlit buoy DS-W and the offshore windfarm Baltic 1, which has the typical illumination of offshore wind farms, in two nights during which parallel recordings took place (06.09.2021: two individuals at buoy DS-W, two individuals at microphone 1 in Baltic 1 and one individual at microphone 2 in Baltic 1. 08.09.2021: five individuals at buoy DS-W, two individuals at microphone 1 in Baltic 1 and five individuals at microphone 2 in Baltic 1.). Based on the lack of a consistent pattern in how bats respond to different types of offshore structures, we consider it unlikely that factors such as lighting have altered the estimated bat migration traffic rate. However, we acknowledge that we cannot rule out this possibility.

Also, it is likely that the method of converting the activity to a bat migration traffic rate in the described conservative manner can diminish or offset at least a possible short-distance attraction effect, whereas the type of activity (e.g. exploration behaviour) may be more sensitive to

being affected by possible attraction effects. The reason is that even if attraction within the recording distance of the ultrasound devices occurred, the resulting number of individuals and bat migration traffic rates would not differ, as both a passing and a attracted bat would result in one individuum count.

4.2.4. Behaviour of bats

When observed in direct flight over the sea, bats are predominantly described as flying low above sea level (Ahlén et al., 2009; Brabant et al., 2019; Rydell et al., 2014; Skiba, 2007a). In the few acoustic surveys at offshore wind turbines, bat activity was also higher at platform level than at nacelle level (Brabant et al., 2019; Ecocom, 2015). Seebens-Hoyer et al. (unpublished results) placed microphones at different heights from 10 to 100 m at an offshore structure and recorded about one third of all bats higher than 10 m above sea level. Because in our study we recorded at or below 10–20 m at all sites except at the lighthouse, we certainly missed a proportion of bats flying higher. At the lighthouse, where we recorded bats at a height of nearly 40 m above sea level, we missed bats passing at low levels. Nothing is known about possible offshore migration at altitudes higher than 100 m, as it has been described for common noctules over land (O'Mara et al., 2019). However, Lagerveld et al. (2024) calculated flight altitudes of up to several hundred meters for radio-tagged offshore migrating *Nathusius' pipistrelles*. If an additional part of the offshore migrating bat population migrates at such very high altitudes, our estimate for the bat migration traffic rates would be even more underestimated.

Bats not emitting echolocation calls during each wing stroke are less likely to be detected. In North America, some migratory bat species have been observed flying for several seconds without emitting echolocation calls (Corcoran and Weller, 2018). Ahlén et al. (2009) observed noctules (*N. noctula*) at Sea in parallel with radar and ultrasound devices and found that all individuals echolocated. Anecdotal observations made from an unlit boat in the German Baltic Sea confirms the presence of non-echolocating bats, mostly soprano pipistrelles (*P. pygmaeus*), offshore (Pommeranz, H., unpublished results). Hence, this behaviour also leads to an underestimation.

In summary, some factors could violate the assumption of our approach, which could potentially lead to an underestimate of bat migration traffic rates. The most important of these factors is the limited detection range of the ultrasonic devices, the choice of separator threshold, and the fact that we only consider bats flying at height at which they are recorded by the microphones. Observational data of bat activity at different-sized offshore structures does not provide support for the assumption that bats were attracted to these structures, yet we cannot rule out this possibility, which would lead to an overestimation of the bat migration traffic rates. We therefore call for complementary surveying methods such as imaging techniques to test whether our assumptions are valid.

4.3. Applicability as method and value for bat protection

We offer a method for estimating the number of individuals of offshore migrating bats from acoustic recordings and extrapolating these to a bat migration traffic rate that can be applied to other regions of the world. Our approach takes into account the characteristics of ultrasonic devices and the detection ranges of different bat species. It does not include bats migrating high above sea level (Lagerveld et al., 2024) or non-echolocating bats (Corcoran and Weller, 2018). However, it allows us to generalize our results over large spatial scales and across many study sites using different equipment. Such an approach is urgently needed given the paucity of accessible recording sites. Bat migration traffic rates allow defining critical thresholds above which a collision risk is predicted that should trigger appropriate mitigation measures, such as a temporary shutdown of turbines at times of high bat activity during spring and especially autumn migration (see Figs. S2, S3 in the Supplementary Material 4), similar to spatial planning

recommendations to protect migratory birds at offshore turbines (Schwemmer et al., 2022). Because methods for detecting bat collisions with offshore wind turbines are still inadequate (Dempsey et al., 2025; Hooker et al., 2025; Molis et al., 2019; Sato and Kawaguchi, 2025; Solick and Newman, 2021; Weaver et al., 2025), the exact extent of the risk is unknown. Once the activity and collision risk have been linked statistically, as it has been done for onshore wind turbines (Behr et al., 2023; Korner-Nievergelt et al., 2013), the acoustic activity measured at wind turbines can be used as an indicator for the risk of bats to collide with the blades. Until such methods are established and broadly available our study can fill the current knowledge gap by providing a method to estimate the extent of affected individuals and – on this basis – specify thresholds at which protection measures should be applied. From our point of view, collisions are likely to occur whenever bats approach the rotor swept zone of offshore wind turbines. It is therefore likely that the expected number of collisions increases with the bat migration traffic rate. The high level of protection of bats in the EU, reflected in the individual-based protection under the EU Habitats Directive, will certainly require mitigation measures even at relatively low bat migration traffic rates of several hundred bats per km and year.

5. Conclusions

The high bat migration traffic rates in the German territorial seas of the North Sea and the whole German Baltic Sea indicate a high risk of collisions between bats and offshore wind turbines in these areas. This underlines the urgent need to implement effective protection measures, especially in view of the expansion target of 70 GW in Germany (WindSeeG, 2025) and those of other countries. In contrast to offshore wind turbines, mitigation measures such as feathering and curtailing the operation of wind turbines are already being practiced in around 30% of onshore wind turbines in Germany (Voigt et al., 2022). We argue for the implementation of efficient curtailment schemes for offshore wind turbines as well, especially in the Baltic Sea with its high bat activity. Such curtailment regimes are partly in place offshore, too, e.g. in single wind farms the Netherlands (Ministerie van Economische Zaken, 2016) and Denmark (Energietyrelsen, 2024a, 2024b). As bats migrate mainly during nights with low wind speeds (Brabant et al., 2021; Lagerveld et al., 2021; Seebens-Hoyer et al., 2022), the revenue losses are likely to be rather small. However, the benefits for bat conservation could be immense. The implementation of curtailment regimes appears to be the appropriate response (Frick et al., 2020; Rodrigues et al., 2015; Whithy et al., 2024), given the legal protection of European bats at both national and international level and the requirements of the Bonn Convention, signed by Germany and many other countries bordering the North and Baltic Seas. It would also ensure that the addition of offshore wind farms does not add an unacceptable risk to populations of the two main migratory species, *Pipistrellus nathusii* and *Nyctalus noctula*, which already appear to be declining (BfN, 2025; Van Schaik et al., 2025). Bats have a low reproduction rate (one to two juveniles per year) and tend to be long-lived, they do not easily compensate for additional human-induced mortalities, and small changes in mortality can have significant effects (e.g. Altringham, 2011; Frick et al., 2017; Voigt et al., 2012, 2024). It can be assumed that the increased mortality at wind turbines has negative effects on the conservation status of bat populations (e.g. EUROBATS, 2017; O'Shea et al., 2016; Voigt and Kingston, 2015; Voigt et al., 2024). For bat species migrating across the sea and travelling long distances on land, the cumulative effects of offshore and onshore wind turbines play a major role, even if the mortality rate per wind turbine appears to be low (Frick et al., 2017; Friedenberg and Frick, 2021).

This study is the first approach to calculate the number and traffic rate of low flying and echolocating migrating bats offshore. It provides an estimate of the magnitude of how many individuals migrate offshore and, hence, are potentially at risk to collide with the blades of offshore wind turbines. Our results fill the knowledge gap until workable collision monitoring methods are available offshore. It can be applied in

spatial planning procedures for offshore wind farms and to define mitigation measures like curtailment schemes during times of intense offshore migration of bats. The bat migration traffic rate can be determined in situations where bats migrate directionally offshore e.g. between two land masses like in the Baltic Sea, the English Channel (Brabant et al., 2019; Hooker et al., 2025; Lagerveld et al., 2024), the Irish Sea (Hooker et al., 2025), the central Black Sea or the Mediterranean Sea. It might be less suitable in situations where bats migrate parallel to land masses as in the Western Black Sea (Dundarova et al., 2021) or along the US East Atlantic Coast (Peterson et al., 2014), where regular occurrence of local bats must be expected.

Our results should be verified with other methods, especially imaging methods such as radar and thermal imaging, as soon as these are available. Other urgent issues that need to be addressed include the impact of structures and ALAN on offshore migrating bats, bat behaviour at offshore wind turbines and the correlation between bat activity and fatalities at offshore wind turbines.

CRediT authorship contribution statement

Antje Seebens-Hoyer: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Lothar Bach:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Henrik Pommeranz:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Christian C. Voigt:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Volker Runkel:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Pius Korner:** Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Petra Bach:** Writing – review & editing, Investigation, Conceptualization. **Michael Götsche:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Reinhold Hill:** Writing – review & editing, Investigation, Conceptualization. **Annette Pommeranz:** Writing – review & editing, Investigation. **Sandra Vardeh:** Writing – review & editing, Conceptualization. **Tobias Böhme:** Investigation. **Matthias Götsche:** Investigation, Conceptualization. **Hinrich Matthes:** Investigation, Conceptualization.

Declaration of competing interest

Several authors (Lothar and Petra Bach, Tobias Böhme, Matthias and Michael Götsche, Annette and Henrik Pommeranz and Volker Runkel) work as experts for bats in onshore wind energy and other planning projects. Reinhold Hill works as an expert on birds in offshore wind energy planning. Volker Runkel co-owns the bat detector company ecoObs GmbH, which produces batcorders. Antje Seebens-Hoyer is employed at the nature conservation NGO “NABU Mecklenburg-Vorpommern”, her main work are the offshore bat studies. The other authors named above received project fees from these. As none of the authors currently or in the past has worked as paid expert on bats in commercial offshore wind energy projects, we declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2026.111741>.

Data availability

Data and R code will be made available if requested.

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