Baseline surveys of Birds, Bats and Marine Mammals in areas for Offshore Wind Farms in the Danish North Sea (North Sea I)

Bats – Baseline surveys 2023-2025 North Sea I

Energinet Eltransmission A/S

Date: 10. October 2025

Contents

Rev. no.	Date	Description	Done by	Verified by	Approved by
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Preface

This report on 'Baseline surveys of Bats in areas for Offshore Wind Farms in the Danish North Sea (North Sea I)' was commissioned by Energinet to NIRAS. The work was realised through a back-to-back collaboration agreement between NIRAS and DCE/Aarhus University, see Declaration of contributions below. The report summarises existing knowledge about bats for the North Sea in general, for the North Sea I pre-investigation area. and presents data on bats obtained in the bat baseline survey programme, conducted over two years from 2023 to 2025. Data from the second year of baseline surveys (April 2024 to April 2025) are presented for the first time in this report. An analogue survey programme was conducted during the first year of the baseline surveys (April 2023 to April 2024). Detailed information from the first survey year is also described in a separate report and referenced here where relevant. This report presents and analyses data from both the second year and across both survey years. As such, the results and conclusions of the report represent a stand-alone description of the status of the North Sea I pre-investigation area as it relates to bats.

Front page illustration: Dawn at Horns Rev 3 wind farm during a North Sea I survey to service monitoring stations in December 2023. Credit: S Brinkløv.

Declaration of contributions

The first section of chapter 1: Introduction and objective was provided by Energinet.

Researchers from the Department of Ecoscience, Aarhus University, carried out the field work, data analysis and authored this report. Responsible for field work: Signe Marie Mygind Brinkløv (SB), Astrid Særmark Uebel (ASU), Thomas W. Johansen (third party contractor), Esben Terp Fjederholt (ETF), Lars Haugaard, Michael Schmidt, Morten Elmeros (ELM) and Simeon Quirinus Smeele (SQS), data analysis: SQS, ASU, Klara Johanna Grethen (KJG) and SB, review of relevant literature: SB, ASU, SQS and ELM. The report was authored by SB, SQS, ASU (main authors), KJG and ELM. All authors approved the final version of the report.

The report was peer-reviewed by Julie Dahl Møller from Aarhus University, and quality assured by DCE (Camilla Uldal) and NIRAS (Rasmus Bisschop-Larsen (RBL). Søren Granskov (SGRA) from NIRAS gave final approval for publication of the report.

Energinet has seen and commented on draft versions of the report. The comments and author replies are available here, along with a copy of the final report: https://dce.au.dk/udgivelser/oevrige-dce-udgivelser/eksterne-udgivelser/2025.

The report is also published by the Danish Energy Agency (DEA) as part of the tender for offshore wind farms in the area North Sea I.

We thank Vattenfall A/S for access to and assistance with PAM deployments on wind turbines in Horns Rev 3, Energinet for access to and service of the PAM deployment on the Horns Rev 3 offshore substation (OSS), the landowners for access to coastal deployment sites for the onshore detectors and Motus receivers, Maritim Consult for assistance with the custom setup to conduct bat PAM from buoy stations, and BioConsult, OS Energy and Comet Trawl (third-party contractors) for their contributions to offshore survey planning and execution.

List of key terms and abbreviations

Relevant terms and abbreviations used in the report are listed and explained (in English and Danish) in table 1.1 below.

Table 0.1 Explanation of relevant terminology and abbreviations including Danish and English terms.

English (abbreviation)	Danish	Explanation
Pre-investigation area	Forundersøgelsesområde	The area pre-defined by The Danish Energy Agency as North Sea I.
Survey area	Undersøgelsesområde	The offshore area for which field investigations have been carried out and is presented, along with available supplementary data and information. The survey area includes the North Sea I pre-investigation area plus a 20 km buffer zone around it.
PAM	Passiv akustisk overvågning	Passive Acoustic Monitoring (Programmed ultrasonic recordings by a stationary recording device)
Motus	Motus	Wildlife radio tracking system
NOVANA	Det Nationale Overvågningsprogram for Vandmiljø og Natur	The Danish national monitoring programme for aquatic environment and nature, run by the Agency for Green Transition and Aquatic Environment
OWF	Havvindmøllepark	Offshore wind farm
OSS	Offshore transformerstation	Offshore substation (platform directing power from offshore wind turbines to land)
WT	Vindmølle	Wind turbine

Summary

This report compiles the results from two years of baseline surveys of bats (April 2023 - April 2025) for the 1.400 km^2 North Sea I pre-investigation area and a 20 km buffer zone around the pre-investigation area. The eastern and western perimeters of the pre-investigation area are located approximately 20 km and 80 km from the coast, respectively. The report also sums up existing, albeit limited, available information of relevance. The primary data collection effort included passive acoustic monitoring (PAM) from offshore stations on buoys, on the transition piece of existing offshore wind turbines and an offshore substation in the wind farm Horns Rev 3, and from vessels conducting bird baseline surveys within the pre-investigation area. The offshore PAM was supplemented by 11 PAM stations on shore along the western coast of Jutland. Efforts to catch, tag and radio-track bats were also initially part of the first survey year.

Bats were detected on a total of 18 out of the 22 offshore buoy stations that were included in the bat PAM programme across both survey years. Eleven stations recorded bats during the first survey year, and 17 stations recorded bats during the second survey year. Nine of the buoy stations recorded bats in both survey years. A single bat was recorded on a buoy station during spring, all other bat records on buoy stations were from the autumn, between start of August and end of September. Bats were also present in five out of 20 deployments (10 per year) on wind turbines in Horns Rev 3, on the single OSS PAM station added during the second survey year, and on seven nights out of the 97-day collective period where bat activity was monitored during vessel surveys of birds.

The offshore bat records included several species: Nathusius' pipistrelle (*Pipistrellus nathusii*), species assigned to the complexes *Eptesicus*/*Nyctalus*/*Vespertilio* and *Myotis* (based on a conservative approach not identified to species), common noctule (*Nyctalus noctula*), soprano pipistrelle (*Pipistrellus pygmaeus*) and one record identified as either Nathusius' pipistrelle or common pipistrelle (*Pipistrellus pipistrellus*).

Nathusius' pipistrelle, a species well-known for long-distance migration, was the most common species found offshore during the two-year survey period. It was also the only species documented beyond 27 km offshore, including records from one of the buoy stations (NS06) approximately 80 km offshore. Most bat passes, also of Nathusius' pipistrelle were, however, recorded on stations less than 40 km from the coast.

Bat occurrence offshore coincided with temperatures mostly above 15̊C (estimated at 2 m above mean sea level) and mean wind speeds mostly below 8 m/s (estimated at 10 m above mean sea level). Easterly winds were an important predictor of autumn activity at favourable temperature and wind speeds. The few nights with records from spring (one night from buoys, four nights from wind turbines) included lower temperatures (down to 8̊C) and higher wind speeds (up to 11 m/s).

Overall, the offshore bat activity was low and clustered onto specific dates, compared to the significant bat activity along the coast during the two-year survey period. Activity of Nathusius' pipistrelle increased for nearly all stations at the end of August. The activity peaks observed at the land-based stations could relate to migration but were not reflected in similar peaks offshore.

During the first year of the baseline surveys, in autumn 2023, 13 Nathusius' pipistrelles were caught in northern and western parts of Jutland and tagged with radio-transmitters to obtain movement vectors for these individuals. Two of the tagged bats were since registered on radio-receivers along the North Sea coast of Germany, documenting transnational bat migration over at least 270 km and 400 km, without any further data points to detail their routes. The tagging effort was not included in the second year of bat baseline surveys but a third track is added in this report (Department of Ecoscience, Aarhus University, own data) to show a male Nathusius' pipistrelle following the North Sea coastline south passing by ten receiver stations in Denmark, Germany and The Netherlands after departing from its capture and tagging point near Skjern, Western Jutland.

It is inconclusive whether the offshore records of bats reflect foraging activity, migration activity or both. Based on the results of the bat surveys, the observed activity offshore could reflect foraging flights from and to the coast during a period of mainly land-based intense foraging activity, which may be related to migration activity mainly along the coastline. The activity recorded by PAM stations on the transition pieces of wind turbines and the OSS PAM station added in the second year included numerous feeding buzzes, suggesting that bats could target permanent structures at sea for such foraging bouts or follow insects to them.

It is noteworthy that all offshore activity coincided with the expected migration periods in autumn (predominantly) and spring, whereas no activity was observed by the offshore survey effort during summer in either of the two survey years. Some bat activity in the pre-investigation area, e.g., higher altitude flight, was undoubtedly missed beyond the detection range of the passive acoustic monitoring stations. Still, the level of activity was low in comparison to the level observed at the onshore stations. Based on the evidence available, the offshore activity of bats in the North Sea I pre-investigation area is likely related to migration but it seems probably that bats are migrating mainly over land and along the coastline, while opportunistically following foraging opportunities offshore into the area, whereas no evidence points to the presence of a major migration corridor through the area. More migration activity at altitudes beyond the acoustic detection range of the PAM stations cannot be ruled out by the baseline surveys.

1. Introduction and objective

To accelerate the expansion of Danish offshore wind production, the Finance Act for 2022 and the subsequent Climate Agreement on Green Power and Heat of 25 June 2022 established the framework for developing a minimum of 9 GW of offshore wind capacity in Danish waters.

To realize these political commitments and significantly increase offshore wind energy production, the Danish Energy Agency has prepared a development plan for offshore wind farms in three designated areas: the North Sea, the Kattegat, and the Baltic Sea. As part of this process, the Agency has initiated a wide range of feasibility studies in the areas. This report concerns the environmental pre-investigations of bats.

The North Sea I area covers approximately 1,400 km^2, divided into three sub-areas designated for offshore wind development. Located 20-80 km off the coast of West Jutland, each of the three sub-areas will be connected to the onshore grid through designated export cable corridors.

In May 2025, the Danish Parliament adopted the tender framework agreement, which determined that two of the three sub-areas in North Sea I – specifically Nordsøen I Midt and Nordsøen I Syd – will be included in the first tender round. The third sub-area, Nordsøen I Nord, will remain in a pool of potential future tender sites.

The map in Figure 1.1 shows the location of the two sub-areas - Nordsøen I Midt and Nordsøen I Syd – which will be tendered for in autumn 2025 (Source: ens.dk/energikilder/nordsoeen-i-syd-og-midt-havvindmoelleparker/). The area Nordsøen I Nord is north of Nordsøen I Midt, whereas the darker blue area to the west is for future development of offshore wind.

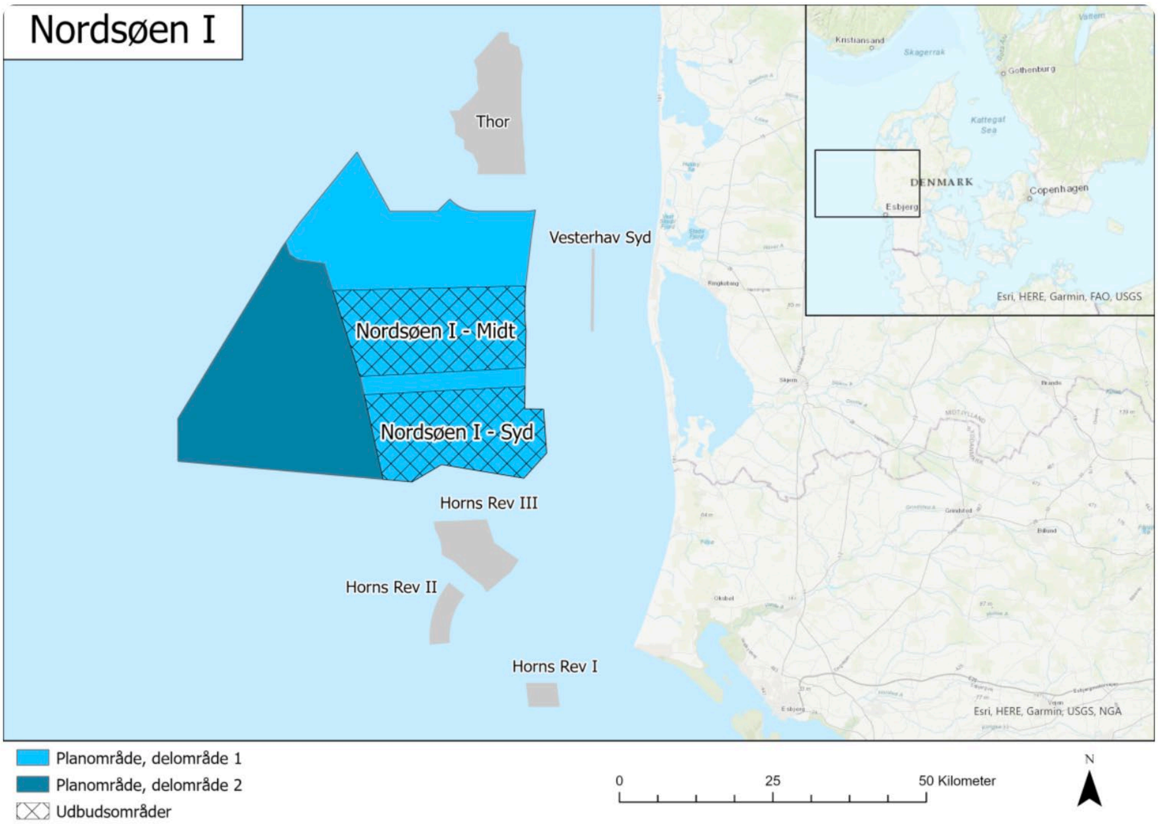


Figure 1.1. Map showing the overall area (light blue and darker blue) for offshore wind development in the Danish North Sea. The two sub-areas, Nordsøen I Midt and Nordsøen I Syd will be part of the tender from Danish Energy Agency in autumn 2025.

The tendering process for Nordsøen I Midt Offshore Wind Farm (OWF) and Nordsøen I Syd OWF will commence in autumn 2025. The deadline for Nordsøen I Midt OWF is set for spring 2026, while the deadline for Nordsøen I Syd OWF will follow in autumn 2027. According to the current schedule, Nordsøen I Midt OWF is expected to be operational by 2032, with Nordsøen I Syd OWF coming online in 2033.

The North Sea I pre-investigations for bats were carried out on behalf of Energinet Eltransmission A/S by Aarhus University/DCE in collaboration with NIRAS during 2023-2025 and includes offshore and onshore field surveys based on passive acoustic monitoring and tagging of bats. The baseline survey data are used to map the spatial and temporal presence of bats in and around the North Sea I area, with reference to the west coast of Jutland.

1.1 Objective

The objective of the environmental baseline surveys is to collect new data and compile existing data from the North Sea to provide a status for the pre-investigation area to serve as input for environmental permitting processes for future concessionaires.

This technical report compiles data from two years of pre-investigations in the survey area for the project North Sea I during 2023-2025. The first year of pre-investigations was initiated in April 2023 and concluded in April 2024, followed by a second survey year from April 2024 to April 2025. The results from the field surveys are supplemented with existing data and information compiled from available sources. This additional relevant information is summarized in Chapter 2.

The report can be used as a stand-alone document and includes distribution and presence data on bats from both years. The results from the first survey year are also presented in a separate report (Brinkløv et al. 2024), which holds more detailed information about some survey components and is referenced here, where relevant. Data from the two years have been analysed either combined or separately, depending on the objective of each sub-analysis. Bat occurrence and activity are summarized per year. Models to predict offshore activity use data combined from both survey years.

1.2 Survey design

The baseline surveys of bats relied primarily on passive acoustic monitoring (PAM) with buoy PAM stations as the main offshore component, supplemented by PAM stations on existing offshore structures. The surveys were designed on the assumption that bats may occur throughout the entire pre-investigation area but are more likely to occur closest to shore. The survey design included a total of six components (Figure 1.2):

- 22 offshore PAM stations on temporary buoys in the pre-investigation area and a surrounding 20 km buffer zone (23 buoy stations are indicated in figure 1.2, see explanation below in section 1.2.3)
- A rotation of offshore PAM stations on existing wind turbines in Horns Rev 3, within the 20 km buffer zone
- A single PAM station added during the second survey year on the Horns Rev 3 offshore substation (OSS)
- A single recorder deployed on vessels conducting surveys for the bird baseline surveys
- 11 PAM stations on land along the west coast of Jutland
- Tag-based radio-tracking of bats was temporarily included in addition to passive acoustic monitoring to gain information on bat migration routes.

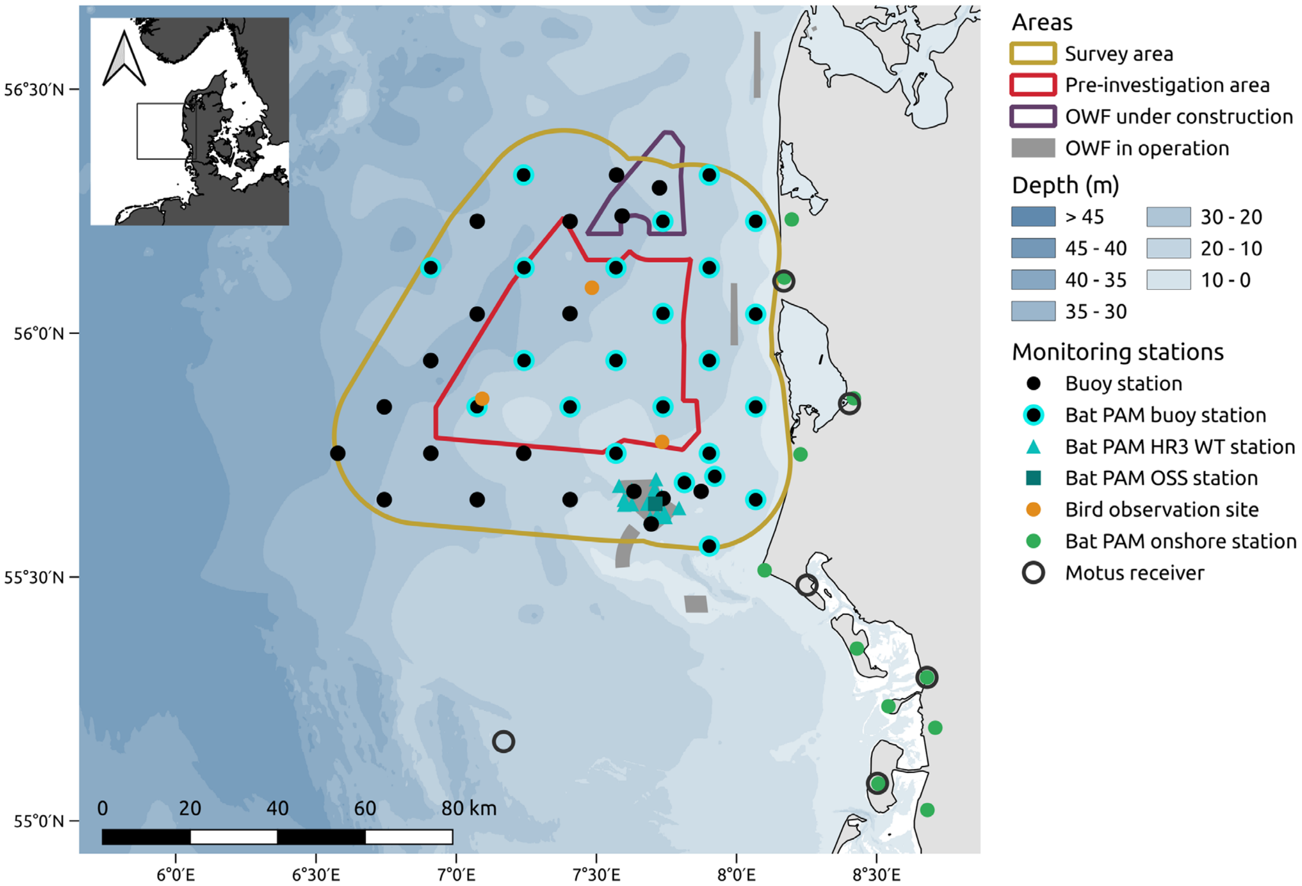


Figure 1.2. Map of onshore and offshore PAM stations and Motus radio-receivers deployed in the North Sea I baseline surveys for bats. Red outline: North Sea I pre-investigation area. Yellow outline: offshore survey area, including the pre-investigation area and a 20 km buffer zone around it. Light grey areas show, from south to north, the OWFs (offshore wind farms) Horns Rev (HR) 1, HR2, HR3, Vesterhav Syd and Vesterhav Nord. Purple outline: Thor OWF under construction. Orange points: the three fixed observation sites from the ship-based bird surveys (left to right: SW, N and SE). Green points: approximate locations of onshore PAM stations. Open black circles: approximate locations of Motus radio receivers. Open circle offshore: Motus receiver from third party project. WT = wind turbine. OSS = offshore substation.

Figure 1.3. Photos from the four offshore PAM components. Left to right: buoy station, Horns Rev 3 wind turbine station on transition piece, OSS station and recorder on bird survey vessel. The arrowheads indicate placement of the SM4BAT FS microphone. Photo credits: S Brinkløv/Aarhus University, Vattenfall A/S, Energinet, TW Johansen/SeNatur.

1.2.1 Passive acoustic monitoring from offshore buoys

A total of 22 bat PAM stations were deployed on buoys as the main component of the offshore survey efforts. The bat PAM stations were mounted on a subset of 39 yellow spar buoys deployed in a grid pattern across the North Sea I pre-investigation area and a 20 km buffer zone surrounding it (Figure 1.2 and 1.3). Figure 1.2 and map figures in the Results chapter show 23 bat PAM buoy stations because of a mix-up resulting in one being deployed and conducting PAM at a wrong location for a single deployment. For any given deployment period, no more than 22 offshore buoy stations were active.

The buoys were serviced in synergy with the marine mammal baseline surveys subject to weather conditions, with the goal to ensure data collection from all four seasons. The offshore buoy stations were distributed with nine stations located within the pre-investigation area and 13 stations located within the buffer zone, with emphasis on the area between the coastline and the eastern border of the pre-investigation area where most bat activity was expected (Figure 1.2). A latitudinal transect of four stations was included near the northern and southern boundary of the pre-investigation area, respectively.

The positions of the export cable tracks were not specified at the start of the pre-investigations and were therefore not considered in the survey design.

1.2.2 Passive acoustic monitoring from Horns Rev 3 offshore wind turbines

In addition to the offshore buoy stations, the bat baseline surveys included deployment of PAM stations on operational wind turbines in the Horns Rev 3 (HR3) area. These were facilitated by the HR3 operator Vattenfall A/S. HR3 is located just south of the North Sea I pre-investigation area, within the southern part of the buffer zone included in the survey area (Figure 1.2). The timing, location (which turbine), and duration of the HR3 deployments on wind turbines were subject to operator service schedules and convenience, which dictated the number and locations of stations deployed over the year. Ultimately, deployments were made on a total of 10 separate wind turbine stations during the two survey years. The wind turbines in Horns Rev 3 are 1-1.5 km apart and the stations were deployed at the level of the transition piece, approximately 15 m above mean sea level (Figure 1.3).

1.2.3 Passive acoustic monitoring from Horns Rev 3 offshore substation

A single PAM station was added to the OSS in Horns Rev 3 during the second survey year in July 2024 to supplement the offshore monitoring effort. As for the PAM stations on wind turbines (section 1.2.2), service of this station was contingent on operator service schedule and coordinated with technicians from Energinet.

1.2.4 Passive acoustic monitoring on offshore bird surveys

The offshore bat survey effort also included PAM from a recorder installed onboard during ship-based bird surveys as part of the North Sea I project's baseline survey programme for birds (Figure 1.3). The bird surveys transited from Esbjerg Port and visited three predefined bird observation points (Figure 1.2).

1.2.5 Passive acoustic monitoring from stations on shore

To supplement the offshore PAM effort, the bat baseline surveys incorporated 11 onshore PAM stations, installed along the western coast of Jutland to map bat activity over coastal land areas and serve as a reference for offshore bat activity. From north to south, the approximate locations of the land-based stations were: Husby, Stadilø, Skjern Enge, Nyminde Plantage, Blåvand, Fanø, Kammerslusen, Mandø, Rejsby, Rømø, and Ballum (Figure 1.2). Onshore stations were to the extent possible serviced bi-monthly with the aim to keep them running nightly throughout the year with emphasis on spring, summer and autumn.

1.2.6 Radio-tracking

The final component of the bat baseline survey programme included installation of five radio receiver stations at coastal locations along the west coast of Jutland (Figure 1.2 and 1.4) and trapping and tagging of bats during the migration period in autumn 2023 in an effort to obtain movement vectors of the tagged individuals (www.motus.org). The methods, equipment and results of the tagging effort was part of the first year of the baseline surveys and are detailed in the year one report (Brinkløv et al. 2024), but the radio-tracking component was foregone from the survey programme by Energinet before the start of the second survey year.

Figure 1.4. Photos from the onshore PAM and Motus components. Left: combined coastal PAM and Motus receiver station. The arrowhead indicates placement of the SM4BAT FS microphone. Right: Nathusius' pipistrelle ready for release with Motus radio-tag. Photo credits: L Haugaard and S Brinkløv/Aarhus University.

2. Existing data and knowledge

Human activity impacts biodiversity globally. Bats are not exempt from this impact, but despite accounting for close to a quarter of the World's mammal species, the impacts of anthropogenic activities, including expanding infrastructure, on the conservation status of bats have only gained recent focus (Burgin et al. 2018, Voigt et al. 2024b). Bats provide ecosystem services of both ecological and economic value, including pest control, pollination and seed dispersal (Ancillotto et al. 2017, Ghanem & Voigt 2012, Williams-Guillén et al. 2016, Yu & Muchhala 2023). Despite their minute size, bats are long-lived and have slow reproductive rates, as females only give birth to a single or few pups per year (Wilson & Mittermeier 2019). Consequently, even small changes in bat mortality rates may impact their conservation status (Frick et al. 2017, Voigt et al. 2012, 2022). Bat fatalities may be direct, from infections, as exemplified by 'white nose' syndrome in North America (Frick et al. 2010), collisions with road and railway traffic or with wind turbines (Merlet et al. 2025). Fatalities may also have indirect causes, like habitat degradation or displacement from habitat, e.g., by wind turbines or other infrastructure developments (Voigt & Kingston 2016, Frick et al. 2020). The need to monitor bat populations and adequately inform management and conservation initiatives, is not only urgent and widely acknowledged but also a legal prerequisite for avoiding delays in construction projects to expand infrastructure or boost renewable energy initiatives.

Studies of bat movements over the North Sea are in general sparse and especially so for the part of the North Sea surrounding Denmark. The following sections summarize conservation status of relevant bat species and potential impacts of wind farms on bats based on available background information, e.g., from scientific literature and consultancy reports. Data and knowledge assimilated during the first year of the North Sea I baseline surveys is treated in the results and discussion of this report and are not integrated in Chapter 2. Latin names of bat species are included at first mention in the following sections.

2.1 Bat conservation status

At least 17 species of bats occur regularly in Denmark (Elmeros et al. 2024). A potential finding of the grey long-eared bat could bring the number to 18 species but was not verified by DNA analysis. Several of these are long-distance migrants that also occur offshore (Table 2.1, Figure 1.4). All of them feed on insects and use echolocation, the emission of ultrasonic calls and the echo-feedback from these calls, for hunting and short-range orientation. The volant and nocturnal nature of bats means that they are not straightforward to monitor and information about their population sizes, presence, movement patterns and activity even over land and particularly offshore is still severely lacking.

All bat species in Denmark are legally protected by their adoption onto Annex IV of the European Union Habitats Directive (https://eur-lex.europa.eu). The directive obliges member states to establish and ensure strict measures of protection for bats within their natural range, including the adoption of monitoring schemes and prevention of disturbances and incidental killings of bats that may threaten the conservation status of bat populations. In addition, some species appear in Annex II of the directive where they inform the designation of special areas for conservation as part of the Natura 2000 network.

The Danish Red List categorizes eight of the 17 species as least concern and the rest as either data deficient, vulnerable, near threatened or endangered (Elmeros et al. 2019). Notably, in the context of bat migration, the status according to the Danish Red list and the Article 17 assessments of conservation status apply to populations occurring in Denmark during the breeding season without considering the status of the flyway populations. The more common species, including the serotine bat (*Eptesicus serotinus*), Nathusius' pipistrelle (*Pipistrellus nathusii*), common pipistrelle (*P. pipistrellus*), soprano pipistrelle (*P. pygmaeus*), particoloured bat (*Vespertilio murinus*), and common noctule (*Nyctalus noctula*) have a favourable conservation status in both (Atlantic and continental) biogeographic regions in Denmark (Fredshavn et al. 2025). However, these national assessments are primarily based on distribution range, while the population sizes and trends are unknown. Daubenton's bat (*Myotis daubentonii*) and the pond bat (*M. dasycneme*) have unfavourable-inadequate and unfavourable-bad conservation status due to population declines (Fredshavn et al. 2025).

For the long- and medium distance migratory species documented offshore over the North Sea, the European conservation status is generally Unfavourable or Unknown (Table 2.1, https://nature-art17.eionet.europa.eu/article17/). Given the migratory behaviour of many bat species, an international or fly-way population level approach is needed to manage the species and the threats from wind turbines (Voigt et al. 2012, 2024a, 2024b).

*Table 2.1. Migratory behaviour and current EU Conservation status of bat species observed over the North Sea. The list was compiled from Petersen et al. 2014 and Seebens-Hoyer et al. 2021. Migratory behaviour is adapted from Hutterer et al. 2005. The EU conservation status is listed for each of the three most relevant biogeographic regions (https://www.eea.europa.eu) bats may migrate to and from, potentially crossing the North Sea I pre-investigation area. Some observations and studies on occurrence of the bat species included in the table predate the split of Pipistrellus pipistrellus and P. pygmaeus into two species (Jones & Barratt, 1999). The two species have very similar ecology and until documented otherwise both species must be expected to occur offshore. ATL: Atlantic biogeographic region, CON: Continental bio-geographic region, BOR: Boreal biogeographic region. FV: Favourable, U1: Unfavourable-Inadequate, U2: Unfavourable-Bad, XX: Unknown (https://nature-art17.eionet.europa.eu/article17/). Asterisks indicate species at high** or medium* level of collision risk with wind turbines in open habitats according to Rodrigues et al. 2015.*

Scientific Name	Common Name	Migratory behaviour	EU conservation status		
			ATL	CON	BOR
*Eptesicus nilssonii**	Northern bat	Short - Medium	XX	U1	FV
*Eptesicus serotinus**	Serotine bat	Short - Medium	U1	U1	XX
*Nyctalus leisleri***	Leisler's bat	Long	U1	U2	XX
*Nyctalus noctula***	Common noctule	Long	XX	U1	U1
*Pipistrellus nathusii***	Nathusius' pipistrelle	Long	XX	U1	U1
*Pipistrellus pipistrellus***	Common pipistrelle	Short - Medium	U1	U1	XX
*Pipistrellus pygmaeus***	Soprano pipistrelle	Short - Medium	FV	U1	XX
*Vespertilio murinus***	Parti-coloured bat	Medium - Long	XX	U1	FV

2.2 Potential impact of offshore wind turbines on bat populations

From an ideal conservation perspective, wind facilities would only be planned and exist in areas without bat activity. Less optimal but more realistic, they should target areas with as little bat activity as possible, of as few bat species as possible, and with adaptive curtailment schemes to mitigate the loss of and decrease the impact on bats from wind energy production.

Bats move over species-dependent ranges between their summer and winter habitats. Some species can migrate over ranges up to 2,000 km, including significant ranges offshore (e.g., Hutterer et al. 2005). Wind turbines onshore may pose a population level threat to both local and migratory bat species, due to mortality and potential barrier or displacement effects (Voigt & Kingston 2016, Rodrigues et al. 2015). Bat fatalities caused by wind turbines are at best difficult to quantify. On land, carcass searches can be used to quantify fatalities to some extent, but bat carcasses quickly decay or are removed by scavengers, leaving little physical evidence and introducing uncertainty to the method (Korner-Nievergelt et al. 2015). There is currently no way to quantify bat fatalities offshore. Fatalities seem to be generally caused by direct impact (Rollins et al 2012, Lawson et al. 2020), although Baerwald et al. (2008) suggested that barotrauma could be a major cause of bat fatalities at wind turbines, arising from internal injuries caused by pressure differences over the airspace surrounding the wind turbine. However, the exact cause of death is irrelevant to the level of mortalities and the need to mitigate the impact of wind turbines on bat populations.

The level of collision risk for European bat species with wind turbines in open habitats is indicated for the relevant species in Table 2.1 (based on Rodrigues et al. 2015 and Elmeros et al. 2024). The risk assessment builds on a combination of fatality studies on land and knowledge of the species-specific ecology, including flight and migratory behaviour. While this information is primarily derived from onshore studies, the Eurobats guidelines for consideration of bats in wind farm projects are applicable both on- and offshore (Rodrigues et al. 2015). The numerical mortality per wind turbine might seem low (ca. 14 bats per wind turbine per year on average for onshore wind turbines across Central Europe, Voigt et al. 2022), but the cumulative effect of wind turbines in a species' distribution range may threaten the conservation status of populations (Frick et al. 2017, Friedenberg & Frick 2021). More solid baseline information is therefore vital to assess and potentially predict large-scale cumulative effects, especially in this age of massive green energy expansion.

2.3 Existing knowledge of bat activity offshore and over the North Sea

Petersen et al. (2014) reviewed historic and non-systematic bat records from structures (e.g., oil rigs) and vessels in the North Sea over a period from 1960 to 2012. The total number of findings included single individuals from five species: Nathusius' pipistrelle (20 records), northern bat (*Eptesicus nilsonii*, 1 record), Leisler's bat (*Nyctalus leisleri*, 1 record), common noctule (2 records), and the particoloured bat (6 records). Other records also include the common pipistrelle, and the serotine bat, but Nathusius' pipistrelle is the most frequently observed bat species offshore in the North Sea (Lagerveld et al. 2021, Seebens-Hoyer et al. 2021). It is also one of the species found in highest numbers killed under onshore wind turbines (Rodrigues et al. 2015, EUROBATS 2017, Voigt & Kingston 2016). Apart from the species listed above, offshore accounts of bats from the inner Danish waters and the Baltic Sea include Daubenton's bat, the pond bat, the soprano pipistrelle, the common pipistrelle, and the brown long-eared bat (*Plecotus auritus*) (Ahlén et al. 2009, Seebens-Hoyer et al. 2021, Christensen & Hansen, 2023). Although these records are useful for documenting which species are likely to occur at sea, they are not representative of activity as they are incidental, non-systematic, and most encounters are likely not documented. Notably, even the vessels hired for these baseline surveys shared verbal accounts of visual bat encounters onboard the vessel fleet during activities offshore, also in the North Sea but unrelated to the North Sea I project. However, as no formal documentation system is in place, such encounters are mostly not reported or quantified systematically.

Prior to these baseline surveys, no previous studies of bats existed from the North Sea I pre-investigation area, but there was evidence suggestive of bat migration across the southern parts of the North Sea (Lagerveld et al. 2021, Seebens-Hoyer et al. 2021), including southern parts of the Danish North Sea (Lagerveld et al. 2021). Migration may also occur between southern Norway, Denmark and The British Isles (Petersen et al. 2014). Lagerveld et al. (2021) used passive acoustic monitoring over 480 autumn nights between 2012 and 2016 from four locations 15 m above sea level and 15-25 km off the coast of the Netherlands to document the presence of bats and model the offshore occurrence of Nathusius' pipistrelle as a function of weather parameters. They found that migration activity of Nathusius' pipistrelle is strongest in the beginning of September and is correlated with wind direction (highest at east-northeasterly tailwinds), wind speeds (highest at wind speeds < 5 m/s, measured at 10 m above sea level), and temperature (highest at > 15°C). Ranges for the weather variables used in their analyses were, however, not disclosed. Although bat activity was higher (67 % of observations) at wind speeds < 5 m/s, 31 % of the observed activity occurred at wind speeds up to 8 m/s, whereas little activity (2 %) occurred at wind speeds > 8 m/s. The results of the model are likely only applicable for low altitudes (< 45 m above sea level). The study used presence/absence of bats per night as a measure of occurrence, as absolute numbers of the individual bats recorded were not possible to derive. They recorded bat activity on 11-25 % of nights at the four monitoring stations. The highest occurrence (25 %) was found at the station closest to shore (15 km).

Brabant et al. (2021) also found a negative correlation between wind speed and bat activity for Nathusius' pipistrelle but no significant correlation of migration activity with moon phase, cloud cover, atmospheric pressure, rain, or visibility. Offshore studies of species other than Nathusius' pipistrelle indicate that wind speed tolerance in bats is likely species dependent and higher for some species (Hatch et al. 2013).

Ahlén et al. (2009) studied offshore and coastal bat activity in inner Danish waters and the Baltic Sea and found that bats migrating north in spring arrive at the coastline widely dispersed and do not seem to follow narrow flight corridors, whereas autumn departures from shore were characterized by accumulated activity at specific departure points consistent between years. These periods of pronounced activity comprised from few up to circa 250 individuals, differed with years and species, and occurred mid-August to early October, peaking in late August. The migration periods observed by Ahlén et al. (2009) and Lagerveld et al. (2021) for Nathusius' pipistrelle are also confirmed by observations from Germany, where offshore migration activity occurs in spring from end of April to May and in autumn from August to beginning, or occasionally, end of October (Seebens-Hoyer et al. 2021).

In the study by Ahlén et al. (2009), bats moving over land towards coastal departure points often followed forest edges, tree rows or coastlines, and took off from the coast alone or in small groups of a few individuals. Further, the study indicated that foraging activity is not uncommon several kilometers from the coast, that all bats observed flying over the sea echolocated, and that they often flew low (< 10 m) above the water surface during migratory and foraging flights offshore. Several sources support the observation of low flight height for bats flying offshore but also note that noctules may fly at heights of 40+ m above the water surface (Meyer 2011, Skiba 2007, summarized in Seebens-Hoyer, et al. 2021). Further, Seebens-Hoyer, et al. (2021) note that bats are regularly observed on anthropogenic structures offshore and may change flight height once they encounter such structures, which may affect their collision risk with turbine blades. Most bats recorded offshore at wind turbines in the southern North Sea were recorded by detectors located 16 m above sea level, but 10% of the bat records were made with detectors 93 m above sea level (Brabant et al. 2020). Studies using PAM of bats from the ground or sea surface level will inherently only document low flight heights as they are limited by detection distances. Recent studies show that bats utilize beneficial weather conditions to increase migration speed and migrate at heights of hundreds of meters at wind speeds above 10 m/s both onshore and offshore (Lagerveld et al. 2024, Hurme et al 2025).

In 2022, the Danish Energy Agency initiated a national screening of the potential of the offshore wind potential in Denmark. This work is still ongoing but has for bats resulted in a report which summarises information from available offshore surveys and studies and uses it as input for a preliminary sensitivity map of relative risks to bats from Danish offshore wind energy (Brinkløv et al. 2025). As evident from that report, no dedicated bat investigations were carried out for the offshore wind farms (OWFs) in Horns Rev, Vesterhav Nord and Vesterhav Syd and no initial bat pre-investigations were planned for the Thor OWF, located just north of the North Sea I pre-investigation area and partially within the 20 km buffer zone included in the North Sea I survey area (Figure 1.2). However, for the Thor OWF, bat surveys were added in autumn (September to November) 2023 in response to the increasing focus on bats in relation to wind energy and included passive acoustic monitoring with a single SM4BAT FS recorder, mounted with the microphone circa 8 m above sea level, from each of the two vessels conducting geophysical surveys in the area (https://ens.dk/media/2092/download). The surveys recorded 12 bats in total offshore (six per vessel), all from September, circa 25 km from the coast and including two bat species: Nathusisus' pipistrelle and one record of Daubenton's bat. The vessel returned to port at wind speeds > 8 m/s.

The pre-investigations for the formerly planned area for the North Sea Energy Island included two surveys, one in autumn 2022 and one in spring 2023, each including the deployment of eight buoy-based bat PAM stations at distances ranging from 75 to 125 km from shore. No bats were recorded during either of these two surveys (Brinkløv & Elmeros 2024).

2.4 Biology and behaviour of Nathusius' pipistrelle

The long-distance migrant Nathusius' pipistrelle occurs commonly across most of Denmark (Elmeros et al. 2024). It is a relatively small insect-eating bat species (forearm length 32-37 mm, body mass 5-11 g (Dietz et al. 2009, Russ 2022) feeding primarily on flies and mosquitoes but also moths and beetles (Elmeros et al. 2024). Nathusius' pipistrelle emits echolocation calls of either downward frequency modulated sweeps or quasi-constant frequency with most energy at 36-40 kHz. Both migration and foraging activity, which are not mutually exclusive, have been documented for Nathusius' pipistrelles at sea in the Baltic (Ahlén 1997, Ahlén et al. 2009, Kruszynski et al. 2020, Rydell et al. 2014), as has migration over the southern North Sea (Lagerveld et al. 2024). Spring migration for this species happens in April-May, when the bats arrive at breeding sites in Northern Europe. The south-west bound autumn migration occurs mainly during August and September (Pētersons 2004, Voigt et al. 2012, Rydell et al. 2014).

3. Methods and surveys

Besides non-systematic observations from the coastline, offshore structures or vessels of passing bats or dead or live specimens, available techniques to survey bats offshore include radar, infrared or thermal video, and acoustic monitoring. Radar and video techniques are not widely used, costly and difficult to deploy and maintain in the rough offshore environment and currently do not enable species identification. Passive acoustic monitoring is still the most cost-effective survey method that enables species identification to a large degree and is used extensively in bat studies and investigations worldwide, albeit with a strong need for common user guidelines on methods, documentation and data infrastructure systems (Brinkløv et al. 2025, Asmus et al. 2025). It is also the main method used here, supplemented by radio-tagging and tracking of bats.

3.1 Passive acoustic Monitoring (PAM)

Passive acoustic monitoring with autonomous ultrasound recorders from Wildlife Acoustics (model SM4BAT FS with waterproof SMM-U2 microphone) was used to map bat activity both in the offshore survey area for North Sea I and along the coast. These commercial detectors are capable of real-time, full-spectrum recordings that maintain spectral and amplitude information, and have user-adjustable settings for sample rate, filtering, recording schedule and triggering of recordings. The microphone characteristics (sensitivity and directional response) are available from the manufacturer website: https://www.wildlifeacoustics.com/products/song-meter-sm4bat (under Ultrasonic microphone plots). The recorders save data to two SD memory cards and were used with external 12V batteries to optimize run time.

The detection range for ultrasonic bat calls depends on a variety of factors. These include the intensity and frequency of the bat call, the angle between the bat and the microphone, as bats emit their calls in a directional sound beam, and the microphone may not be equally sensitive from all angles of sound reception. Detection range further depends on ambient temperature and humidity, which contribute to frequency-dependent attenuation of the call, internal noise of the recording system, and ambient noise, e.g., from wind, waves, rain, vessels, and electrical sources (Brinkløv et al. 2023). Even under optimal conditions, realistic estimates of detection range do not exceed 25-30 m for Nathusius' pipistrelle (echolocating at 35-40 kHz) and 50-60 m for the common noctule (echolocating at 20-25 kHz) (Voigt et al. 2021). Such limitations are inherent to passive acoustic monitoring studies of bats and important to keep in mind. The use of multiple detectors increases the chance of recording bat presence, but bats still go unnoticed if they pass outside the detection range of the recorders.

The recorders were programmed to save recordings when triggered by sounds above a set amplitude and frequency threshold. A frequency trigger setting of 15 kHz was used, meaning that sound above this threshold must be present for recordings to be saved on the device. Echolocation calls from the bat species expected to occur in the area do not go below this threshold. The frequency setting was combined with a dynamic amplitude threshold determining at which signal-to-noise level an acoustic signal triggers a recording. This amplitude threshold was set at 6 dB for the first set of deployments offshore and onshore but was so low that recordings were triggered nearly continuously each night (i.e., triggered predominantly by ambient noise from wind or waves and not by bat calls). Consequently, to maintain battery and storage space, the threshold was adjusted to 12 dB in subsequent deployments. Two of the offshore stations, HR3_4 and T3/NS26, were programmed to record continuously each night during active deployments to collect information about background noise and verify the performance of the recorders.

The recorders on buoy stations were programmed to ensure battery power for at least one month per season, with focus on the expected spring (April-May) and autumn (August-October) migration periods. Prior to and after each deployment/service offshore, and during regular service checks of onshore stations (every one to two months), the microphone sensitivity was tested to ensure functionality, replace microphones if needed, and limit data loss. The recorder deployed on each bird survey vessel was installed with the microphone positioned either along the midline or to the lee side of the vessel pointing skyward at an angle of 45° and away from reflecting surfaces.

3.2 Bat tagging and radio-tracking with Motus

To obtain directional information on migration routes from individual bats potentially also active over the North Sea, the first year of the bat baseline surveys included the installation of five Motus VHF-radio receivers along the west coast of Jutland (Figures 1.2 and 1.4), catching bats, and tagging them with small radio-transmitter tags. This was done in autumn 2023.

The Motus wildlife tracking system was developed in Canada and is gaining momentum primarily across Canada, the Americas and Northern Europe (www.motus.org). Based on telemetry, each Motus tag transmits a unique radio signal which can be recorded by receiving stations within the Motus network to track animal movements, including the migratory movements of birds and bats (Bach et al. 2022, True et al. 2023). The manufacturer states a maximum detection range of up to 20 km, but actual detection range depends on many factors: weather conditions, landscape topography, flight behaviour of the tagged animal, the position of the transmitter relative to the receiver station antennas, antenna length and height above ground, transmitter strength of the tag model and battery power. The data collected from tagged animals across receivers installed within the Motus network are compiled in a collective database (https://motus.org/explore) forming a collaborative foundation for research and environmental investigations.

Specifications and detailed methods for the Motus receiver set-up and the catching and tagging procedure are given in the first-year technical report (Brinkløv et al. 2024). The Motus component, including catching and tagging bats, was not part of the second survey year, but the results from year one are recapped in this report to support its stand-alone status and supplemented with recent updates not from this project.

3.3 Analyses of passive acoustic monitoring data

Once recovered from the passive acoustic monitoring (PAM) stations, the acoustic recordings were uploaded and backed up on local data servers, then processed with sound analysis software to automatically detect and extract recordings with bat call sequences from nearly 20,000 hours of audio data.

3.3.1 Bat call detection

A subset of deployments was initially analysed with the commercial software SonoChiro® (v. 4.1.4, south boreal classifier, run at maximum sensitivity, https://sonochiro.biotope.fr/en/) and the output manually verified by an expert. To further increase processing speed and performance, a convolutional neural network was trained to obtain models for detection of bat calls offshore and onshore. The neural network was based on the open-source algorithm AnimalSpot (Bergler et al. 2022), which is designed to detect and classify animal vocalisations and can be run on a high-performance computing cluster. Once the detection performance of AnimalSpot had been tested and exceeded the performance of the commercial software (by detecting more calls and fewer false positives out of the same, manually annotated dataset from the first year of offshore surveys), AnimalSpot was used for final detection and classification of species from both survey years.

The detection model was optimized using data from most deployments by adding calls and noise examples to ensure high performance despite the occurrence of new noise types. The final models used to analyse the data included roughly 10,000 calls and 10,000 noise examples. The model sequentially analysed each recording in 20 ms windows with a 10 ms overlap, i.e., 0-20 ms, then 10-30 ms, and so forth, to predict if bat calls were present. The maximum duration of each recording was 15 s.

The number of bat recordings from PAM does not represent individual bats and cannot be used to directly estimate the actual number of individuals migrating or foraging in the study area (Brinkløv et al. 2025). On the one hand, methodological constraints on acoustic detection range mean that most of the survey area is not covered by the PAM effort, although the probability of documenting bat activity increases with the number of detectors used, leading to an underestimate of individuals. On the other hand, the same individual may appear in multiple recordings, potentially inflating the count. Bat recordings are sometimes interpreted as being from the same individual if they are spaced closely in time, but it cannot be determined whether they represent the same or different individuals. For the offshore analysis, we use the absolute number of recordings with bat call detections as the basic measure to describe nightly bat activity. For onshore analyses, activity was quantified as activity minutes per hour of a night: the number of minutes overlapping with at least one 3–5 second audio chunk with ≥5 call detections for the same species.

3.3.2 Bat call species classification

The limited number of bat detections offshore (from buoys, wind turbines and the OSS in Horns Rev 3, and from bird surveys) allowed manual review, verification and identification of all offshore detections to species or species complex after the automated analysis by AnimalSpot, based on species-specific echolocation call characteristics (e.g., Barataud 2015, Runkel et al. 2021). Manual review was done in Raven Lite, v. 2.0.5 (K. Lisa Yang Center for Conservation Bioacoustics 2024), by visualizing calls in spectrograms, spectra and listening to recordings at 1/10 real time speed. As part of the manual verification process, call sequences indicative of specific behaviours – explorative behaviour (approach phase), foraging (buzzes) and social calls were also noted, along with the number of individuals per recording.

For the 11 PAM stations on land, AnimalSpot's detection model output over 10 million detections, not feasible to review manually. Instead, a second model was trained to classify bat calls into the following categories: Nathusius' pipistrelle (Pnat), common pipistrelle (Ppip), soprano pipistrelle (Ppyg), a low frequency species complex including *Nyctalus*, *Eptesicus* and *Vespertilio* species (hereafter referred to as ENV), a *Myotis* species complex (M) and brown long-eared bat (Paur). Categories other than echolocation were included to filter out false positives. The noise and social call categories were included, because initial models often misclassified buzzes into the *Myotis* sp. category and social calls into the ENV category regardless of the actual species that produced these calls due to structural similarities.

More than 21,000 training examples were used for the classification model. Training data were extracted from files stored as species documentation in the NOVANA programme for bats, recorded from locations across Denmark between 2013 and 2021 and verified to species by experts (e.g., Søgaard et al. 2018, Brinkløv et al. 2021, Kjær et al. 2023, Elmeros et al. 2024b). The noise examples used in the model were errors identified during development of the detection model (where the model predicted a call, but manual verification found no call) and additional sound clips from the NOVANA recordings. The model made predictions in 20 ms windows with 5 ms overlap for all detections. Despite high performance, the model may still have missed detections (which we have no way of quantifying) and occasionally misclassified calls. To make sure the classification results were robust, a species (complex) was only considered as present, if there were at least five calls within a 3-5 s window (files of 5-15 s duration were split into five second windows, windows shorter than three seconds were not included). The performance of the automated species classifier was validated with a set of 154 recordings including examples from buoy and land locations, six species or species complexes, and several noise classes. The validation files had not been used as training data, and not all species (complexes) could be included as they were too rare to find manually. All calls that were either visible in the spectrogram or audible at 1/10 times real time playback, including calls too faint to trigger the SM4BAT FS recorders, were then annotated. The recordings were run through the detection and classification models to quantify the performance, using two main parameters: precision and recall. Precision is the fraction of detections that are true positives (true positive / (true positive + false positive)). Recall is the fraction of calls detected by the model (true positive / (true positive + false negative)). The performance parameters of the model for detecting and classifying Nathusius' pipistrelle was 1.00 (precision), and 0.71 (recall). The AnimalSpot model also performed well for the ENV species complex, but less well for classification of species within the ENV complex. For this reason, we used the third-party commercial classifier BatSonic (https://www.biosonic.se/) to automatically go through data files predicted as ENV species by AnimalSpot for a subset of the land stations and station years. This decision was based on a preliminary test made on 210 mixed recordings of manually identified ENV species recorded by the North Sea I offshore and onshore survey effort, supplemented by additional expert annotated NOVANA recordings to a total validation dataset of 273 recordings, which were classified by the BatSonic autoID with 92% accuracy.

3.3.3 Noise analyses for select offshore buoy stations

Noise analysis was done in MatLab (v. 2025a, Mathworks) to examine background noise fluctuations at the offshore buoy stations and visualize the effect of ambient noise and water on equipment function. The noise analysis was run on all deployments from the two buoy stations HR3_4 and T3/NS26, for which detectors were programmed to record continuously from sunset to sunrise. All files were treated with three Butterworth bandpass filters matching a) the frequency band used by the AnimalSpot model (1-90 kHz), b) the 10 kHz frequency band typical for echolocation calls of species in the ENV complex (15-25 kHz), and c) the 10 kHz frequency band typical for echolocation calls of nathusius' pipistrelle (35-45 kHz). The RMS (root-mean-square) level was measured for each set of files treated with each of the three filters. These levels are normalised to the inherent clip level of each recording chain, i.e., they reflect relative, rather than absolute, measures. For each filter treatment, 90% quantiles were determined across all files recorded each night. The first second of each unfiltered file was also Fourier transformed, and the resulting power spectra were averaged over 30 mins chunks.

3.3.4 Data preparation and covariates for statistical analyses

To optimize data quality, the offshore data were curated and filtered according to several inclusion criteria prior to statistical analysis. All timestamps were standardized to UTC, and recordings were assigned to night-dates by associating all post-midnight recordings with the preceding calendar date. The following filtering steps were applied:

- Nights with no recordings (i.e., no noise, no bat calls) were excluded to reduce the risk of including recordings with device or microphone malfunction. During almost all nights at least one noise event triggered a recording. A total lack of recordings was rare and interpreted as a risk of severely reduced sensitivity.
- Battery-related exclusions: Nights with low battery levels, as identified by a reduced number of summary entries, were excluded since recorders were only active during parts of these (see Figure 4.2 and 4.7).
- Location verification and exclusion of partial recording nights: for practical purposes, recorders were sometimes activated while on land or on board the service vessel prior to deployment. If they were pre-activated to start recording on a specific date, the first recordings were made starting at midnight, resulting in less than a full night of monitoring. Conversely, for some deployments, the recorder was still active when recovered. To ensure that only full nights where a recorder was deployed on its offshore location were included in the analysis, we excluded the first night after deployment and the last two nights before retrieval.
- Manual exclusions: Nights with clearly reduced microphone sensitivity or other technical failures were removed based on manual quality checks of recordings.
- Schedule inconsistencies: some deployments were excluded from analyses based on deviations in recording schedule from the remaining deployments over the two survey years. These included Spring 2023, where

recorders were set to use a lower amplitude threshold and start after sunset to conserve battery, the fall 2023 deployment at NS13, the summer 2024 deployment at NS33, and the fall 2024 deployments at NS13, NS21, and T3-NS26.

Following data curation, three binary datasets of presence/absence per night were created, including: all bat species, Nathusius' pipistrelle only, and ENV species only.

For the onshore dataset, bat activity was summarized per species and per hour. Only hours between sunset and sunrise were included in the analysis.

Weather data was downloaded from the ERA5 dataset from Copernicus, based on reanalysis of satellite data and multiple in situ sensor data (https://cds.climate.copernicus.eu/). The following weather variables were included in the analysis:

- Precipitation in mm.
- Temperature at 2 m above sea level, converted from Kelvin to Celsius
- Wind speed in m/s at 10 m above sea level, based on the northward and eastward directions
- Wind direction in degrees, calculated from the same two variables as wind speed.

For the onshore analysis we included additional variables:

- Atmospheric pressure in Pascal
- Total cloud coverage, as the fraction of the sky covered in clouds

Data was downloaded for all locations and dates with audio data available. For the offshore dataset, which was modelled per night, data were summarised by taking the value at sunset for that location and date. For the onshore dataset, which was modelled per hour, values were taken per hour for all hours between sunset and sunrise.

Sunset and sunrise for the offshore data were downloaded from SunEarthTools (www.sunearthtools.com) for the location 56° 16' 48.46" N, 8° 07' 09.57" E, approximately half a kilometre from the coast and at the centre of a north-south transect through the survey area. Time was standardised to UTC. For the onshore data, sunset, sunrise, and lunar phase were extracted at each stations' location using the R package *suncalc* (v.0.5.1, Thieurmel & Elmarhraoui, 2025). Lunar phase ranged from 0 to 1 with 0 indicating new moon, 0.25 the first quarter, 0.5 full moon and 0.75 the last quarter.

Distance to coast was included by calculating the Euclidean distance, using the function *st_distsance* from the R package *sf*, (v. 1.0-19, Pebesma & Bivand 2023), between the station location and the closest coastal location from the function *ne_coastline* from the R package *rnaturalearth* (v. 1.0.1, Massicotte P & South A 2023).

3.3.5 Statistical analysis of offshore data

For the offshore dataset we ran Bayesian binomial models using night per station as the unit of observation. Bats were scored as present if at least one manually verified recording existed for that station and night. Data analysis was limited to the autumn migration season indicated by the data plus some buffer before and after (1. August to 15. October). All models were written in Stan (Gelman et al. 2015) with mildly informative priors centred around no effect. Models were fitted using the R package *cmdstanr* (v. 0.8.1, Gabry et al. 2024) with four chains and default settings. Divergent transitions and Rhat values were monitored. All results are reported at the mean posterior prediction and the 89% posterior interval.

We tested the effects of distance to coast, date, station type, temperature, wind direction and wind speed. For each variable we used a directed acyclic graph (DAG) and the backdoor criterion to decide which other variables to include to avoid spurious correlations. A DAG represents all causal relationships in the form of arrows. The backdoor criterion is used to, e.g., control for the fact that wind direction could both influence temperature (example: warmer winds from the south) and bat activity (example: less migration with head wind from the south or southwest). In some models, we included additional variables to make specific predictions (e.g., at 20 km from the coast), to increase precision or to account for pseudoreplication. Distance to coast was included in kilometres as linear predictor with a prior limited to negative slope (since bat activity was not expected to increase further from the coast), which translates to exponential decay in a binomial model. Date was included as Julian day with a B-spline smoother from function *bs* from the basic R package *splines* (R Core Team 2024) with five knots and three degrees, resulting in a very smooth prediction. Temperature was included with a B-spline smoother like date, but with only three knots to restrict the model to predicting only a single optimal temperature. Wind direction was included by taking the sine and cosine component and fitting both as linear predictors. Wind speed was included in the same way as temperature, assuming it would have a negative effect only, with the exception for the model testing the direct effect of wind speed, where it was included as interaction with wind directionality (see below for details). Station type, station ID and unique date were all included as varying effects.

3.3.5.1 Hypothesis testing

Distance to coast: We hypothesised that the probability of a bat being recorded on a given night at the peak of the autumn migration season decreases exponentially with distance to coast at temperature 18˚C and wind speed 3 m/s. The temperature and wind speed variables were held at non-extreme values considered favourable for migration activity, based on background knowledge. 18˚C was chosen, as it reflects the high end of regularly observed values at which bats are likely to be active. 3 m/s was chosen as it reflects the low end of regularly observed values at which bats are likely to be active. Since wind turbines and the OSS are in a very narrow spatial location, station type was included. To account for pseudoreplication, station ID was also included. Peak of the migration season was determined from the model prediction (the date at which the model predicted the highest probability of observing bat activity) and was chosen for the prediction to reflect the point in time most important for this study.

Night of year: We hypothesised that the probability of a bat being recorded during a given night at 20 km from the coast, 18˚C, 3 m/s wind speed, 0 mm precipitation and northerly wind, has a single peak in autumn around mid-September. To account for pseudoreplication, station ID and unique date (as opposed to Julian day, which was the main predictor) were also included. We used 20 km from the coast to reflect the closest possible location of a wind turbine. We included northerly wind, because it reflects tail wind and should lead to optimal conditions for migration. Caution is needed in interpreting the results, since only two years are included and temporal autocorrelation (many days in a row with similar values) in unobserved variables can lead to spurious peaks.

Station type: We hypothesised that the probability of a bat being recorded during a given night at the peak of the migration season with 18˚C and 3 m/s wind speed is higher at wind turbines and the OSS than at buoys at comparable distance (30 km from the coast). To account for pseudoreplication, station ID was also included.

Precipitation: We hypothesised that the probability of a bat being recorded during a given night at the peak of the migration season with 18˚C and 3 m/s wind speed at 20 km from the coast is highest with no precipitation and declines exponentially with increasing precipitation. Since precipitation is more likely with offshore winds, wind direction was included and predictions made for northerly winds. To account for pseudoreplication station ID was also included as varying effect.

Temperature: We hypothesised that the probability of a bat being recorded during a given night at the peak of the autumn migration season at 20 km from the coast and 3 m/s wind speed increases with temperature until it reaches a peak, after which it declines again. Since temperature and probability of bat presence are partly driven by wind direction, wind direction was also included, and model predictions were made for northerly wind. To account for pseudoreplication, station ID was also included.

Wind direction: We hypothesised that the probability of a bat being recorded during a given night at the peak of the autumn migration season with 0 mm precipitation, 18˚C, at 20 km from the coast and 3 m/s wind speed is greatest with northern wind (tail wind) and lowest with southern wind. To account for pseudoreplication station ID was also included.

Wind speed: Finally, we hypothesised that the probability of a bat being recorded during a given night at the peak of the autumn migration season with 18˚C at 20 km from the coast is highest around an optimal wind speed if wind direction is optimal. From the raw data it looked like the optimal direction is anything easterly (0-180˚), wind direction was therefore included as categorial interaction with wind speed, with a separate B-spline smoother for wind speed at easterly and westerly winds respectively. Settings were the same as for temperature to allow a single optimum. To account for pseudoreplication station ID was also included.

3.3.6 Statistical analysis of onshore data

All statistical analyses of onshore bat data were also performed in R (R Core Team 2024), using bat activity of each species group as the basic unit, quantified as activity minutes per hour of the night, with the hours of the night defined as strictly after sunset and before sunrise. To assess which factors contributed most to the activity of bats onshore across the whole year, we first performed a random forest analysis, using the R package *ranger* (v. 0.17.0, Wright & Ziegler 2017). Random forest is a machine learning approach based on hierarchical decision trees that predict factor importance. The algorithm constructs 500 decision trees each based on a random subset of data and factors. The more a factor contributes to improve the predictive performance across the decision trees, the higher its importance score.

For the random forest, we selected all extracted weather variables, including temperature, wind speed, wind direction (as ordered factor: taking the sine and cosine component), precipitation, atmospheric pressure, and cloud coverage. Further, we investigated temporal variables including a scaled hour of the night by dividing the seconds from sunset by the length of the night, the day of the year as a Julian calendar day, and the year of data collection. As day of the year and temperature are strongly correlated, we could not assess the two factors separately but added a measure of how strongly the temperature deviated from the norm within a month by scaling and centring the temperature within each month (i.e., scaled temperature). To analyse the effect of light, we added the lunar phase (as ordered factor: new moon, first quarter, full moon, and last quarter). Lastly, we included the species group and station to account for species and spatial-based variation. Based on residual diagnostics, we applied a log1p transformation to the activity minutes per hour, which computes the natural logarithm of (1 plus the value), to stabilize variance while handling zeros.

To assess whether variable importance differed between species groups, we performed additional random forest analyses for each species group, using the same set of factors. The brown long-eared bat was excluded from the species-specific analysis due to the low sample size for this species.

Secondly, we specifically focused on the highest activity period of the Nathusius' pipistrelle, the most abundant species during the autumn migration plus a buffer (same as for the offshore data, from 1. August to 15. October). We fitted a generalized additive mixed model (GAMM) with a binomial error distribution and logit link to model the probability for bat activity per hour of the night. The model was fit using the bam function in the R package *mgcv* (v. 1.9-3, Wood 2011). Smoothing parameters were estimated via fREML and discrete approximation used to improve computational efficiency. The model was adjusted for temporal autocorrelation between hours of the night using an AR(1) structure with rho = 0.275. Residual diagnostics were applied to assess model adequacy.

In the model, we tested the effects of temperature, wind direction and wind speed. Precipitation and atmospheric pressure were not added has they were too strongly correlated with wind speed and temperature. Weather effects were fit with smooth terms, temperature and wind speed were centered, and wind direction treated as cyclic cubic spline. For the light conditions, we included a tensor product smooth for the interaction between lunar phase (as cyclic spline) and cloud coverage (centered). To assess seasonal changes and daily activity patterns, we added a station-specific smooth for the hour of the night (scaled relative to sunset/sunrise) and the day of the year, and a tensor interaction between the day of the year and the scaled hour. We added a random factor-smooth interaction between day of year and observation year to allow for inter-annual variation in seasonal trends. Additionally, to capture unexplained daily variation we included a smooth of unique observation timestamp with increased degrees of freedom for the smooth (k = 500).

As for the offshore data, we expected to find a peak temperature, peak wind speed and northern wind (tailwind) to be the preferred wind direction with the highest probability for bat activity. Further, we hypothesised to find a peak of bat activity in mid-September, with the highest probability for activity during the first half of the night. In terms of the spatial distribution of bat activity, we expected to find the clearest migration pattern for the station in Blåvand, as a likely point where migrating bats transition from onshore to offshore. The island stations south of Blåvand (Fanø, Rømø, and Mandø) were likewise expected to be indicative of migration activity.

4. Results of surveys

The total effort of the baseline surveys for bats included offshore passive acoustic monitoring (PAM) from buoys, wind turbines, an offshore substation (OSS) and vessels, in addition to PAM from stations on the coast. The results of the PAM effort are described below in separate sections for each station type. Bats were also caught and radio-tagged during the first survey year to gain data on migratory movement patterns. More detail from the tagging effort is included in the report presenting results from the first year alone (Brinkløv et al. 2024).

4.1 Offshore passive acoustic monitoring

The overall bat activity recorded offshore is summarized across the two survey years in table 4.1. The top section of the table refers to the first survey year and the bottom section to the second survey year. Note that some numbers have changed from the version of the table shown in the first-year technical report: the number of nights surveyed by station NS06 has increased because one of the deployments at this station had an error in the station name programmed in the recorder, causing less than the full number of nights monitored to be read from the metadata. No bats were recorded on NS06 during the deployment, but it adds to the number of nights surveyed for NS06 (was 80, is now 106). The remaining changes all led to a more conservative data set with fewer nights surveyed, as the decision was made during the data curation process to omit nights with no wave files recorded, even if summary files existed for those nights (see section 3.3.4).

Table 4.1. Summary of bat activity recorded on offshore PAM stations on buoys, on wind turbines and the OSS in Horns Rev 3, and on bird vessel surveys. The table only lists stations that recorded bats, along with the survey effort (number of full and partial nights surveyed per station, followed by number of full nights in parentheses), the number and percentage of full nights surveyed that included bat recordings, the number of bat recordings per station, which species were detected, the distance of each station to the coastline, how many individuals were present per recording and if the recordings contained feeding buzzes (indication of foraging activity) and/or social calls. Pnat = Nathusius' pipistrelle, ENVsp = Eptesicus/Nyctalus/Vespertilio species complex, Nnoc = Nyctalus noctula, Myosp = Myotis species, Ppyg = soprano pipistrelle.

Station	Nights surveyed	Nights with bats	Recordings with bats	Species detected	Distance to coast (km)	Individuals per recording	Feeding buzzes	Social calls
First year (10 April 2023 - 9 April 2024)								
NS06	106 (84)	1 (1%)	1	Pnat	78	2	No	Yes
NS19	173 (99)	1 (1%)	1	Pnat	40	1	No	No
NS25	156 (100)	2 (2%)	2	Pnat	25	2	Yes	No
T3/NS26	120 (72)	4 (6%)	8	Pnat, ENVSp	27	1	Yes	No
NS28	122 (75)	4 (5%)	4	Pnat, ENVSp	18	1	No	No
NS30	120 (83)	4 (5%)	10	Pnat, ENVSp	16	1-2	Yes	No
NS31	172 (92)	4 (4%)	4	Pnat, ENVSp	16	1	No	No
NS33	135 (89)	6 (7%)	17	Pnat, ENVSp	7	1-2	Yes	No
NS34	177 (92)	9 (10%)	21	Pnat, ENVSp, Ppyg, Myosp.	4	1	No	No
NS35	166 (92)	9 (10%)	19	Pnat, ENVSp	6	1-2	Yes	No
HR3-4	133 (82)	3 (4%)	3	Pnat, ENVSp	24	1	No	No
A02	38 (37)	3 (8%)	3	Pnat	38	1	No	No
A05	61 (58)	2 (3%)	70	Pnat	36	1	Yes	No
A06	55 (52)	2 (4%)	10	Pnat	35	1	Yes	No
C03	27 (26)	2 (8%)	3	Pnat, ENVSp	35	1	No	No
Bird vessel (SW)	45 (45)	1 (2%)	27	ENVSp	68	1	No	No
Second year (10 April 2024 - 10 April 2025)								
NS06	160 (155)	1 (1%)	1	Pnat	78	1	No	No
NS14	154 (149)	1 (1%)	1	Pnat	59	1	No	No
NS16	164 (160)	1 (1%)	1	Pnat	48	1	No	No
NS19	176 (171)	3 (2%)	3	Pnat	40	1	No	No
NS20	179 (174)	5 (3%)	5	Pnat	36	1	No	No
NS24	187 (181)	1 (1%)	1	Pnat	28	1	No	No
NS25	149 (145)	1 (1%)	1	Pnat	25	1	No	No
NS27	191 (154)	5 (3%)	8	Pnat, Ppyg	14	1	No	No
NS28	147 (126)	3 (2%)	4	Pnat, Ppyg	18	1	No	No
NS29	180 (175)	1 (1%)	1	Pnat	15	1	No	No
NS30	159 (154)	5 (3%)	5	Pnat, Ppyg, Nnoc	16	1	Yes	No
NS31	115 (111)	6 (5%)	8	Pnat, ENVSp	16	1	Yes	No
NS32	188 (183)	8 (4%)	21	Pnat, Ppyg, ENVSp	8	1-2	Yes	No
NS33	174 (120)	6 (3%)	9	Pnat, Pnat/Ppip, ENVSp	7	1	No	No
NS34	154 (149)	7 (5%)	15	Pnat, Nnoc	4	1	Yes	Yes
NS35	147 (142)	7 (5%)	10	Pnat, Ppyg, ENVSp	6	1	Yes	No
HR3_4	81 (77)	6 (8%)	13	Pnat	24	1	No	No
G05	70 (67)	1 (1%)	2	Pnat	26	1	No	No
OSS	135 (131)	13 (10%)	126	Pnat, Ppyg, Nnoc, ENVSp	29	1	Yes	No
Bird vessel (SE, N, SW)	17 (17)	5 (29%)	11 (1, 4, 6)	Pnat, ENVSp	(39, 35, 68)	1	Yes	No

The first year of baseline surveys resulted in 203 recordings of bats offshore, including 90 from PAM stations on buoys, 86 from wind turbines in Horns Rev 3 and 27 from the bird surveys. No PAM station was included on the OSS in Horns Rev 3 for the first survey year. The second survey year produced 246 bat recordings offshore: 107 from buoy stations, 2 from the wind turbines, 126 from the OSS and 11 from the bird surveys.

Manual review of the offshore bat recordings revealed some recordings with at least two individuals present (at least seven recordings from the first year and at least one from the second year, see Table 4.1.

Figure 4.1 presents distribution maps for the activity recorded offshore in each of the two survey years and collectively across both survey years. In both survey years, most bat activity was recorded on stations close to the coast, within the survey area buffer zone surrounding the pre-investigation area, between the pre-investigation area and the coastline of western Jutland. Whereas activity was most pronounced towards the north-eastern corner of the survey area in year 1, it was more evenly distributed along the coast in year 2. Notably, the NS06 station to the far west in the survey area, close to the outer limit of the 20 km buffer zone and west of the pre-investigation area (Figure 4.1, left side of map) recorded bat passes in the autumn of both survey years.

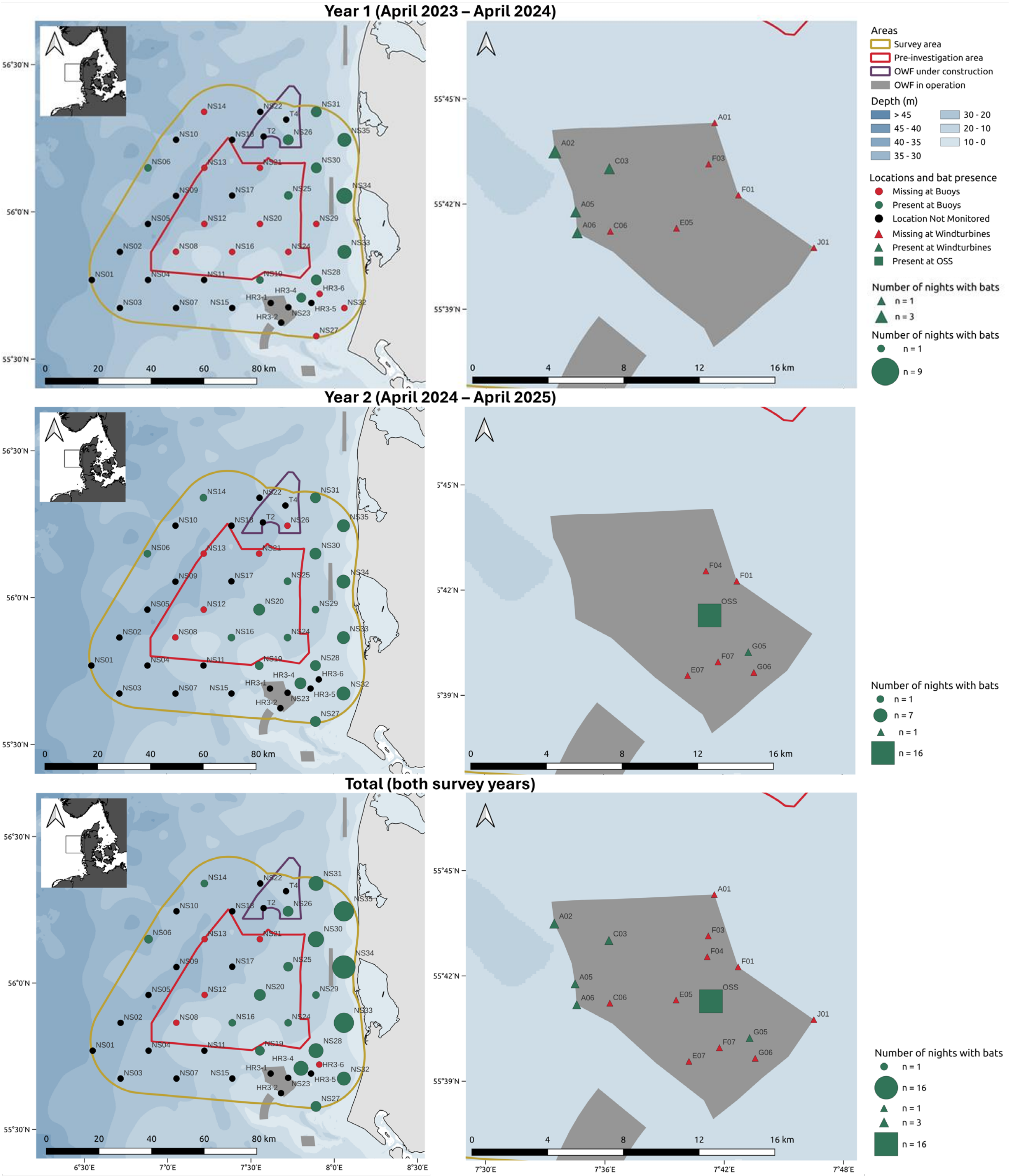


Figure 4.1. Map of offshore PAM stations on buoys and wind turbines where bats were detected during the baseline surveys. Top panel: results from year 1 (April 2023 - April 2024). Center panel: results from year 2 (April 2024 – April 2025). Bottom panel: results based on the total, two-year survey period. Left side includes the entire offshore survey area, on the right the HR3 part of the survey area is enlarged. Bat PAM stations are shown with station numbers. Green locations recorded bats and are scaled by the number of nights they recorded bats (up to nine nights per station = largest green point). Triangles: PAM stations on wind turbines in Horns Rev 3. Points: buoy locations. Stations in red monitored for bats but had no bat records. Black locations were not monitored. Observations from the bird surveys are not shown in the figure. OWF: Offshore wind farm. Note that the OSS PAM station was not added before July 2024.

4.1.1 Passive acoustic monitoring from offshore buoys

Figure 4.2 shows an overview of deployments and the survey effort from the 22 buoy stations and Figures 4.3 and 4.4 show bat activity from the buoy stations that recorded bats during the first- and second-year surveys, respectively. The activity overview was modified from Brinkløv et al. 2024 to better visualize intervals not monitored versus intervals that were monitored but during which bats were not recorded (Figures 4.3 and 4.4).

Figure 4.2. Deployment overview for the 22 bat PAM stations on buoys. Top: results from the first survey year (10. April, 2023, to 9. April, 2024). Bottom: results from the second survey year (10. April, 2024, to 9. April, 2025). Due to a mix-up during the deployment in winter, 2023, NS28 was deployed at the location of HR3_6. For this reason, the overview from the first year includes 23 stations. This was corrected during the following deployment. Orange points show nights where bats were recorded and are not scaled by the number of detections per night. Greyscale bars and black points are both indicators of recorder functionality. Grey bars are colour-scaled by the number of summary entries made by the recorder per night and fade into lighter shades recorders ran out of power and recorded only partially through the night. Black points indicate that a recorder was triggered during that night and made recordings, but those only included bats where black and orange points coincide on the same night. The black points are scaled by the number of trigger events (larger: more recordings triggered, smaller: fewer recordings triggered) and are present without grey bars for deployments where recorder summary files could not be recovered. The fact that recordings were still triggered indicates intact recorder functionality. Absence of black points means that no recording was triggered. Purple shading: expected migration periods based on literature.

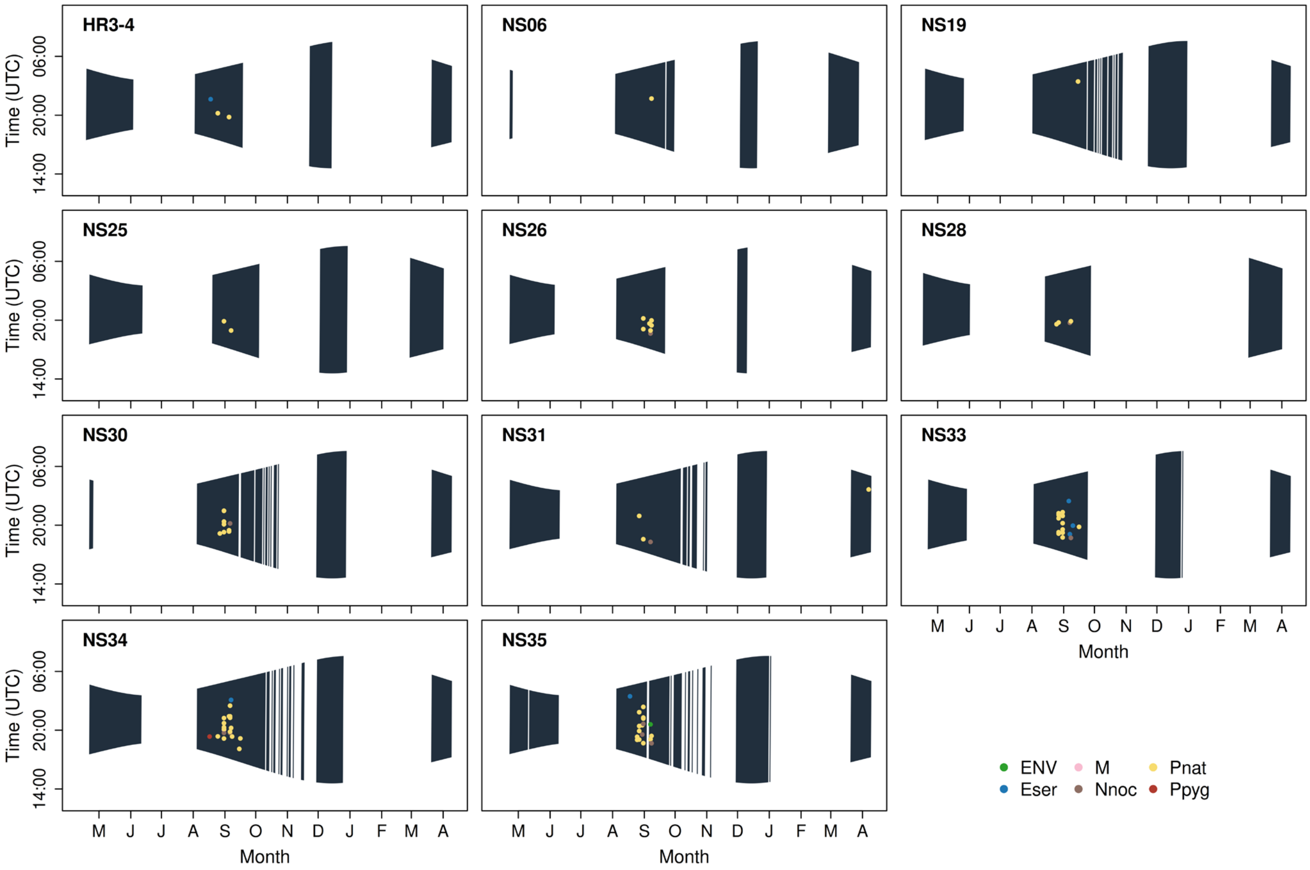


Figure 4.3. Nightly bat activity recorded on the offshore buoy stations during the first survey year, from 10. April, 2023 to 9. April, 2024. Bats were recorded on 11 out of 22 stations in total. Data points represent bat recordings. Dark background: night from solar sunset to solar sunrise. White background: periods without active deployments. Points represent bats and are colour-coded by species (or species complex in cases where identification to species was uncertain): ENV (green): Eptesicus/Nyctalus/Vespertilio species complex, Eser (blue): serotine bat, M (pink): Myotis species complex, Nnoc (brown): common noctule, Pnat (yellow): Nathusius' pipistrelle, Ppyg (red): soprano pipistrelle.

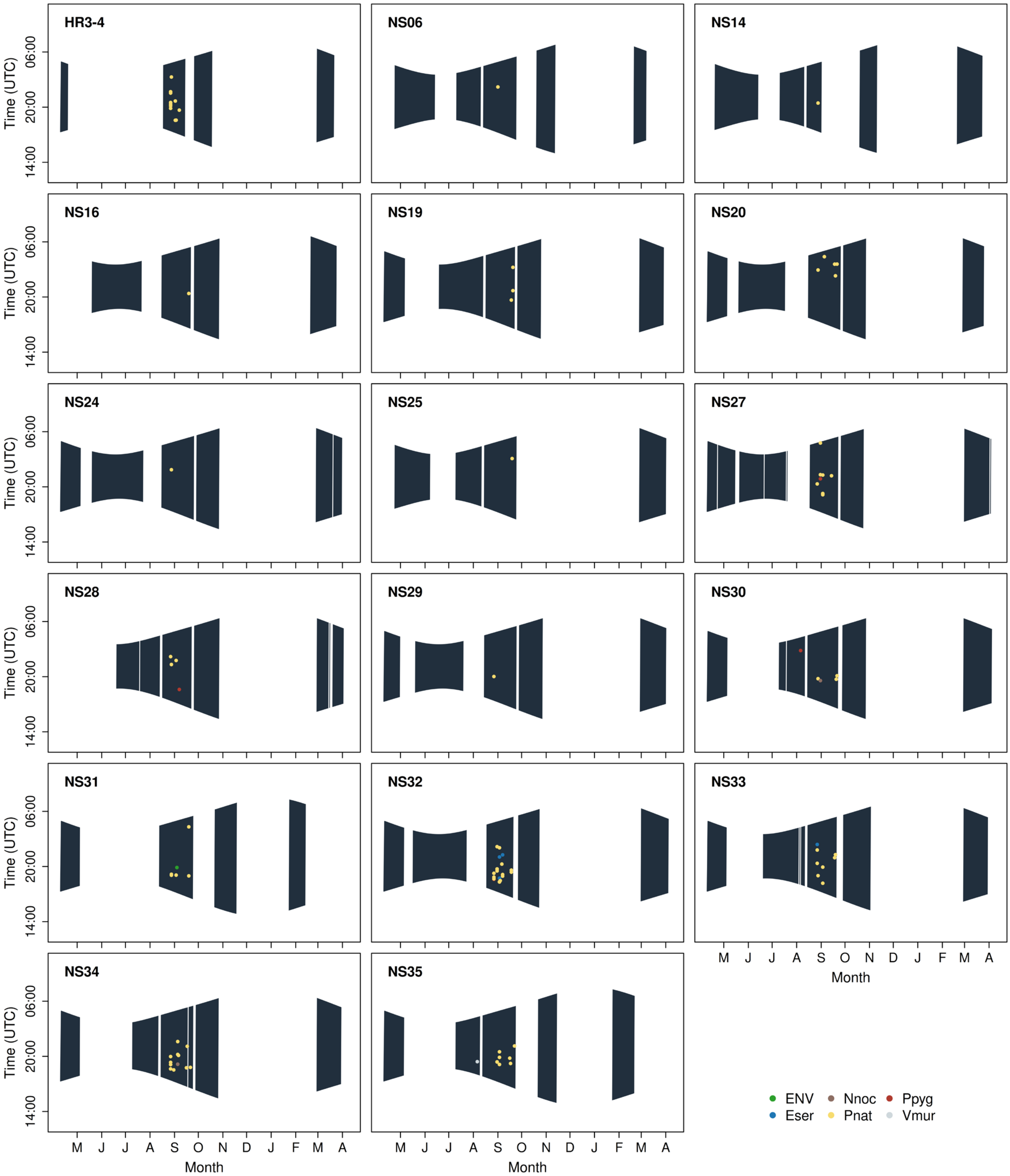


Figure 4.4. Nightly bat activity recorded on the offshore buoy stations during the second survey year, from 10. April, 2024 to 9. April, 2025. Bats were recorded at 17 out of 22 stations in total. Data points represent bat recordings. Dark background: night from solar sunset to solar sunrise. White background: periods without active deployments. Points represent bats and are colour-coded by species (or species complex in cases where identification to species was uncertain): ENV (green): Eptesicus/Nyctalus/Vespertilio species complex, Eser (blue): serotine bat, Nnoc (brown): common noctule, Pnat (yellow): Nathusius' pipistrelle, Ppyg (red): soprano pipistrelle, Vmur (grey): particoloured bat.

Bat activity on the buoy stations was low overall but increased notably during the autumn migration period. A single record of Nathusius' pipistrelle was obtained from the buoys in spring 2024, all other bat activity recorded on the buoy stations was from autumn.

In 2023, the autumn activity occurred over 16 nights in total, including seven nights in the last half of August 2023 (17/8, 19/8, 25/8, 27/8, 28/8, 30/8 and 31/8) and nine nights from beginning to mid-September (1/9, 5/9, 6/9, 7/9, 8/9, 9/9, 10/9, 15/9 and 16/9). Of these, one single night (31/8) accounted for 31% of the bat activity observed in autumn 2023, and four nights accounted for 69% of the autumn activity: 27/8, 31/8, 7/9, and 8/9.

In autumn 2024, activity was distributed over 22 nights on seven dates in August (6/8, 7/8, 12/8, 27/8, 28/8, 29/8, 31/8) and 15 nights in September (1/9, 2/9, 3/9, 4/9, 5/9, 6/9, 7/9, 14/9, 16/9, 17/9, 18/9, 19/9, 20/9, 21/9 and 22/9). Nearly half (48%) of the observed activity from buoy stations in autumn 2024 was focused on just four nights, three in late august (27/8, 28/8 and 31/8) and one in beginning of September (3/9).

Out of the total number of full nights surveyed per buoy station over the course of each year (72-100 nights per station in year 1, 77-183 nights per station in year 2), the fraction of nights surveyed with bats did not exceed 10% in the first year and 8% in the second year (Table 4.1).

The buoy stations recorded the following species and species complexes: Nathusius' pipistrelle (one record from NS33 was assessed as possibly common pipistrelle), ENV species, common noctule, soprano pipistrelle and *Myotis* species (not further specified but likely Daubenton's bat). Nathusius' pipistrelle was the bat species most frequently recorded and occurred on all buoy stations that recorded bats (Table 4.1, Figures 4.3 and 4.2), with 63 recordings in year one and 89 recordings in year two, corresponding to 72% and 83% of the activity recorded on buoy stations per year. ENV species represented the second most common species (22% of recordings in year one, 23% of recordings in year two, counting both recordings classified only as ENV and those classified further to species within the ENV complex). Only few records were of soprano pipistrelle and *Myotis* sp.

Notably, Nathusius' pipistrelle was the only bat species recorded at stations beyond 27 km from the coast (compare Table 4.1 and the activity distribution map in Figure 4.1, Nathusius' pipistrelle was the sole species recorded on stations NS06, NS14, NS16, NS19, NS20, NS24, NS25, NS29 and HR3_4).

As noted in Table 4.1, several recordings from the buoys included feeding buzzes, indicative of foraging activity. Social calls were also noted for some recordings.

4.1.2 Offshore background noise assessment

Since it was not possible to continuously monitor recorder functionality offshore, we relied on recorder summary files, and the presence of sound recordings with or without bat calls as indicators of a working system. During nights when a recorder is actively monitoring and enabled to trigger recordings if a passing bat emits vocalisations (echolocation or social calls) that pass the set amplitude and frequency threshold, it creates a log entry every minute. These log entries are saved to a text file for the entire monitoring period, which can be checked later for missing entries that serve as indicators of proper system functionality. E.g., if a recorder logs fewer entries over consecutive nights, this reflects the battery being drained (see also text explanation of greyscale bars in Figure 4.2). With the threshold settings used here, most nights included at least one recording, e.g. of noise from wind, waves or the radar of a passing vessel. In cases, where data had to be recovered due to read errors on the recorder memory cards, the summary file was partially scrambled and if no files existed for the corresponding period, triggered files were reviewed and used as an indicator of proper recorder function (see also text explanation of black points in Figure 4.2). To further validate the robustness of the setup, two stations (HR3_4 and T3/NS26) were programmed to record continuously nightly (back-to-back recordings were saved throughout the night without the use of triggering) for the purpose of visualizing fluctuations in ambient noise and the influence of such on recorder sensitivity. Figures 4.5 and 4.6 display the results of the noise analysis.

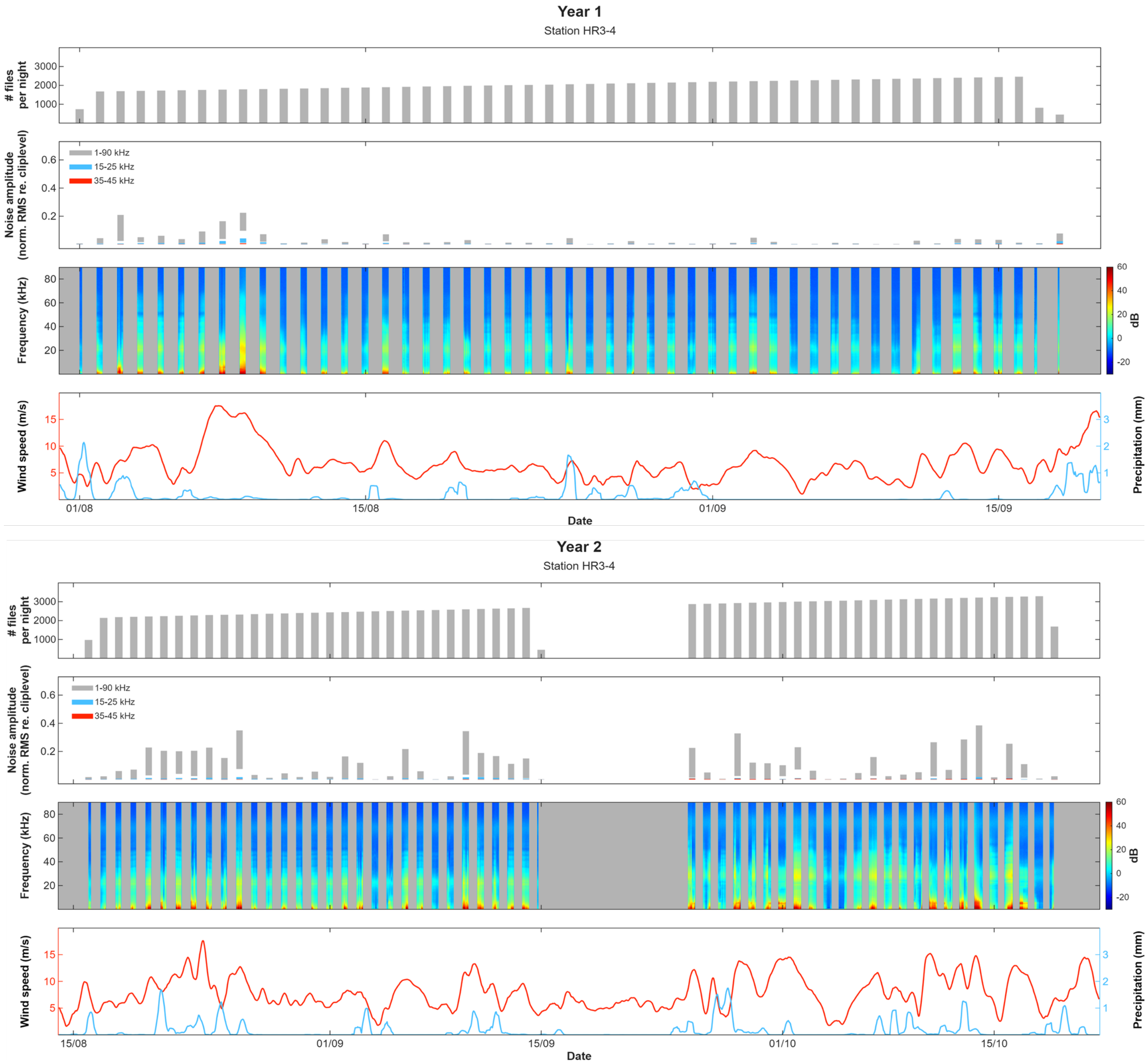


Figure 4.5. Noise quantification from continuous monitoring during autumn deployments in both years on buoy station HR3_4. Top subfigure: autumn deployments from year 1, bottom subfigure: autumn deployments from year 2. First panel: Number of files recorded per night during the deployment. The systematic increase reflects the seasonal change in night length. Second panel: 95% quantiles of the noise amplitude per night in three different frequency bands: BatSpot bandwidth (1-90 kHz), ENV bandwidth (15-25 kHz) and Pnat bandwidth (35-45 kHz). Third panel: Spectrogram of recorded files (first second in each file and averaged over 30 min chunks) during the deployment. Fourth panel: Wind speed (red) and precipitation (blue) shown as 10hr moving average over the duration of the deployments.

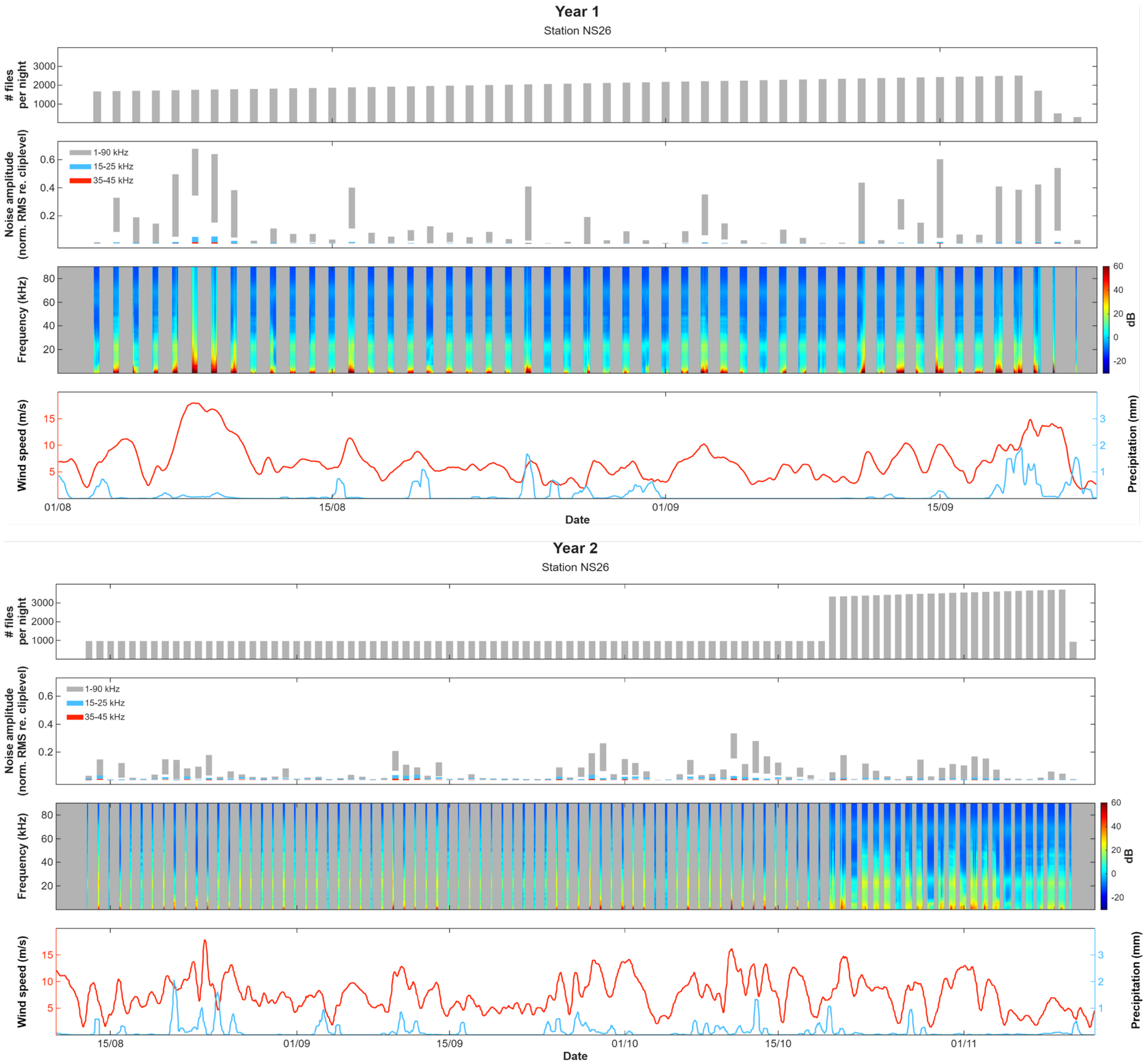


Figure 4.6. Noise quantification from continuous monitoring during autumn deployments in both years on buoy station T3/NS26. Top subfigure: autumn deployments from year 1, bottom subfigure: autumn deployments from year 2. First panel: Number of files recorded per night during the deployment. The systematic increase reflects the seasonal change in night length. Note that there was a setting error for this station during the first autumn deployment in year 2, resulting in an equal number of hours monitored per night until mid-October. Second panel: 95% quantiles of the noise amplitude per night in three different frequency bands: BatSpot bandwidth (1-90 kHz), ENV bandwidth (15-25 kHz) and Pnat bandwidth (35-45 kHz). Third panel: Spectrogram of recorded files (first second in each file and averaged over 30 min chunks) during the deployment. Fourth panel: Wind speed (red) and precipitation (blue) shown as 10hr moving average over the duration of the deployments.

Noise was analysed across all deployments on the two buoy stations HR3_4 and T3/NS26. The long-term spectrograms in the noise illustrations in Figures 4.5 and 4.6 visualize how background noise fluctuates over time during the autumn deployments, where both bat presence and weather impact was expected. Comparing the spectrogram profiles with the wind speed and precipitation plots shows first, that background noise correlates well with wind speed, i.e., as wind picks up, so does the contribution from wind noise. While this may mask bat calls, the trigger algorithm of the commercial SM4BAT FS recorder may partially compensate for this by monitoring noise in several frequency bands. Importantly, the noise load in frequency bands relevant for detecting bat calls looks negligible based on the minimal noise amplitude in the 15-25 kHz (ENV species) and 35-45 kHz (Nathusius' pipistrelle) frequency range, even on windy nights. Second, moisture from precipitation (blue plot in panel four) or submersion does not show a long-term effect on the sensitivity of the equipment based on the noise profile. If the recorders suffered serious impact, electrical shortage or water build-up following heavy precipitation, it would be evident in the spectrogram either as intervals of heavy noise (internal electrical noise from the recorder) or, conversely, of severely decreased sensitivity, corresponding to almost entirely blue bars in the spectrogram. As a third point, the noise amplitude of the three separate frequency bands (second panels in Figures 4.5 and 4.6) shows that increasing ambient noise offshore is not just reflected in the low frequency band but also visible in the 35-45 kHz band on very windy days, although the lower frequency band may be more severely masked, resulting in lower detection probability for lower frequency species.

4.1.3 Passive acoustic monitoring from Horns Rev 3 offshore wind turbines and OSS

The wind turbine deployments in Horns Rev 3 were contingent on the turbine servicing schedule and much less systematic over time and space. Results from these deployments serve as a supplement to those from the buoy PAM stations and provide baseline data about bat activity around anthropogenic structures in the North Sea.

Ten deployments were achieved per year, out of which four recorded bats during year one and two recorded bats during year two (Table 4.1, Figures 4.7 and 4.8). Recordings from the first year numbered 86 in total, 80 of which were recorded in late spring/early summer 2023 on three nights (12/5, 20/5 and 2/6). The rest were from five nights in autumn, 2023 (8/9, 9/9, 15/9, 16/9 and 2/10), coinciding with dates where bats were also recorded on buoy stations, except for the early October record. Only two bat recordings resulted from the second-year deployments on wind turbines, both from Spring (15/5, 2024). Unfortunately, three of the deployments in autumn 2024 were put out much later than originally planned and ran out of battery shortly thereafter.

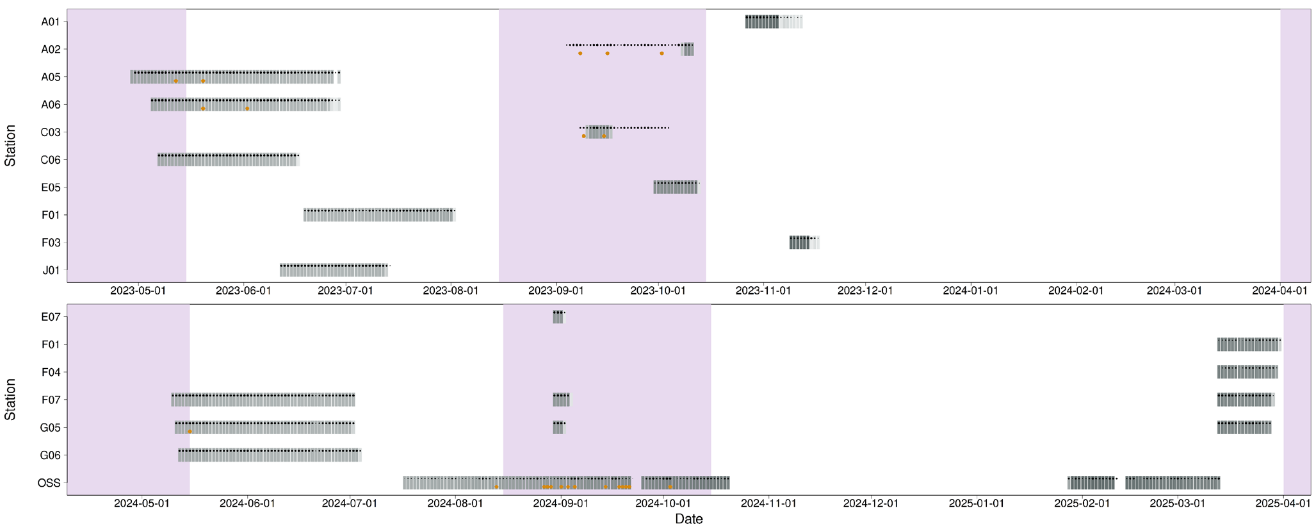


Figure 4.7. Deployment overview for the PAM stations deployed on wind turbines and the OSS in Horns Rev 3 during the two survey years. Top: results from the first survey year (10. April, 2023, to 9. April, 2024). Bottom: results from the second survey year (10. April, 2024, to 10. April, 2025). Orange points show nights where bats were recorded and are not scaled by the number of detections per night. Greyscale bars and black points are both indicators of recorder functionality. Grey bars are colour-scaled by the number of summary entries made by the recorder per night and fade into lighter shades recorders ran out of power and recorded only partially through the night. Black points indicate that a recorder was triggered during that night and made recordings, but those only included bats where black and orange points coincide on the same night. The black points are scaled by the number of trigger events (larger: more recordings triggered, smaller: fewer recordings triggered) and are present without grey bars for deployments where recorder summary files could not be recovered. The fact that recordings were still triggered indicates intact recorder functionality. Absence of black points means that no recording was triggered. Purple shading: expected migration periods based on literature.

Nathusius' pipistrelle was also the bat species most frequently recorded at the wind turbines, including all but one record from autumn 2023, which was identified to the ENV species complex. Note that the activity overview in Figure 4.8 includes both wind turbine deployments and the OSS. The latter gives rise to the high species diversity observed in year two.

The wind turbine stations were active for up to 16% of full nights in a full year (Table 4.1, Figure 4.7). Bats were present in up to 8% of the total number of full nights surveyed per wind turbine station over the course of the entire year and 10% of the total number of full nights monitored by the PAM station on the OSS.

The spring 2023 records were from two different wind turbines, A05 and A06 (Figures 4.7 and 4.8). On one of those nights (20/5), activity could stem from the same individual of Nathusius' pipistrelle foraging first around A05 (58 recordings within 20 minutes, including 137 feeding buzzes, example recording shown in Figure 4.9), and subsequently moving on to station A06, which is the next wind turbine south of A05, where records occurred at a slight delay of circa 10 minutes (nine in total all within 10 minutes of each other). A05 also recorded at least one foraging Nathusius' pipistrelle on 12/5, as evidenced by multiple feeding buzzes on the total of 12 recordings clustered within 10 minutes.

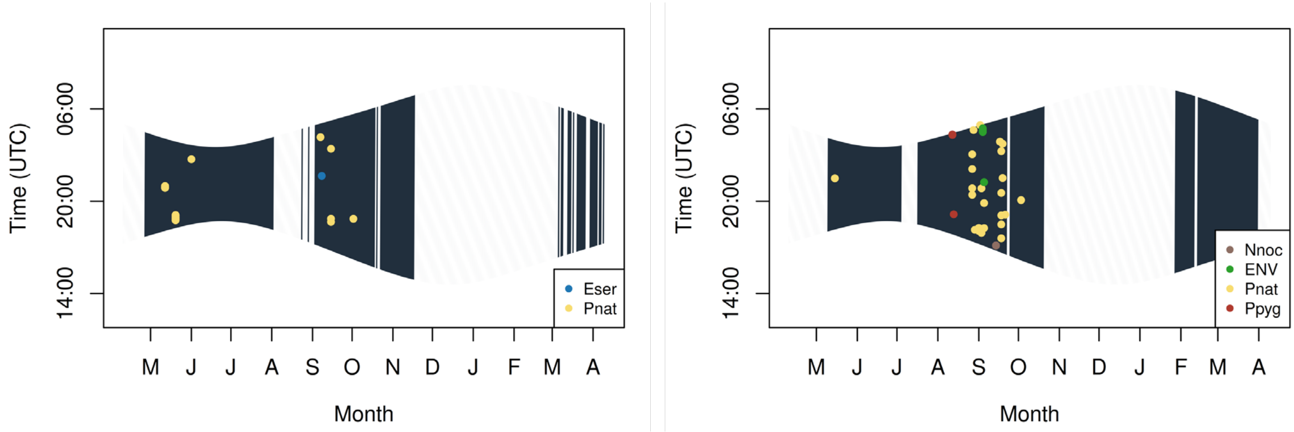


Figure 4.8. Nightly bat activity recorded during the two-year baseline surveys from offshore wind turbine stations and the OSS in Horns Rev 3. Left: activity recorded during the first survey year, from 10. April, 2023, to 9. April, 2024. Right: activity recorded during the second survey year, from April 10, 2024, to April 9, 2025. Data points are activity minutes. Each data point represents a minute with at least five call detections within a 3-5 second window (see section 3.3.2). Dark background: night from solar sunset to solar sunrise. White background: periods without active deployments. Points represent bats and are colour-coded by species (or species complex in cases where identification to species was uncertain): ENV (green): Eptesicus/Nyctalus/Vespertilio species complex, Eser (blue): serotine bat, Nnoc (brown): common noctule, Pnat (yellow): Nathusius' pipistrelle, Ppyg (red): soprano pipistrelle. Note that the number of active detectors varied during the deployment periods shown (see Figure 4.7).

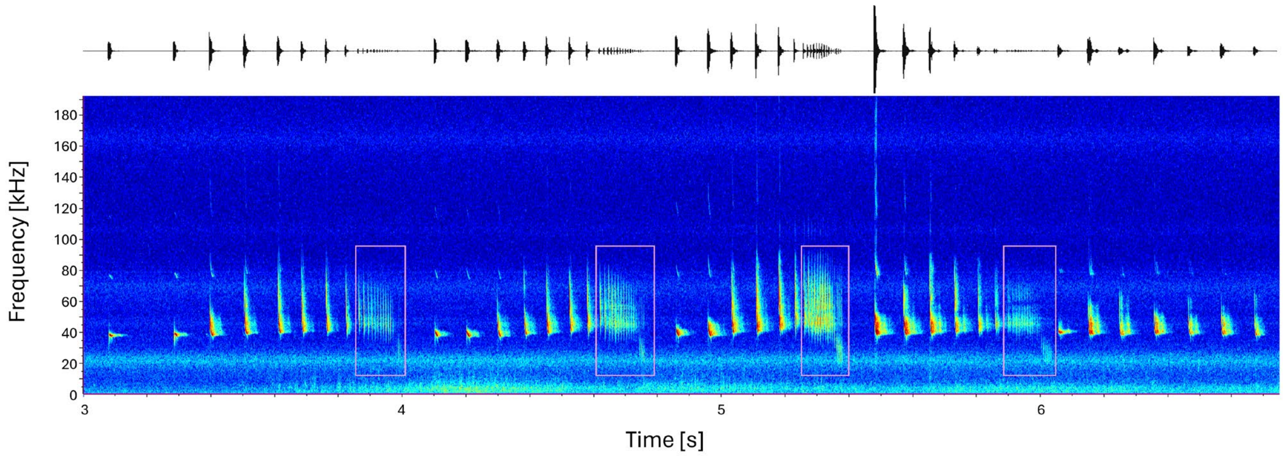


Figure 4.9. Example recording from HR3 wind turbine A05 documenting foraging activity of a Nathusius' pipistrelle (from wav-file HR-A-A05_20230520_203051). A total of 137 feeding buzzes were recorded in 20 minutes, this example visualizes four of them (outlined in pink). The black waveform in the top panel shows the relative amplitude of the recorded echolocation calls as a function of time, the bottom panel displays the relative power of the call frequency content of those same calls across the same time axis in a spectrogram (window size 1024 samples, Hann window, 50% overlap).

4.1.4 Passive acoustic monitoring from bird vessel-surveys

The bird baseline surveys included a total of eight ship-based surveys per year in the pre-investigation area. A single SM4BAT FS recorder was deployed on the vessel before each of these surveys. Each deployment lasted the duration of the bird survey from the ship's departure until its return to Esbjerg Port, including visits to three fixed observation points offshore (South-East, South-West and North, see orange locations in Figure 1.2). Each bird survey lasted 4-7 days and the surveys were conducted according to the overview in Table 4.2.

Table 4.2. Overview of bird surveys with onboard passive acoustic monitoring of bats.

Bird survey	Starting date	Survey duration (days)	Bats (species, date)
April 2023	26/4	5	-
May 2023	17/5	6	-
June 2023	12/6	7	-
August 2023	10/8	6	-
September 2023	15/9	6	ENVsp, 18/9
October 2023	7/10	4	-
December 2023	2/12	7	-
February 2024	7/2	4	-
April 2024	17/4	8	-
May 2024	16/5	7	ENVSp, 19/5
June 2024	12//6	4	-
August 2024	12/8	7	-
September 2024	16/9	7	Pnat, 18/9,19/9,20/9, 22/9
October 2024	23/10	7	Pnat, 29/10
December 2024	9/12	5	-
February 2025	24/2	7	-

In the first survey year, 27 files with bat detections were recorded from the bird survey vessel. All of them were identified to the ENV species complex and were from a single night in autumn (18/9 2023) at the SW fixed observation point. The recordings occurred within less than 15 minutes of each other. No feeding buzzes were present in the recordings but several included approach phase calls, indicating potential foraging or exploratory behaviour. In the second survey year, 11 files with bats were recorded. As in the first year, all the records were of single individuals but more spread in space; from all three of the fixed observation points (Table 4.1), in time; from three separate surveys in May, September and October 2024, and included Nathusius' pipistrelle in addition to ENV species (Table 4.2). Several of the recordings from May 2024 revealed both approaches and feeding buzzes pointing to foraging behaviour.

4.1.5 Offshore bat data correlated with weather conditions

The collected offshore bat records from buoys and the OSS and wind turbine stations in Horns Rev 3 across both survey years are plotted against select weather parameters in Figure 4.10.

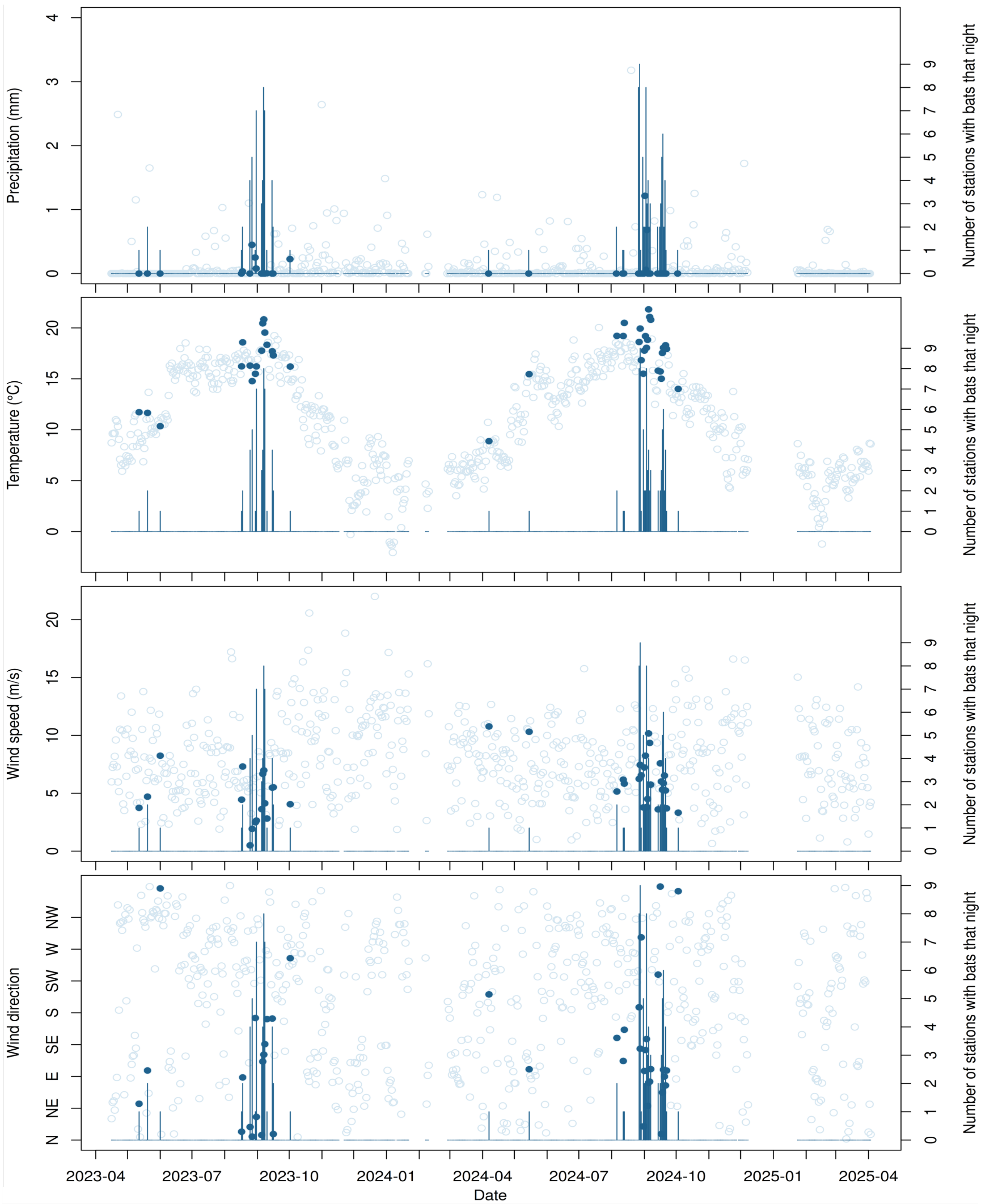


Figure 4.10. Timeline showing the number of offshore stations (buoys, wind turbines, OSS and bird survey vessel) with bat recordings per night and weather parameters (estimated as means for the hour of sunset). Top panel: Nightly precipitation (ERA5 data averaged across all offshore stations, second panel: nightly temperature (ERA5 data at 2 m above sea level at sunset, averaged across all offshore stations). Third panel: nightly wind speeds (ERA5 data at 10 m above sea level at sunset, averaged across all offshore stations). Bottom panel: nightly wind directions (ERA5 data at 10 m above sea level at sunset, averaged across all offshore stations) The length of each bar indicates how many stations recorded bat activity on a given night. Zeros represent nights without recorded bat activity but with active recorders. Open circles show mean estimates of weather variables on nights without recorded bat activity, filled circles show mean estimates of weather variables on nights where bats were recorded.

Bats were present on a few nights with up to 1.5 mm precipitation, but most activity was recorded offshore on nights without precipitation (Figure 4.10 top panel) and mean temperatures above 15°C (15-20°C, Figure 4.10 second panel) The few spring records (2023 and 2024) occurred mostly at lower mean temperatures (8°C-12°C). Offshore bat records occurred at mean wind speeds up to 11 m/s. 92% of the offshore records occurred at mean wind speeds below 8 m/s and 60% occurred at mean wind speeds below 6 m/s. The records at the highest wind speed in both 2023 and 2024 occurred in spring (Figure 4.10, third panel). Disregarding spring due to the low sample size, most activity coincides with wind directions containing an eastern component (Figure 4.10, bottom panel).

The ERA5 weather data was compared to measured weather parameters supplied by Vattenfall A/S from nacelle height at three of the wind turbines that were included in the bat PAM deployments on Horns Rev 3. There was generally good agreement between the measured and re-analysed weather data with correlations > 0.8 for wind speed and temperature and > 0.9 for wind direction.

4.1.6 Variables predicting bat activity offshore

This section presents the results of the Bayesian modelling used to test the hypotheses outlined in section 3.3.5 for correlations of offshore bat activity during the autumn migration period with the following variables: distance to coast, date, station type, temperature, wind direction and wind speed. The outcome of the statistical analysis is presented in figure 4.11.

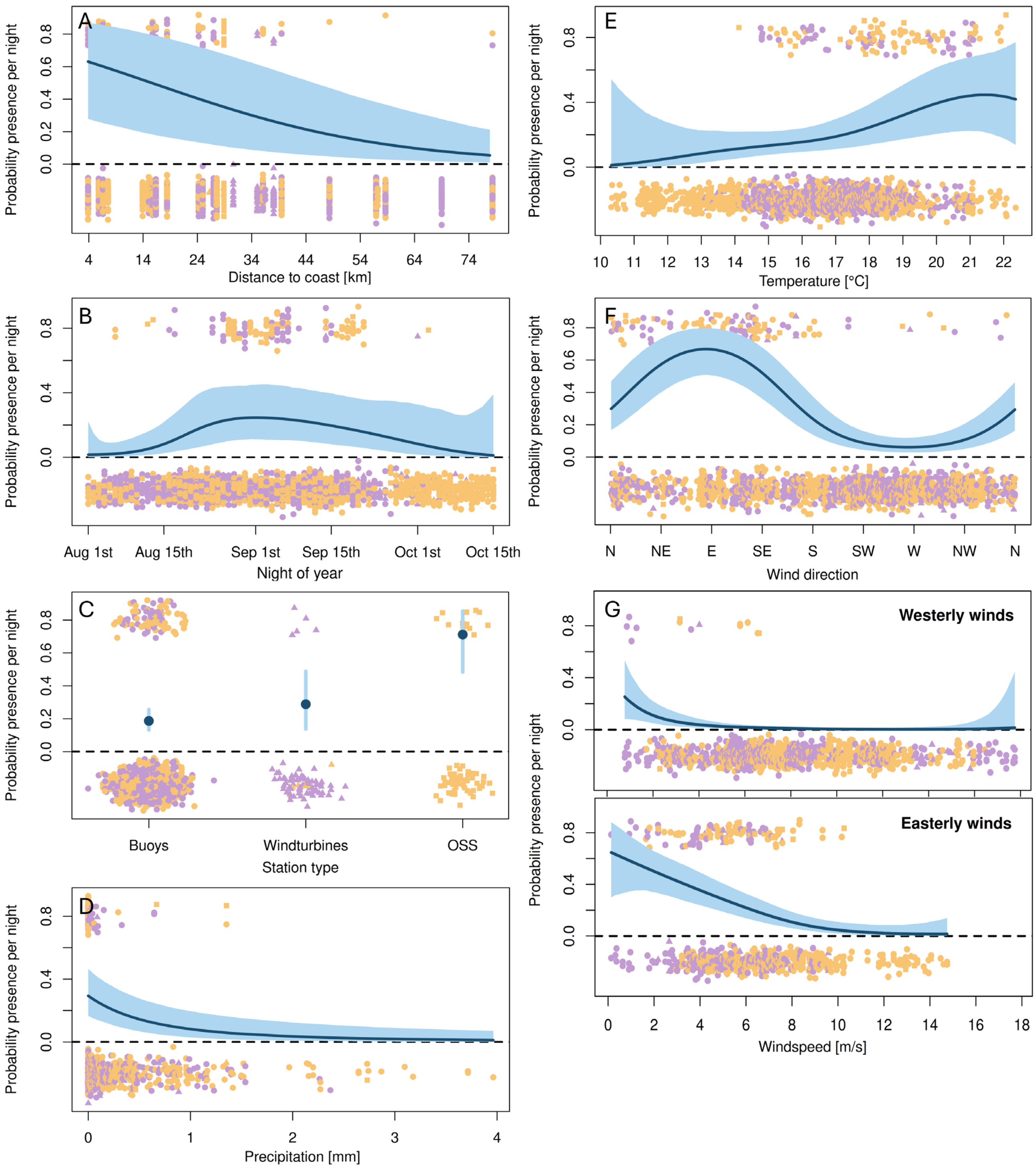


Figure 4.11. Plots of raw data and model predictions for offshore activity. Point markers indicate presence/absence per night. Marker type represents station type (circle = buoy, triangle = wind turbine and square = OSS) and marker colour represents year (purple = 2023, orange = 2024). The average posterior model predictions are shown as dark blue curves (large, filled circles in subplot C). Light blue shaded areas (vertical lines in C) represent the 89% posterior interval for the prediction. Dashed black line represents 0.

The raw data shows that activity is predominantly recorded at stations less than 40 km from the coast (see Figure 4.1). The Bayesian model predicts how bat activity relates to distance to coast and shows a decline from almost 60% at the closest station to less than 20% at 40 km from the coast (Figure 4.11A). However, the model shows large uncertainty, so these are only estimates and the only well supported result is the decline in activity with distance.

The raw data has two very distinct peaks around beginning and end of September (Figure 4.11B). Upon closer examining, almost all these days had an easterly wind. The model that includes the weather variables and restricts the number of peaks that can be predicted also showed a clearly increased probability of observing bat activity from medio August until start October, but data coverage is too low to more narrowly predict start and end times of migration in the surveyed area. It is clear from the raw data alone that offshore activity in the survey area occurs mainly in the months of August and September.

Bat activity was clearly greater at the OSS compared to buoys at similar distance to the coast (Figure 4.11C). Too little data was procured to get a precise estimate of the average bat activity at wind turbines, but the results suggest that it is intermediate between buoys and the OSS and suggests the OSS as a relevant location for long-term and follow-up monitoring to secure more offshore data on bat activity around permanent structures.

The model predicts an exponential decrease in bat activity with increasing precipitation (Figure 4.11D), with much reduced activity at 1.5 mm precipitation and higher.

No bat activity was recorded at temperatures below 14° C during autumn in our dataset (Figure 4.10, top panel and Figure 4.11E). The model output shows an almost linear increase in predicted activity between 14° C and 20° C.

The model predicts a pronounced effect of wind direction on bat activity in the survey area, with highest probability of activity on nights with easterly winds (Figure 4.11F). The model also supports this with an estimate of ca. 55% probability of bats being present with eastern winds vs only ca. 5% with western winds.

The effect of wind speed showed a clear dependence on wind direction (Figure 4.11G, top and bottom panel). With westerly winds, activity is almost exclusively predicted to occur at very low wind speeds. The increase at the very high end is almost certainly a spurious result, as very little data is available and it should be theoretically impossible for bats to make it offshore with headwinds of 18 m/s. With easterly winds, activity is predicted to be stable up to 2 m/s, after which it starts to drop, suggesting that mild easterly wind could even increase bat activity compared to windless nights. However, activity is present up to wind speeds of 11 m/s (Figures 4.10 and 4.11G (bottom panel).

4.2 Onshore passive acoustic monitoring

Each of the 11 PAM stations on land recorded much higher bat activity and species diversity than stations offshore, irrespective of type (buoy, wind turbine, OSS, bird survey vessel). The activity generally remained high throughout summer in both years and was lower but not absent during the months of winter (Figure 4.12-4.14 and 4.17).

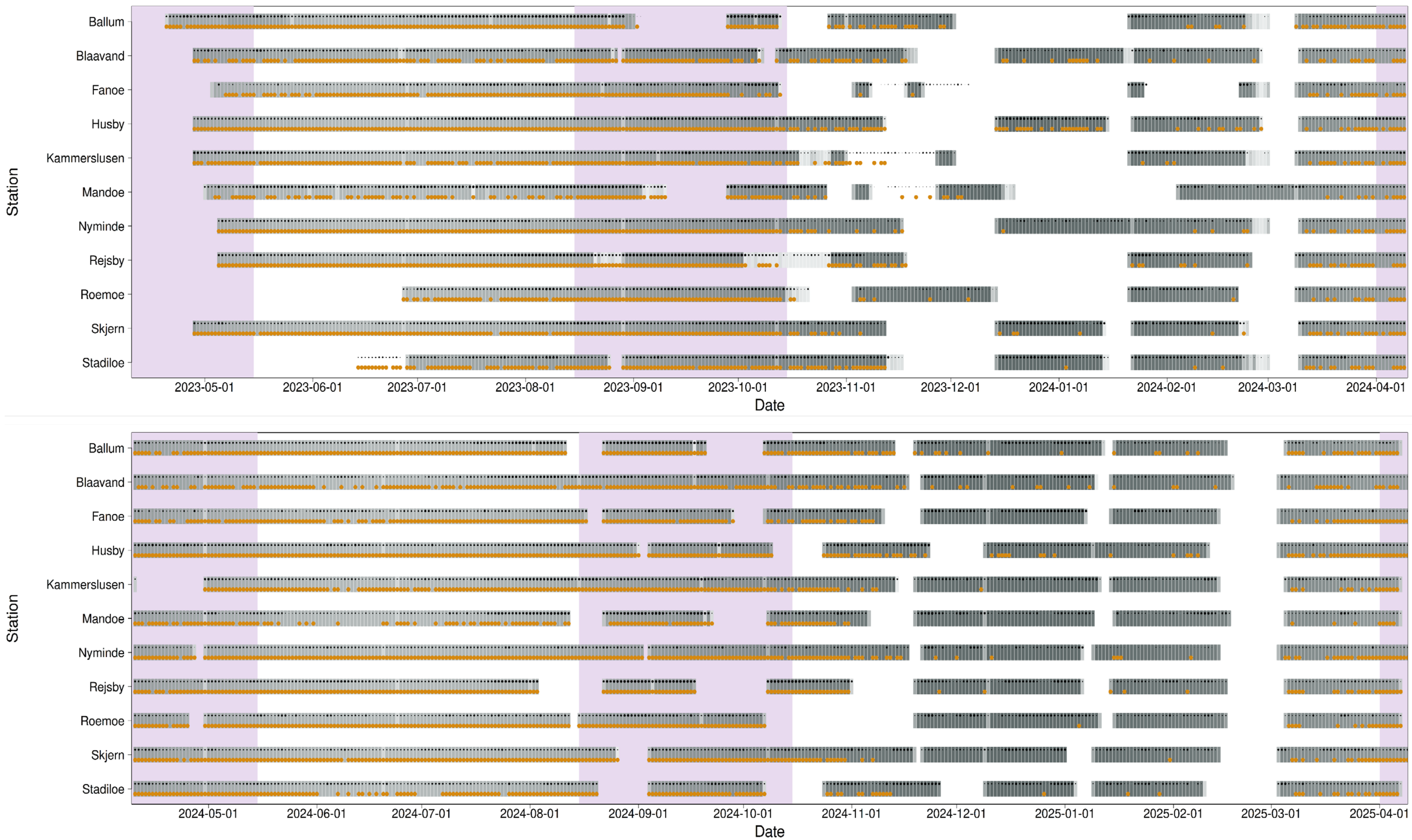


Figure 4.12. Overview of deployments and nights with bat activity for the 11 bat PAM stations on land over the two survey years. Top panel: first survey year. Bottom panel: second survey year. Orange points show nights where bats were recorded and are not scaled by the number of detections per night. Greyscale bars and black points are both indicators of recorder functionality. Grey bars are colour-scaled by the number of summary entries made by the recorder per night and fade into lighter shades recorders ran out of power and recorded only partially through the night. Black points indicate that a recorder was triggered during that night and made recordings, but those only included bats where black and orange points coincide on the same night. The black points are scaled by the number of trigger events (larger: more recordings triggered, smaller: fewer recordings triggered) and are present without grey bars for deployments where recorder summary files could not be recovered. The fact that recordings were still triggered indicates intact recorder functionality. Absence of black points means that no recording was triggered. Purple shading: expected migration periods based on literature.

The coastal PAM stations resulted in a total of 3,196 hours of bat activity across the two years, with highest overall activity at the Husby (713 h) and Rejsby (616 h) stations, and the lowest activity at Mandø (42 h) and Fanø (78 h). The two species groups with the highest overall activity were Nathusius' pipistrelle (1026 h) and the ENV species complex (780 h), whereas the lowest activity levels were documented for the soprano pipistrelle (258 h) and the brown long-eared bat (35 h). The highest median activity per night (summed over species groups) was recorded in August (12 h) and September (13 h) and the lowest (< 1 h) in December and January (Figure 4.13). The figure does not account for the lower survey effort during winter, see Figure 4.12.

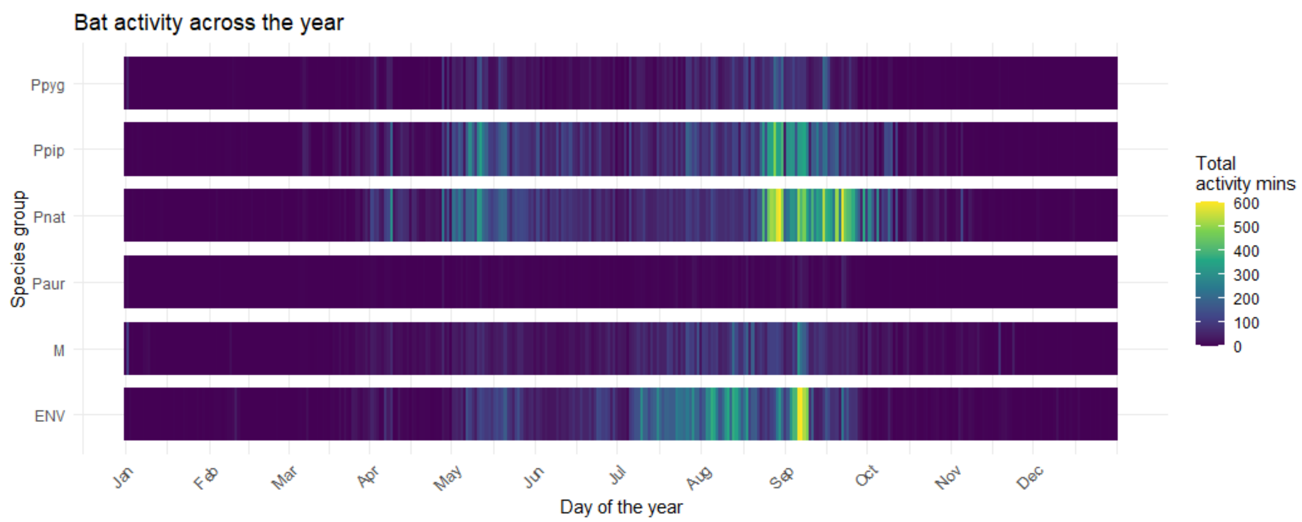


Figure 4.13. Total minutes of bat activity by species per day (averaged across two collection years). The five species groups are shown on the y-axis (Ppyg: soprano pipistrelle, Ppip: common pipistrelle, Pnat: Nathusius' pipistrelle, Paur: brown long-eared bat, M: Myotis species complex), ENV (Eptesicus/Nyctalus/Vespertilio species complex. The x-axis shows the day of the year, as Julian calendar date. The colour gradient indicates the total minutes of bat activity detected during the night of the day Dark blue: zero activity minutes, yellow: approximately 10 hours of activity per night.

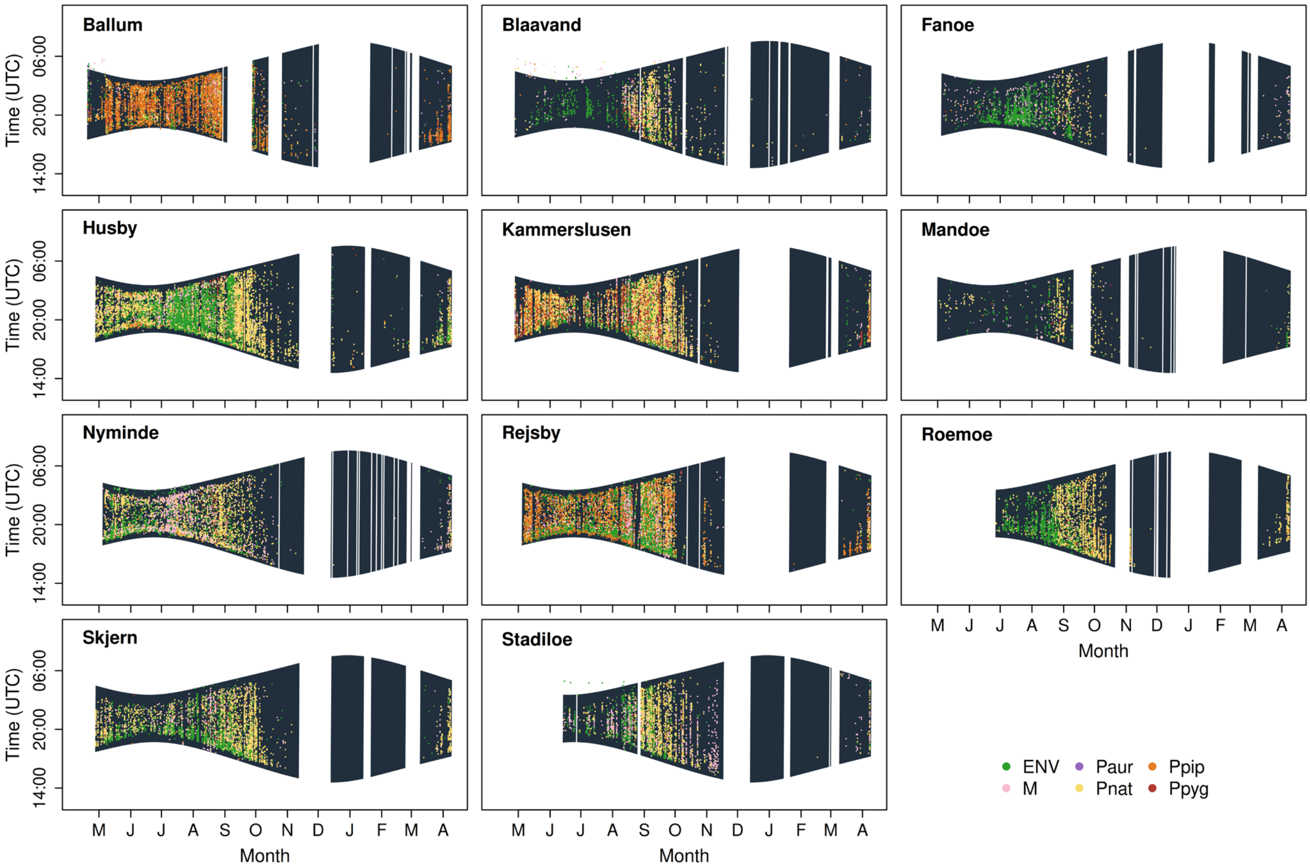


Figure 4.14. Nightly activity overview for the first survey year including all species and all 11 onshore PAM locations. Time (y-axis) ranges from noon on a given day until noon the next day. Data points are activity minutes. Each point represents a minute with at least five call detections within a 3-5 second window (see section 3.3.2). Dark background: night from solar sunset to solar sunrise. White background: days without active deployments. Points represent bats and are colour-coded by species (or species complex in cases where identification to species by AnimalSpot was uncertain): ENV (green): Eptesicus/Nyctalus/Vespertilio species complex, M (pink): Myotis species complex, Paur (purple): brown long-eared bat, Pnat (yellow): Nathusius' pipistrelle, Ppip (orange): common pipistrelle, Ppyg (red): soprano pipistrelle, The station at Rømø was added to the survey programme in late June 2023.

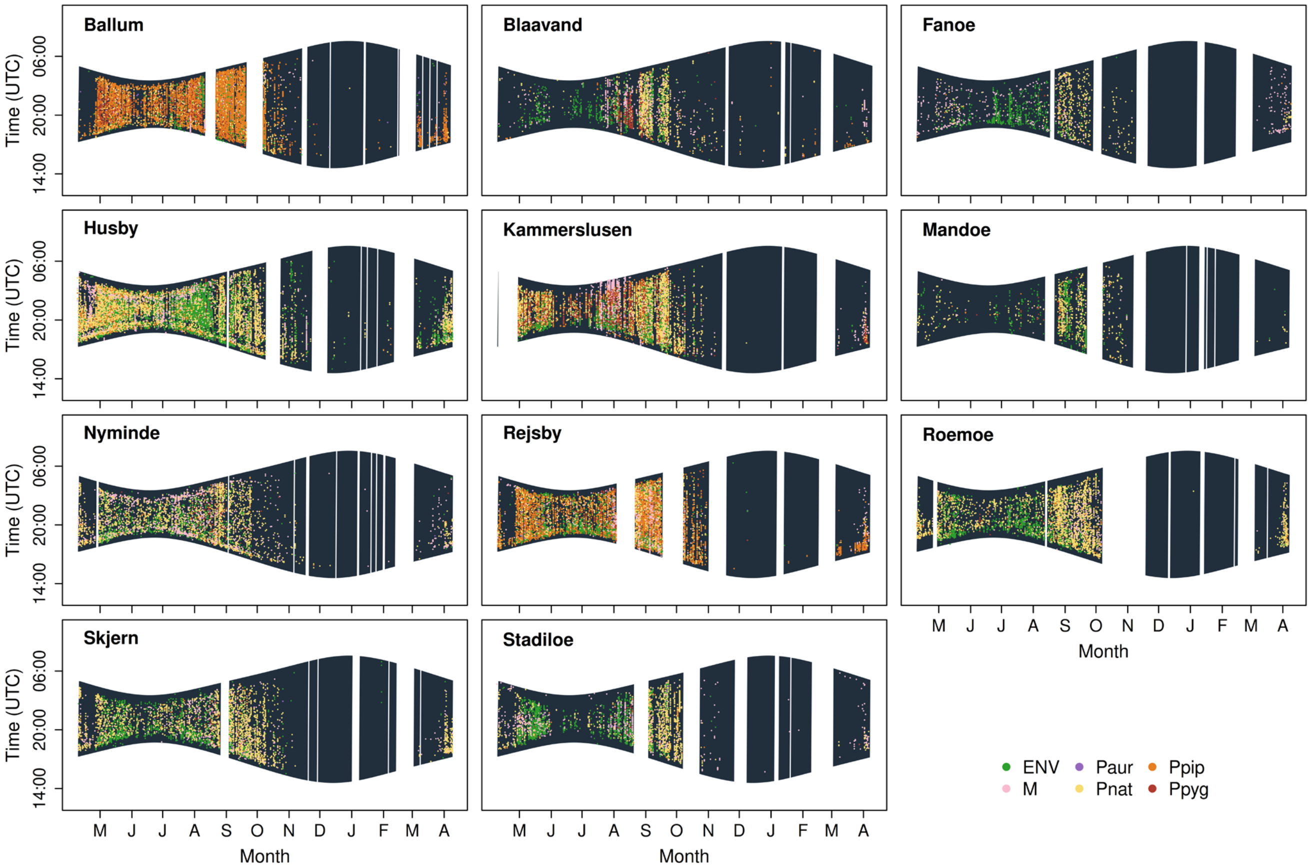
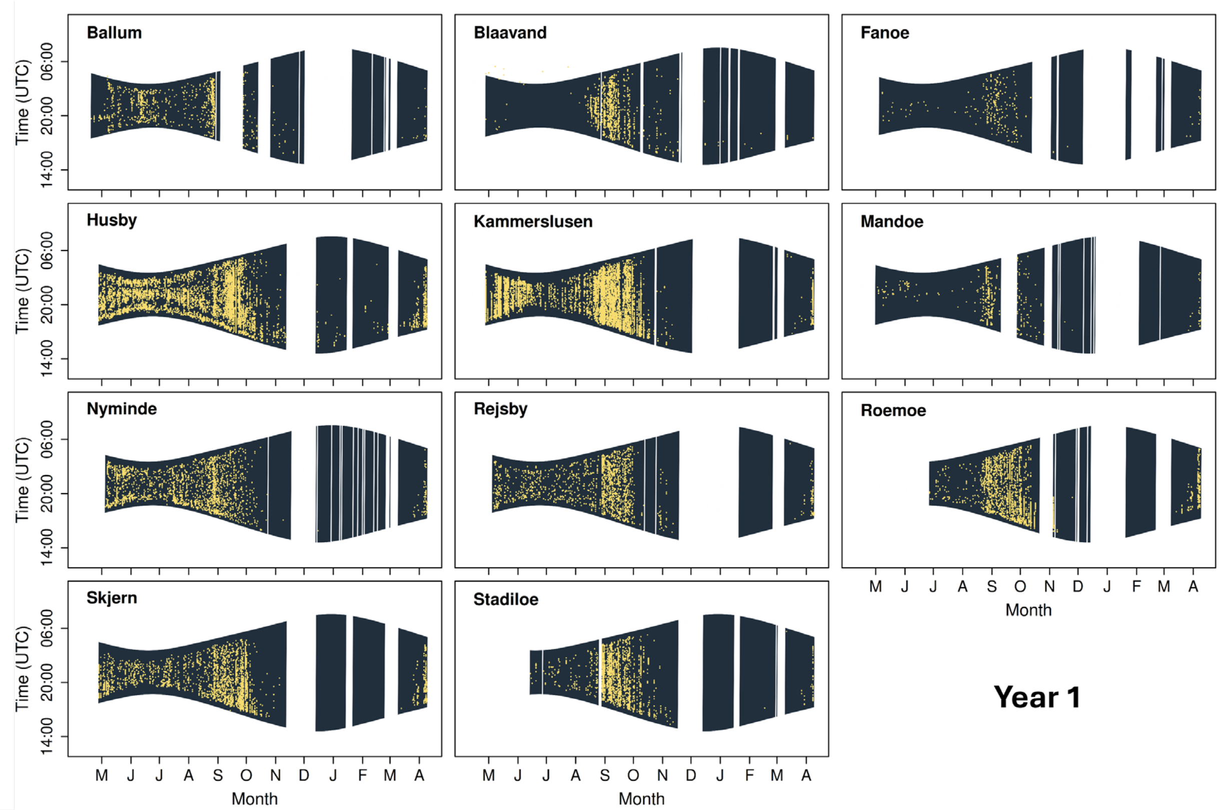


Figure 4.15. Nightly activity overview for the second survey year including all species and all 11 onshore PAM locations. Time (y-axis) ranges from noon on a given day until noon the next day. Data points are activity minutes. Each point represents a minute with at least five call detections within a 3-5 second window (see section 3.3.2). Dark background: night from solar sunset to solar sunrise. White background: days without active deployments. Points represent bats and are colour-coded by species (or species complex in cases where identification to species by AnimalSpot was uncertain): ENV (green): Eptesicus/Nyctalus/Vespertilio species complex, M (pink): Myotis species complex, Paur (purple): brown long-eared bat, Pnat (yellow): Nathusius' pipistrelle, Ppip (orange): common pipistrelle, Ppyg (red): soprano pipistrelle.

Figures 4.12, 4.14 and 4.15 reflect the results from the automated classification by AnimalSpot and include ENV species only as a species complex. The activity plots below visualize activity separately for Nathusius' pipistrelle (Figure 4.16) and the two ENV species common noctule and particoloured bat (Figure 4.16, based on AnimalSpot classifications). As described in the Methods chapter (section 3.2.2), we tested and used third-party software to classify species within the ENV complex at select stations and then compared the activity (Figures 4.17-4.19). As only select land stations and not both years for each land station were included in this add-on analysis, some are left blank in Figures 4.17- 4.19. This should not be interpreted as absence of ENV species at those stations.



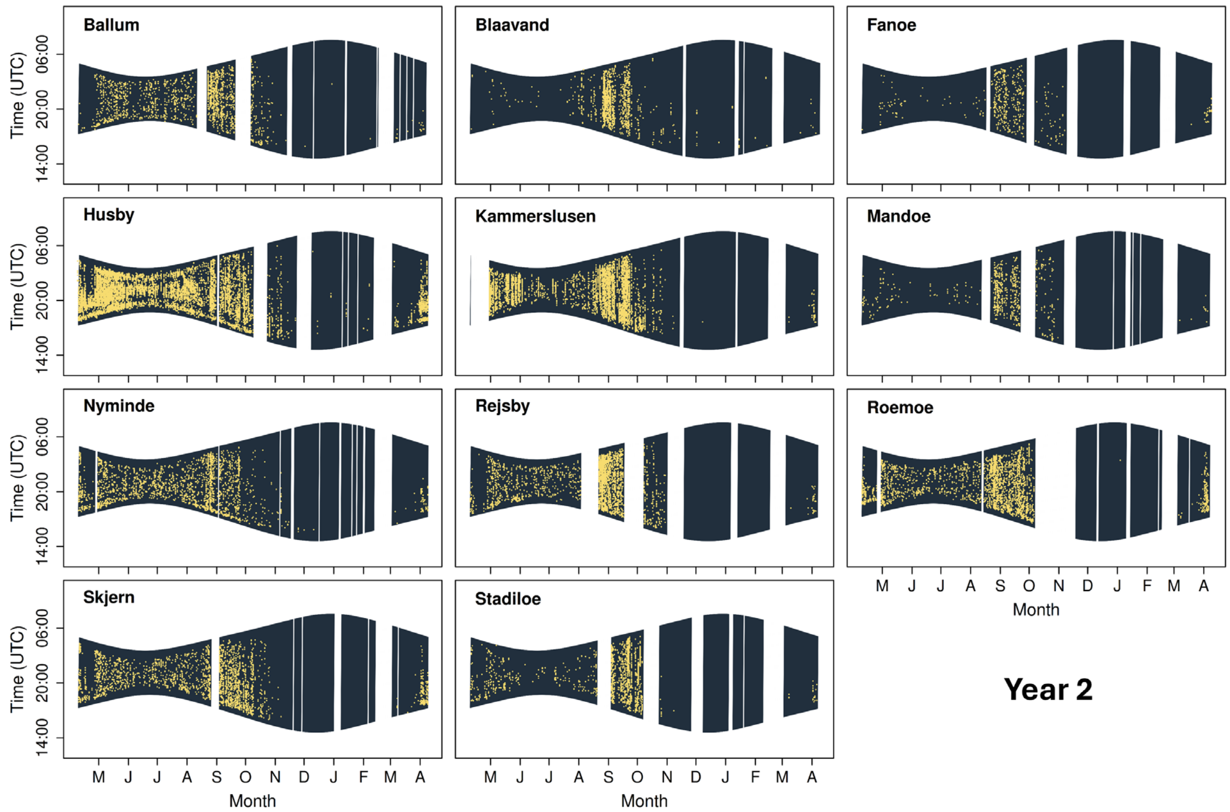


Figure 4.16. Nightly activity overview for Nathusius' pipistrelle across all onshore locations over both survey years. Top half of figure: first year, bottom half of figure: second year. Time (y-axis) ranges from noon on a given day until noon the next day. Data points (yellow) are activity minutes. Each point represents a minute with at least five call detections within a 3-5 second window (see section 3.3.2). Dark background: night from solar sunset to solar sunrise. White background: days without active deployments.

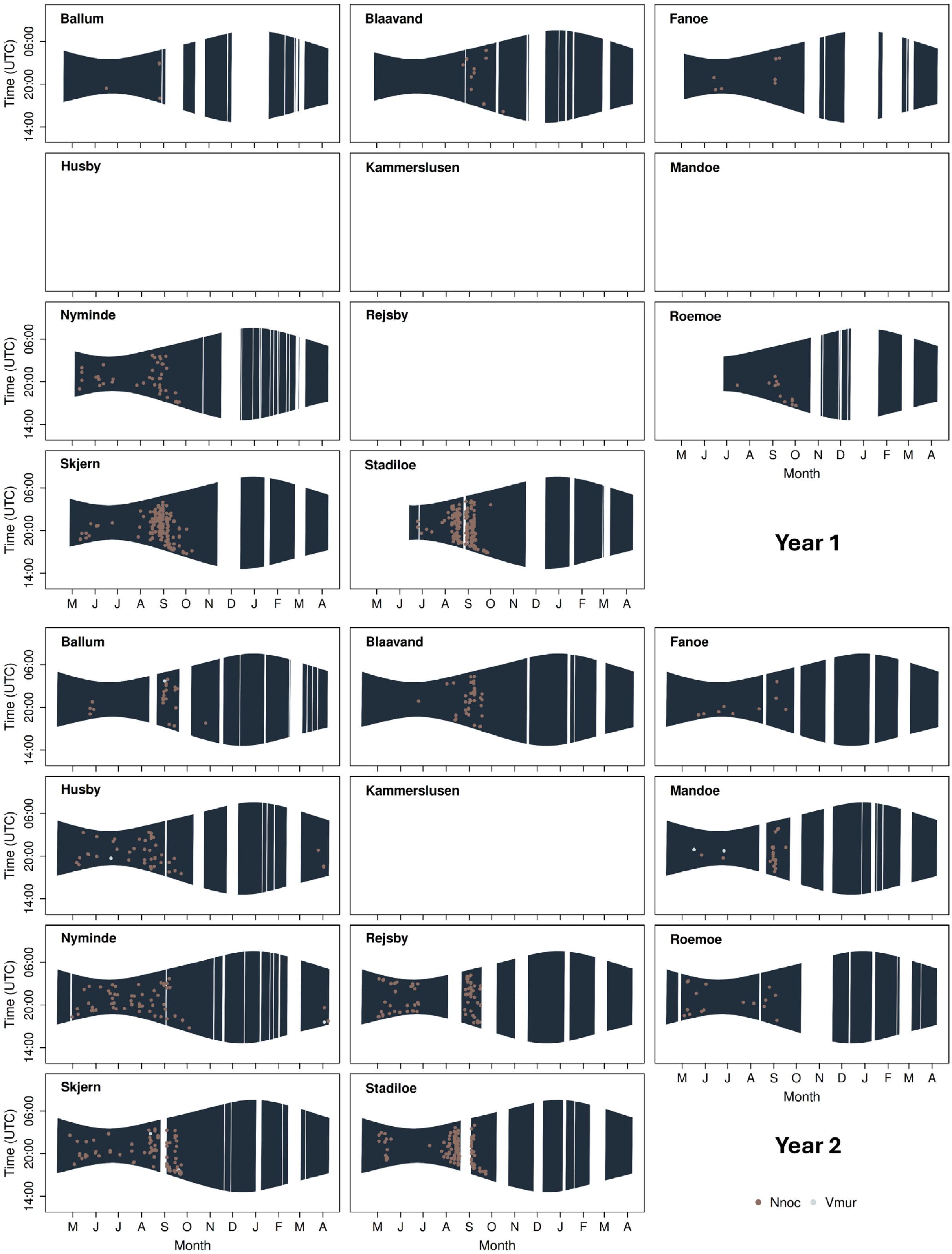


Figure 4.17. Nightly activity overview for select onshore stations over one or two survey years for the common noctule (brown points) and the particoloured bat (grey points). Top half of figure: first year, bottom half of figure: second year. Time (y-axis) ranges from noon on a given day until noon the next day. Data points are activity minutes. Each point represents a minute with at least five call detections within a 3-5 second window (see section 3.3.2). Dark background: night from solar sunset to solar sunrise. White background: days without active deployments. Stations without data points shown were not included in the analyses to separate the ENV complex into individual species.

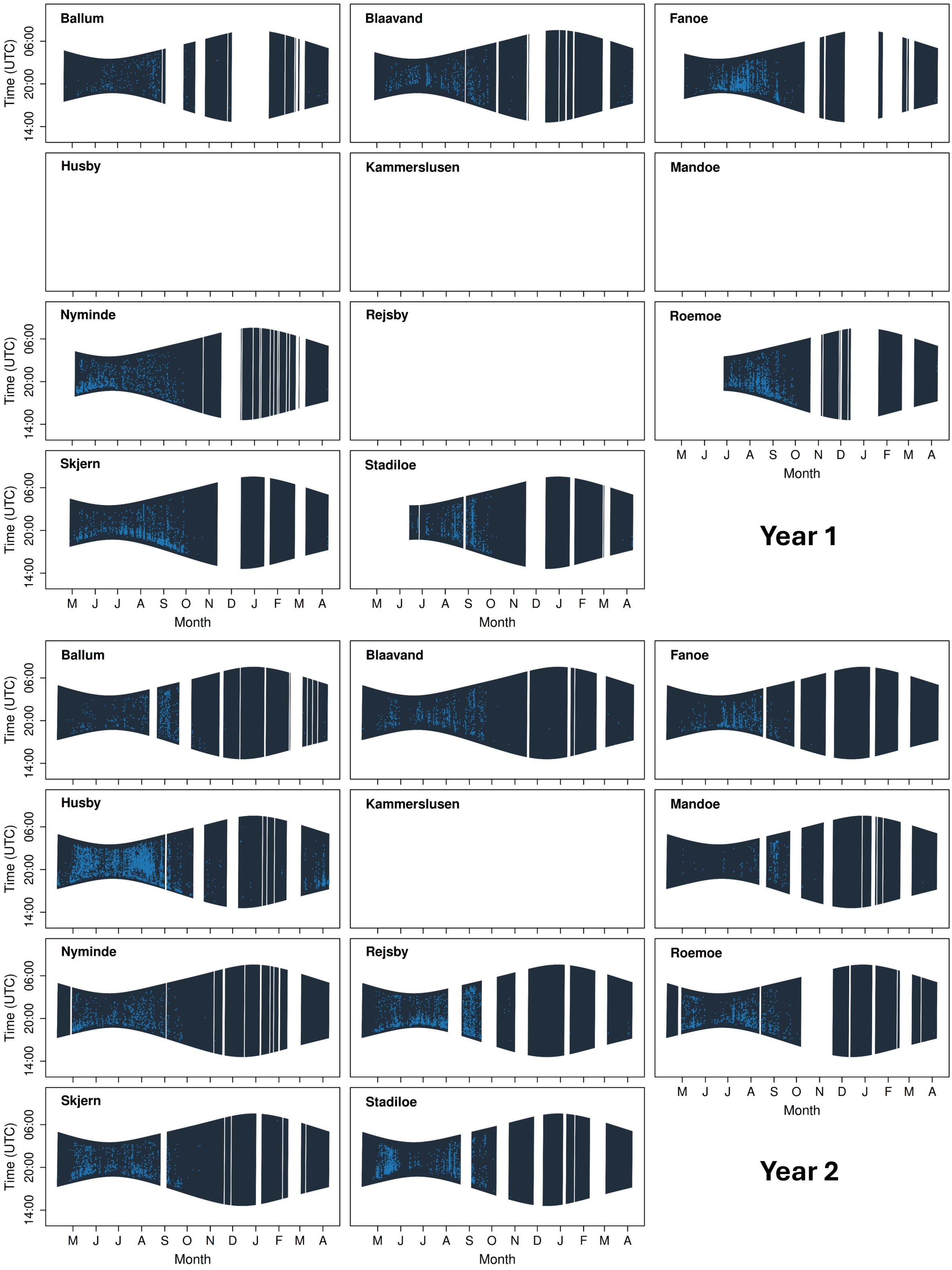


Figure 4.18. Nightly activity overview for select onshore stations over one or two survey years for the serotine bat (blue points). Top half of figure: first year, bottom half of figure: second year. Time (y-axis) ranges from noon on a given day until noon the next day. Data points are activity minutes. Each point represents a minute with at least five call detections within a 3-5 second window (see section 3.3.2). Dark background: night from solar sunset to solar sunrise. White background: days without active deployments. Stations without data points shown were not included in the analyses to separate the ENV complex into individual species.

For Nathusius' pipistrelle, nearly all land stations showed a steep increase in activity consistent across both years and starting at the end of august, within the autumn migration period (Figure 4.16). This pattern was less pronounced for the stations on Fanø and on Mandø, where the activity of Nathusius' pipistrelle was generally low compared to the other stations. At Husby and Kammerslusen, a second activity peak is visible in spring, although for the Husby station, activity also stays high throughout summer.

The classification of the ENV complex into species resulted in very few records of the particoloured bat, which is relatively rare in western Jutland (Figure 4.17). It also revealed pronounced activity peaks for the common noctule (Figure 4.17), starting mid-August and winding down by October, at several land stations, with Skjern and Stadilø showing the most pronounced pattern in both years, out of the stations analysed across both years. The majority of the ENV records were classified by BatSonic as serotine bats and did not reveal similar pronounced activity peaks in the fall as seen for the predicted long-distance migrants Nathusius' pipistrelle and the common noctule (Figure 4.18).

Whether the activity peaks observed on the land stations in autumn are related to migration is speculative in the absence of more movement data to support any conclusions, but the seasonal pattern differs from activity patterns on inland stations in eastern Jutland, and on Fyn and Zealand, where activity increased from April to August dropping a little in September (Elmeros et al. in prep.).

4.2.1 Variables predicting bat activity onshore

For the onshore dataset, the random forest model across species explained 61% of the variance in data, with a mean square error of 0.09 (MSE, average squared difference between predicted and observed values). The variable with the highest overall importance was the Julian calendar date, followed by station and species group. Of the weather variables, atmospheric pressure and wind speed were of highest importance, while lunar phase and year of data collection appeared least important to predict bat activity (Figure 4.19, top left).

The species-specific random forest models explained on average 59% of variance (40% < R^2 < 70%), with an MSE ranging from 0.05 to 0.15. Within species, Julian calendar day also had the highest importance for most of the species groups, along with the station. For the common and soprano pipistrelle, station had higher importance than Julian calendar day. For the ENV species complex, the scaled hour of the night ranked of higher importance compared to other variables than for the other species groups. Additionally, for the soprano pipistrelle, wind speed outranked the other weather variables.

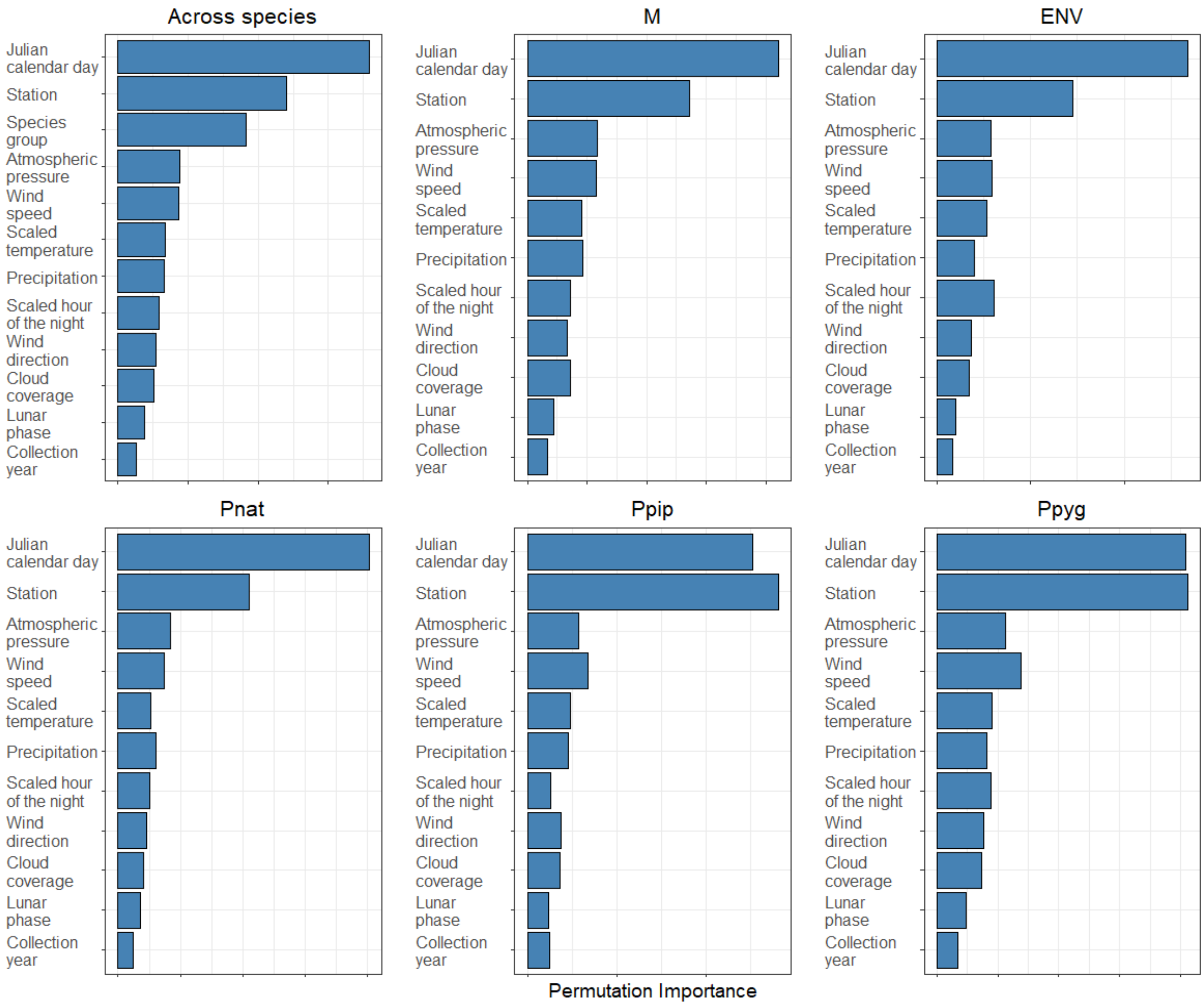


Figure 4.19. Factor importance for predicting bat activity onshore. The first subplot (top left) shows factor importance across all species groups; the remaining subplots show factor importance for each separate species group. Permutation importance is indicated on the x-axis and is only comparable within a subplot. M: Myotis species complex), ENV (Eptesicus/Nyctalus/Vespertilio species complex, Pnat: Nathusius' pipistrelle, Ppip: common pipistrelle, Ppyg: soprano pipistrelle,

In the autumn period, we collected a total of 604 h of bat activity of Nathusius' pipistrelle onshore, with the highest overall activity at Kammerslusen (141 h) and Husby (111 h). The lowest activity was detected at Fanø (10 h) and Mandø (14 h). The night of 29. August had the highest average activity across the two years (10 h).

The GAM model explained 31% of the deviance in the data (adjusted R^2 = 36%). Wind speed, wind direction, and the interaction between lunar phase and cloud cover were significant predictors of bat activity, however, even the wind speed as strongest predictor among these effects only explained 0.15% of variance. The probability of bat activity increased with easterly winds and showed a peak at wind speeds of approximately 4 m/s (Figure 4.20). Temperature had no significant effect on the probability for bat activity.

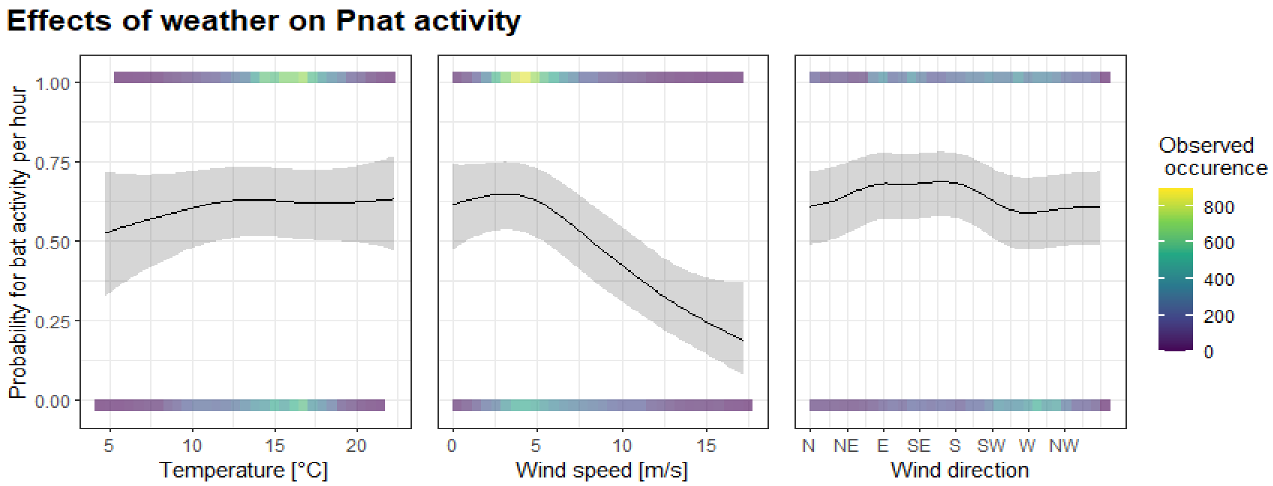


Figure 4.20. Effects of temperature, wind speed and wind direction on onshore activity of Nathusius' pipistrelle. Predicted probability of Nathusius' pipistrelle activity onshore during autumn migration depending on temperature (left), wind speed (center) and wind direction (right) in black. 95% confidence intervals are indicated in grey, and the actual observed activity indicated as density bars. The more observations were made at a certain value of temperature, wind speed or wind direction of either no bat activity (=0) or bat activity (=1) the more yellow the bar. Plot predictions were produced for station Kammerslusen during mid-migration, with all other effects fixed on the median.

Temporal patterns in activity varied among stations, with both scaled hour and day-of-year smooths showing significant variation at most sites. All stations showed a migrational pattern in the probability for activity of Nathusius' pipistrelle, with an initial increase and later decrease, except for Husby, Nyminde, and Rejsby (Figure 4.21). For those three stations the probability was already higher during the start of the autumn migration, especially Husby.

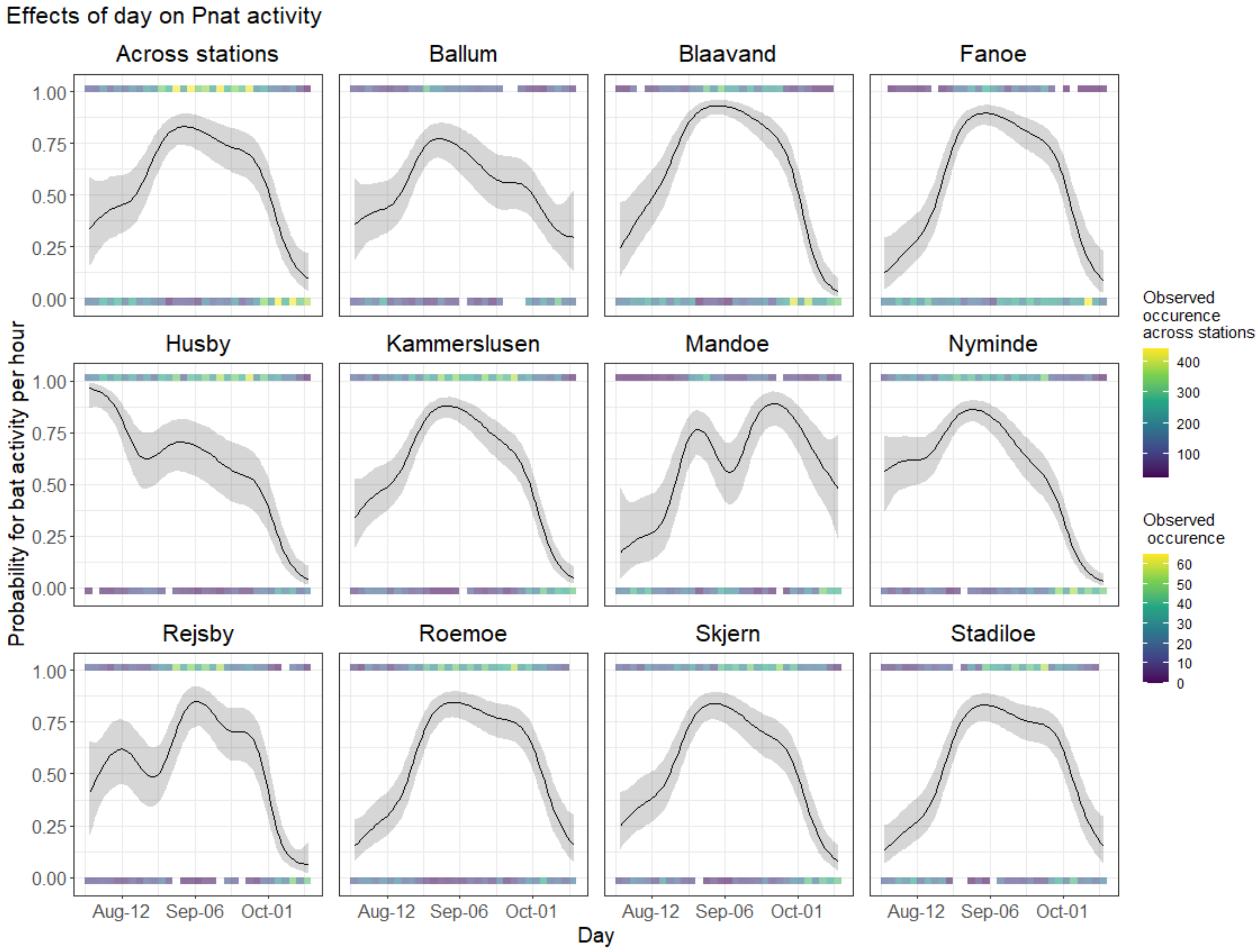


Figure 4.21. Seasonal effects on the activity of Nathusius' pipistrelle at onshore stations. Predicted probability of Nathusius' pipistrelle activity onshore during autumn migration depending on Julian calendar day and station in black. The first panel (top left and top legend) shows an average season effect across stations. Additional panels (with bottom legend) show seasonal effect on observed occurrence per station. 95% confidence intervals are indicated in grey, and the actual observed activity indicated as density bars. The more observations were made at a certain day of either no bat activity (=0) or bat activity (=1) the more yellow the bar. Plot predictions were produced with all other effects fixed on the median.

Seasonal changes in daily activity patterns (i.e., the interaction between day and the scaled hour) also showed a significant effect on the activity of Nathusius' pipistrelle (Figure 4.22). While the probability for bat activity was highest in the early hours after sunset in the beginning of the migration season, it was high throughout most of the night for the mid-migration period. At the end of the migration period, activity was much lower and most pronounced just after sunset. The random smooths for unique time and day-by-year captured substantial unexplained variation, indicating notable short-term and inter-annual fluctuations.

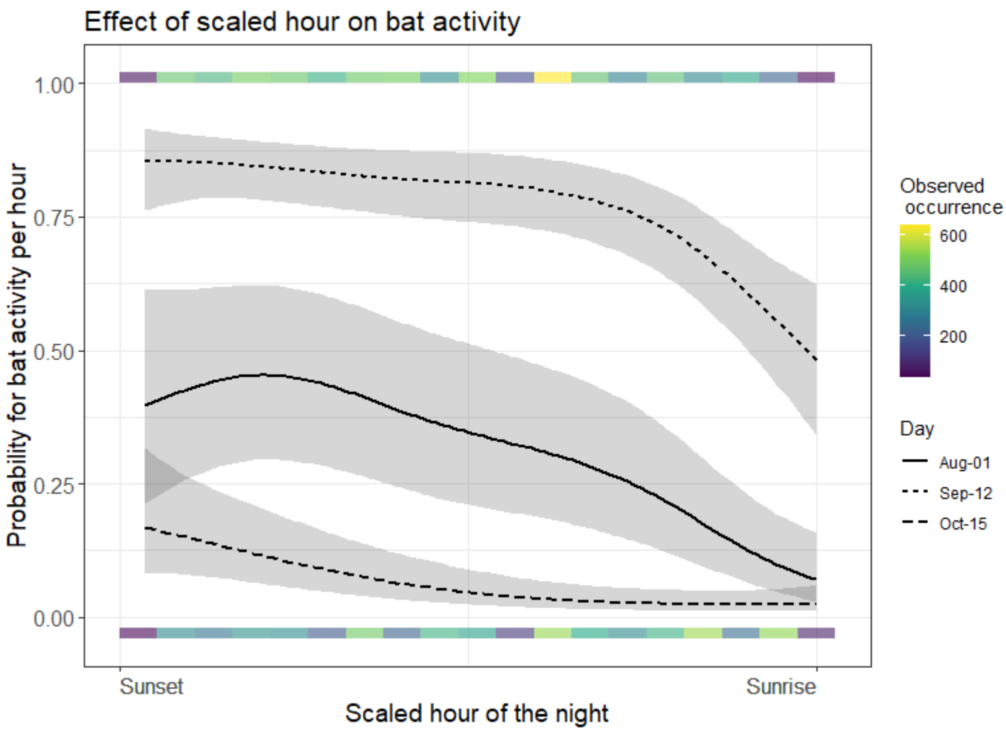


Figure 4.22. Seasonal effects on daily activity patterns of Nathusius' pipistrelle onshore. Predicted probability of Nathusius' pipistrelle activity onshore during autumn migration depending on Julian calendar day and hour of the night (scaled by sunrise/sunset) in black. The three different lines represent the beginning of autumn migration (1. August = solid), mid-season (12. September = dotted) and end-season (15. October = dashed). 95% confidence intervals are indicated in grey and the actual observed activity indicated as density bars. The more observations were made at a certain hour of the night of either no bat activity (=0) or bat activity (=1) the more yellow the bar. Plot predictions were produced for station Kammerslusen, with all other effects fixed on the median.

4.3 Radio-tracking of bats

Two of 13 Nathusius' pipistrelles tagged during the first survey year were each detected in October on a single separate Motus receiver station along the North Sea coast of Germany. Both individuals were females caught and tagged in late September 2023 in Østerild, Thy, North Jutland (see detailed methods and map of capture and receiver points in Brinkløv et al. 2024). Tagging and trapping was not included in the second year survey programme, but an independent project by the Department of Ecoscience, Aarhus University (Elmeros et al. 2023-25) documented a migration track from a male Nathusius' pipistrelle tagged near Skjern, West Jutland, and detected on 10 receiver stations as it was travelling at least 670 km over 8 nights following the coastline through Germany to Reddingsbrigade Maasvlakte on the Dutch coast near Rotterdam (Figure 4.23).

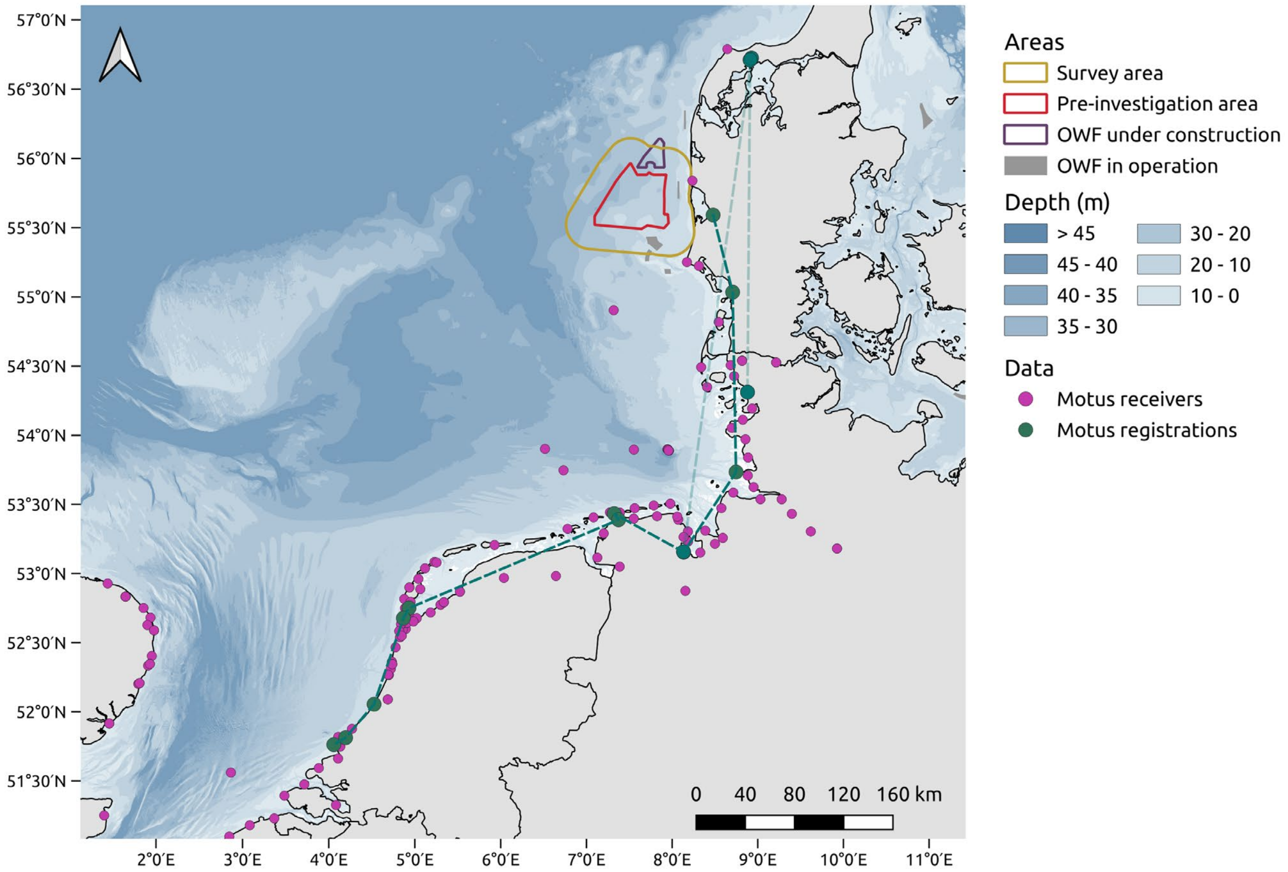


Figure 4.23. Map of active Motus receiver stations along the North Sea coast of Denmark, Germany and the Netherlands in September 2024 and the migration track (dark green dashed lines) of a male Nathusius' pipistrelle tagged near Skjern in autumn 2024. Two straight lines (dashed, faded green) are shown between the capture and tagging site for the two female Nathusius' pipistrelles caught and tagged during autumn 2023 and the Motus stations that each registered one of these tagged bats 22 and 9 days, respectively, after they were tagged. The dashed lines connecting the tagging sites and receiver stations are not representative of the actual flight paths in detail. Coordinates and activity periods of Motus receivers are accessible through the Motus website: https://motus.org/explore/.

5. Discussion and conclusions

Bat activity documented by the passive acoustic monitoring (PAM) effort offshore was much lower across the entire two-year survey period compared to the bat activity observed for the 11 land-based PAM stations on the coast of West Jutland, despite a monitoring effort of 20-50% of full nights in a year by the buoy stations.

The activity offshore was also more focused in time, with 69% and 48% of the records occurring on just four specific nights in August and September in each of the two survey years. The peak of activity observed in the months of August and September aligns with the autumn migration period predicted from existing studies of bat migration over more southern parts of the North Sea (Lagerveld et al. 2019, 2021, 2024). The autumn activity peak was consistent in both years and included records of several bat species but was dominated by Nathusius' pipistrelle (Figures 4.3 and 4.4), also consistent with observations from other parts of the North Sea (Lagerveld et al. 2021, Petersen et al. 2014, Seebens-Hoyer et al. 2021). Bats identified to the ENV species complex had the second highest occurrence offshore. Where possible, species identifications to the ENV complex, which is characterized by significant overlap between call types, call variation and call frequencies, were manually further split into classifications of individual species (see section 3.3.2) and resulted in most records of serotine bats and common noctules with very few records of particoloured bats. A single offshore record of a *Myotis* species, presumably a Daubenton's bat, was also present, together with sparce records of soprano pipistrelle.

Both activity and species diversity were higher for the parts of the pre-investigation area and survey area closer to the coast (Figure 4.1 and Table 4.1). Nathusius' pipistrelle was, however, recorded in the autumn of both survey years at one of the western-most buoy PAM stations, nearly 80 km from the coast and was the only species present for buoy stations further than 27 km from the coast.

The 22 offshore buoy stations were active for 20-27% and 21-50% of full nights in the first and second survey year, respectively. The number of bat recordings per year from the total number of buoy stations was similar (90 in year one, 107 in year two, Table 4.1). The survey effort from additional offshore stations on wind turbine transition pieces and the offshore substation (OSS) in Horns Rev 3 was much less consistent due to the contingency on operator service schedule. The supplementary bat PAM from the vessel-based bird surveys was limited to the short time spent offshore (Table 4.2: 4-8 days per survey in each of eight months of a year). Yet, data from these stations support the pattern from the buoy stations, with most records occurring in September and being of Nathusius' pipistrelle (Figures 4.7 and 4.8, Table 4.2).

Spring activity was low and largely contributed by recordings from the wind turbine stations. The PAM effort from buoys only resulted in a single bat record from spring (April 2024, Figures 4.2 and 4.3), as did the survey effort from the vessel-based bird surveys (May 2024, Table 4.2). In contrast, the wind turbines recorded bats on several separate days during spring (May 2023 and 2024, Figures 4.7 and 4.8), documenting that there is also activity offshore during spring in the North Sea within the survey area and adjacent to the pre-investigation area (Figure 4.1). The PAM station on the OSS was not added until July 2024 and was therefore not part of the monitoring effort in the spring months of April and May during any of the survey years.

Although sparser than the autumn records, the bat activity documented in spring by the wind turbine stations could imply that bats actively visit permanent structures offshore during favourable foraging conditions, as supported by numerous feeding buzzes and approach calls recorded at the wind turbine stations (Table 4.1 and Figure 4.9). During the observed autumn activity peak, feeding buzzes were also recorded on several buoy stations and from both the OSS and the bird survey vessel. Whether this observed foraging activity can be attributed to ongoing migration or directed foraging bouts from the coast not related to migration is uncertain, but it is noteworthy that no activity was observed on the offshore stations during the summer. Overall, however, most offshore activity was recorded in the autumn. Ahlén et al. (2009) noted from inner Danish waters that migration activity seemed more diffuse in spring and may occur through different and more variable routes, e.g. entirely over land if food availability is more reliable here during spring than in autumn. More activity was also generally recorded in autumn than in spring by PAM offshore stations in inner Danish waters and the North Sea (Figures 3-32 to 3-34 in Seebens-Hoyer et al. 2021).

Most of the offshore activity was recorded on stations in the buffer zone between the pre-investigation area and the coastline and correlated with weather parameters, i.e., bats mostly occurred offshore on nights with little to no precipitation at temperatures > 15 °C estimated at 2 m above mean sea level, wind speeds below 8 m/s estimated at 10 m above mean sea level, and with wind directions including an easterly component. It should, however, be stressed that the results from the statistical modelling are associated with uncertainty caused by the low overall activity levels offshore, and as such, are not directly applicable as cut-off values for curtailment. Most of the (few) offshore records from spring, however, coincided with lower temperatures (8-12 °C) than the activity in autumn and wind speeds up to 11 m/s, with potential implications for season-tailored curtailment based on weather parameters.

Discounting northbound migration during the autumn when nearly all offshore occurrences were recorded, bat migration offshore from the west coast of Jutland in the autumn is predicted to occur in a S-SW flight direction. Accordingly, it would be expected to coincide with N-NE tailwinds. Also, easterly winds on warm nights may blow more insects out over the North Sea and promote bat activity not necessarily related to migration. The location of the North Sea I pre-investigation area implies that if migration activity occurs across it, it is likely to be from bats moving along the coast and departing intermittently offshore on foraging bouts, following insect swarms, potentially to permanent structures, as suspected by intense foraging activity recorded by the PAM stations deployed on wind turbines in Horns Rev 3 (Figure 4.9). When wind directions are favourable for long-distance migration, bats may fly higher up in the stronger winds, but outside of the detection range of acoustic detectors at sea level (Lagerveld et al 2024, Hurme et al 2025). Although travel distances of 500-1,500 km are not uncommon for medium to long distance migratory bats species (Fleming 2019, Hutterer et al. 2005), they have rarely been documented across open ocean. Assuming bats adhere to migration transects that represent the shortest possible offshore distances, they would be more likely to cross the North Sea further north or south than the pre-investigation area, e.g. following the coastline south and depart offshore from Blåvandshuk moving south/southwest in autumn. While we could not single out the Blåvand land station as a migration hotspot based on our onshore data, we did see an autumn activity peak for this station as well. Further, the results from the Motus tracking component in year one, together with the detailed migration track added in 2024 (Figure 4.19) from a different project (Elmeros et al. 2023-2025) support the hypothesis that migration activity occurs close to or over land, following the coastline of West Jutland. Additional tagging efforts would be highly useful in supporting this hypothesis further. Further knowledge about the offshore presence of insects would also be useful in this context, as migrating bats apply a fly-and-forage strategy (Šuba et al. 2012, Voigt et al. 2024a).

The land-based PAM stations recorded substantial activity for an area with relatively sparse documentation from the NOVANA monitoring programme (Søgaard et al. 2018). Nathusius' pipistrelle also accounted for significant activity on land where the species diversity was higher across all stations than offshore (Figures 4.14 and 4.15). Further classification efforts of the ENV complex into species resulted mostly in records of serotine bats, a species not expected to be a long-distance migrant and also did not reveal similar pronounced peaks in activity during the autumn migration as did the activity of the common noctule ENV (compare Figures 4.17 and 4.18). The peaks in activity of Nathusius' pipistrelle during spring and particularly in autumn could indicate migration activity along a north-south vector in the western part of Jutland, a hypothesis supported by the results from the Motus tagging, although further empirical support is needed to substantiate those. The onshore PAM results did not suggest specific hotspots or departure points for offshore migration routes over the North Sea I area. To identify such based on acoustic monitoring would likely require high-density grids of PAM stations. The activity of Nathusius' pipistrelle did show a later peak than for the other bat species recorded, from end of August to mid-October at most of the land stations. This pattern was consistent across land stations and could reflect increased foraging activity not related to migration or later migration activity contributed by individuals arriving at a delay from higher latitudes. At Kammerslusen and Husby, where this late activity peak was most pronounced, further monitoring and tagging studies could help verify if migration occurs into and across the pre-investigation area.

The Motus tagging component was part of the first year surveys to provide movement data for individual bat migration patterns, potentially crossing the North Sea through the pre-investigation area and being picked up at third party receiver stations offshore or on the coast of Germany, the Netherlands or the United Kingdom (Figure 4.23) after being tagged in Jutland, or, conversely, if some of the five receiver stations installed on the West Jutland coast, picked up signals from bats tagged abroad in third party projects. The Motus component was high-risk, high-gain but the tagging effort during the autumn of the first survey year did yield a delayed result as two Nathusius' pipistrelles tagged in Denmark were logged on receivers in Germany but without passing by multiple receiver stations (see https://motus.org, Brinkløv et al. 2024). Those results did unfortunately not become available before the Motus component of the second-year survey programme was foregone by Energinet. The much more detailed migration track obtained by the Department of Ecoscience, Aarhus University in a separate project (Elmeros et al. 2023-2025) in autumn 2024 (Figure 4.23) supports migration patterns observed of Nathusius' pipistrelles tagged on the offshore island of Helgoland in the southern North Sea, and is proof-of-concept for the type of valuable information the Motus system can contribute, especially as the network of receiver stations is expanding and the tagging effort is increased on a broad geographical scale (Bach et al. 2022, Mitchell et al. 2025). The single detailed migration track, and the two registrations obtained at coastal points in Germany during the first survey year, point to migrating Nathusius' pipistrelles following the coastline south, but more data should be collected over time to corroborate if this is a main migration route through Denmark. It is unknown whether the tagged bats were only passing through Denmark or spent the summer here.

5.1.1 Statistical modelling

The inclusion of a two-year survey period for the North Sea I project facilitated statistical modelling which would not have been possible for the sparse offshore dataset if only a single year was included. However, to quantify seasonal patterns and estimate inter-annual variation data collection across more years is still needed. The results presented in this report underline the major importance of at least two years of baseline surveys for bats. The addition of further years of baseline monitoring would further help to separate weather effects from temporal and spatial effects, particularly useful for planning and management (e.g., curtailment) and increase the robustness and predictive precision of the analysis.

It should be noted that all offshore model predictions were made for assumed optimal but non-extreme weather conditions. This was done for two reasons. First, if less optimal conditions are modelled, bat activity is likely so low, that the variable of interest does not show any effect relevant for management decisions. Second, in binomial models, values close to zero and one are very hard to visualise due to the logit link, making even strong effects appear insignificant. The overall effect is the same but easier to visualize if fixed at realistic conditions.

The results of the model were well aligned with our first hypothesis that bat activity decreased with the distance to the coast (Figure 4.11A). Since we only allowed for negative effects in the prior, positive slopes are not possible, but if there was no effect in the data, the model could still predict a completely flat slope. The high intercept and large uncertainty are probably due to the inclusion of station type. We recorded much more activity at the OSS, and the model prediction for an 'average' station is therefore higher than for a buoy station. Also, all wind turbines and the OSS are at approximately 30 kilometres from the coast. If we then ask what the average probability of observing a bat is for distances different from 30 kilometres, the model must extrapolate leading to high uncertainty.

Offshore bat activity documented by this dataset is almost exclusively limited to August and September. However, this strongly coincides with periods of easterly wind in both years, which are not typical for fall in Denmark, and therefore it is not possible to draw any firm conclusions about when bat activity is expected to be increased in general (Figure 4.11B). Even when accounting for temperature, wind speed and wind direction, two peaks were present in the model output, if the number of knots was set too high (allowing the model to overfit the data), illustrating the limitations of modelling general trends with B-splines if only two years of data are available.

Bat activity was much higher at the OSS than at buoys at a comparable distance (Figure 4.11C). Note that this result is only based on the single station and single autumn migration season monitored on the OSS, but the pattern is consistent throughout the migration season, suggesting that at least this OSS has increased bat activity. A potential explanation for this is that the OSS is a permanent, large structure, which might allow bats to rest and could also create a wind shadow with increased insect activity and, accordingly, foraging opportunity. Several foraging buzzes and approach sequences were recorded from the OSS (Table 4.1).

Based on the model, bat activity was predicted to decline strongly with increasing precipitation, with nearly no bat activity predicted above 1.5 mm (Figure 4.11D). The effect of temperature is surprisingly small (Figure 4.11E), with the model allowing for even no effect in the 89% posterior interval. From the raw data, there appears to be a clear cut-off at around 15° C, but this is partly due to the temperature staying above 14° C all nights in 2023. Even in 2024, almost all nights with lower temperatures occurred towards the very end of the migration season, at which point bat activity might already be very low due to the effect of season. There is some support for the hypothesis that there is an optimal temperature, after which it becomes too warm for bats to be active, but the data didn't contain any days with extreme temperatures, so the slight decline after 21° C could easily be incorrect. From a theoretical perspective, bat activity is expected to decline at some upper temperature extreme. However, our results suggest that estimating the effect of temperature in autumn over the Danish North Sea can very likely be done with a linear parameter, making interpretation much easier.

The effect of wind direction is strikingly consistent (4.11F), with almost all nights with high activity having easterly winds during autumn. This effect was observed in both years and across station types. Combined with the effect of wind speed, it doesn't appear that bats are necessarily blown off course themselves, as the activity levels are estimated to be highest at low wind speeds, where bats should be able to steer back to the coast. It could be that insects are blown offshore, leading to a foraging opportunity. Bat activity is predicted to persist until ca. 10 m/s, above which the prediction of bat activity approaches zero. As for temperature, this could be due to low data density at extreme wind speeds, but the posterior interval is much narrower, suggesting more data wouldn't fundamentally change the estimates.

The outcome of the GAMM for the onshore data showed similar weather effects on bat activity as offshore (Figure 4.20, relatively high activity at low wind speeds and easterly winds). Any effect of temperature on onshore activity was washed out by seasonal effects in the model used but could be revealed by the inclusion of data across more years. Easterly winds are known to bring more stable weather, potentially offering improved foraging and migration conditions, blowing bats and insects towards the coast of west Jutland and offshore.

The results from both the random forest predictions and GAM modelling point to temporal and spatial effects as better explanatory variables of the variation in the onshore activity of Nathusius' pipistrelle than weather (Figures 4.19-4.22). Local habitat quality and topography also influence occurrence and abundance of bat species and are contained but not analysed further in the spatial effects component. The hour by day pattern of activity for Nathusius' pipistrelle shows that daily activity patterns change over the autumn migration season (including a buffer, so modelled over 1. August-15. October), with the highest probability of activity per hour and activity throughout the night in the middle of the migration season (represented by 12. September, Figure 4.22). The pattern from 1. August with higher activity in the hours following sunset, may be representative of activity patterns during the summer.

5.1.2 Conclusive remarks

A low level of offshore activity was evident from the two-year baseline surveys of bats. Several observations point to migratory activity as a probable explanation for the presence of bats in the North Sea I pre-investigation area. Several of the species found offshore are known to migrate long-distance, particularly Nathusius' pipistrelle which also occurred in the part of the survey area farthest offshore at 80 km distance to the coast. The temporal pattern of bat activity offshore coincided with the period known for bat migration, specifically in autumn, and with activity peaks at land-based PAM stations along the coast. The temporal pattern of bat activity offshore in the autumn also correlated with easterly wind. Finally, the limited evidence from the Motus tagging effort suggests that bats mainly migrate south in the autumn along the coastline, with intermittent flights offshore. The short detection range of ultrasound with the PAM method in air does, however, warrant caution and cause for follow up studies to quantify bat activity and potential migration corridors at higher altitudes during favourable winds in the migration season.

6. Data and knowledge gaps

The survey programme for bats realised here as part of the pre-investigations for the North Sea I project and prospected wind farm area contributes significantly to the baseline knowledge of bat activity in the North Sea north of German waters, not least due to its two-year duration. The commitment to a bat field programme rather than desktop studies as a general component in environmental surveys (baseline and other) is necessary to improve the data foundation for the North Sea and offshore in general. So is the need for open access sharing of raw data and metadata to improve transparency and build a solid knowledge base of use for authorities, concessionaires, scientists and consultants. The lack of such standardized procedures is a major cause for the present data and knowledge gaps for bats offshore and onshore and hinders nuanced knowledge-based decision making (Asmus et al 2025, Brinkløv et al. 2025). It is therefore an encouraging precedence that raw data from the North Sea I baseline surveys are made publicly available.

The lack of systematic data on bat presence/absence, abundance and movement patterns over the North Sea, and of population dynamics and sex distribution of bat species that are part of North Sea flyway populations still, however, represent a significant knowledge gap.

The offshore results from the bat baseline surveys included records of mostly isolated feeding buzzes from buoys but also extended foraging activity (multiple feeding buzzes over a prolonged period) around permanent structures within the Horns Rev 3 wind farm area. As little is known about the behaviour of bats around wind turbines and the factors attracting bats to the turbines, post-construction surveys are a vital add-on to pre-investigations and environmental impact assessments. Without such efforts, it is not possible to properly assess the potential effects of offshore wind turbines in the North Sea, adapt effective mitigation measures in the operational phase and evaluate cumulative impacts of the rapidly expanding wind energy sector on bats.

Methods to provide detailed data on bat migratory paths for individual bats are challenging. The traditional method akin to bird ringing involves capture and ringing (also often referred to as banding) of individual bats to track their movements but requires successful re-capture or recovery of the ring/band and is extremely inefficient and will only document two locations (trapping and recovery sites, Fleming 2019). Further, ringing bats is ethically problematic, due to a relatively high risk of injuries to the bats. Modern tracking methods rely on the attachment of different types of transmitters to animals, such as radio or GPS tags. Information on individual flight paths offshore is highly valuable to indicate if migration occurs across the pre-investigation area. However, methodological challenges mean that GPS tags for tracking bats are currently still either archival, and must be retrieved to recover data, or too large to be used on species such as Nathusius' pipistrelle, of special focus in this context. Radio tags that are small enough for this purpose will only provide data if the tagged bats pass close enough by the receivers that must pick up the signal from the tag. If placed in strategic locations along the coast and explicitly on permanent structures offshore, they can greatly add to data and knowledge gained from passive acoustic monitoring and its accompanying constraints on the acoustic detection range of ultrasonic signals in air.

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