MODELLING OFFSHORE BAT ACTIVITY OVER DANISH WATERS

Scientific Report from DCE – Danish Centre for Environment and Energy No. 691 2026

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Data sheet

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Abstract:	Wind turbines pose a risk for bat populations. Even offshore wind turbines may pose a risk for bats, as they forage and migrate over marine areas. We modelled offshore bat activity for different Danish seas. Activity was summarised and modelled per night as a presence/absence variable. The analyses indicate a relatively higher probability for bat activity in the inner Danish waters compared to the Danish North Sea. Activity decreased with increasing distance to the coast in the North Sea, but no such effect was observed for the inner Danish waters. Bat activity increased with increasing temperatures, with a clear seasonal difference in temperatures where high bat activity occurred. Offshore bat activity decreased with wind speed.
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Contents

Preface

This report contributes to the project "*Environmental mapping and screening of areas for offshore wind in Denmark*", initiated in 2022 by the Danish Energy Agency. The project aims to support the long-term planning of offshore wind farms by providing a comprehensive overview of the combined offshore wind potential in Denmark. It is funded under the Finance Act 2022 through the programme "Investeringer i et fortsat grønnere Danmark" (Investing in the continuing greening of Denmark). The project is carried out by Aarhus University (Department of Ecoscience), NIRAS and DTU Wind.

The overall project consists of four tasks defined by the Danish Energy Agency (https://ens.dk/energikilder/planlaegning-af-fremtidens-havvindmoelleparker)

1. Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.
2. Technical fine-screening of areas for offshore wind based on the sensitivity mapping and relevant technical parameters.
3. Assessment of potential cumulative effects from large-scale offshore wind development in Denmark and neighbouring countries.
4. Assessment of barriers and potentials in relation to coexistence.

A report on a sensitivity map for bats within the Danish offshore regions in Task 1 was published in 2025 (Brinkløv et al. 2025a). Other subjects within Task 1—such as fish, birds, marine mammals, benthic habitats, wind and hydrodynamics, and ecosystem modelling—were presented in separate reports published in 2024 and 2025.

The first report on offshore bat activity provided an overview of published knowledge and outlined areas where relative sensitivity for bat populations to wind turbine developments was expected to be low, medium and high. The sensitivity map was based on expert assessments based on scientific papers and published results from environmental impact assessment (EIA) surveys and preliminary results from recent strategic surveys. The review disclosed differences in methodology and reporting standards, preventing direct comparison between the published results and introducing uncertainty about the feasibility of compiling data from across projects into one coherent analysis to compare bat activity in different survey areas.

This report reassesses offshore bat activity in Danish waters by validating, curating, and analysing data from multiple surveys, sites, recorder types, and collectors to quantify relative offshore activity across regions. As new data emerge, patterns and model robustness may shift, so results should be treated as dynamic and regularly updated through coordinated data collection and organisation.

We thank Energinet, HOFOR A/S, Vattenfall AB and Ørsted Wind Power A/S for access to raw or partially processed survey data and metadata, and the Danish Energy Agency for assistance in obtaining these data. We are particularly grateful for access to recordings from ongoing EIA surveys. Astrid S. Uebel provided valuable assistance in curating and organising the external data in the early phase of the project. The research-based advisory from DCE, Aarhus University, including this report, is solely the responsibility of the authors unless clearly stated in the text.

Sammenfatning

Omstillingen til vedvarende energiproduktion er afgørende for at modvirke klimaforandringer, men produktion af vindenergi kan påvirke flagermusbestande negativt. Undersøgelser af mortaliteten og fortrængningen af flagermus har mest fokuseret på vindmøller på land. Havvindmøller og kystnære vindmøller udgør dog også en risiko for flagermusbestandene, da en række flagermusarter fouragerer over havet eller krydser havområder under sæsonbetingede træk. Omkring Danmark er flagermustræk og fouragerende flagermus tidligere beskrevet over Østersøen, Øresund og den sydlige del af Nordsøen, men der ingen systematiske undersøgelser fra fx Kattegat.

For at integrere natur- og miljøhensyn tidligt i planlægningen af havvindmølleprojekter, iværksatte Energistyrelsen i 2022 en kortlægning af forskellige miljøparametre og en screening af danske farvande i forhold til etablering af havvindmølleparker. Som led i screeningen blev der udarbejdet et følsomhedskort for flagermus baseret på ekspertvurderinger af videnskabelige publikationer og konsulentrapporter fra miljøkonsekvensvurderinger af offshore anlægsprojekter. Gennemgangen afslørede væsentlige metodiske forskelle og mangler i afrapporteringsstandarder, der forhindrede meningsfulde sammenligninger af de publicerede resultater.

Over de seneste år er der gennemført passiv akustisk monitering af flagermus på havet som led i flerårige forundersøgelser af mulige havvindudviklingsområder og levetidsforlængelser for eksisterende havvindmøller. Formålet med denne rapport er at opdatere følsomhedskortet for flagermus baseret på numerisk analyse af flagermusaktiviteten offshore fra eksisterende data, indhentet fra konsulenter og energiselskaber med hjælp fra Energistyrelsen.

Offshore aktiviteten af flagermus blev modelleret for Nordsøen, nordlige Kattegat, sydlige Kattegat, vestlige Østersø, østlige Østersø og Femern Bælt ud fra parametrene: region, lokalitet, dato, afstand til kysten, temperatur, vindhastighed og -retning, nedbør, mølleplacering samt optagehøjde. Flagermusaktiviteten blev opsummeret og modelleret per nat som binær variabel (til stede/fraværende), dvs. sandsynligheden for at registrere en flagermus på en given nat, for at mindske potentielle bias fra de forskellige datatyper og kvaliteter.

Der er ikke data på flagermusaktivitet fra alle danske havområder, så det er vanskeligt at konkludere noget om flagermusbestandes følsomhed overfor vindmøller i f.eks. det nordlige og det sydlige Bælthav, Storebælt og Lillebælt. Da der ikke foreligger bestandsestimater for lokale og flyway bestande af flagermus eller realistiske metoder til at modellere vindmøllers påvirkning af bestandenes bevaringsstatus, er følsomhedskortet inddelt i de tre kategorier' 'lav', 'medium' og 'høj' følsomhed for at sammenligne forskellige delområder. Det skal pointeres, at de tre kategorier er relative, og de kan ikke umiddelbart oversættes til risiko for bestandseffekter. Alt andet lige må der dog forventes at være højere risiko for bestandseffekter fra vindmøller i høj følsomhedsområder, fx i de indre danske farvande.

Det opdaterede følsomhedskort understøtter vurderingen fra det første kort af en generelt højere følsomhed for indre danske farvande end for Nordsøen, samt en afstandsgraduering med højest følsomhed nærmest kysten, som understøttes kvantitativt af dataanalysen for Nordsøen. En tilsvarende

sammenhæng var ikke tydelig for de indre danske farvande. Flagermusaktivitet var tydeligt sæsonbetonet i alle områder, med aktivitetsmaksima i om foråret og efteråret, især i de indre danske farvande og mest markant i efteråret. Sandsynligheden for flagermusaktivitet steg med stigende temperaturer og faldt med stigende vindhastighed.

Estimaterne for flagermusaktivitet var generelt forbundet med høj usikkerhed pga. den begrænsede datamængde. Der var desuden geografisk bias i typen og kvaliteten af data, med rådata kun tilgængelige fra nogle projektområder, kun filtrerede optagelser fra andre og begge typer data fra enkelte områder. Data fra de fleste undersøgelser i Østersøen, det sydlige Kattegat og Femern Bælt var filtreret på forhånd med softwaren *Kaleidoscope* uden mulighed for at validere filtreringen. For to projektområder, hvor ufiltrerede rådata tillige var tilgængelige, viste *Kaleidoscope* en tydelig tendens til at overse kald fra slægterne *Eptecicus*, *Nyctalus* og *Vespertilio*, især i optagelser med meget baggrundsstøj. Det betyder, at de faktiske niveauer af flagermusaktivitet i de indre danske farvande underestimeres og forskelle i forhold til Nordsøen og det nordlige Kattegat sandsynligvis er højere end estimeret ud fra de tilgængelige data, samt at faldet i aktivitet med højere vindhastigheder delvist kan skyldes, at kald er blevet sorteret fra på grund af maskering fra baggrundsstøj. Disse resultater påpeger vigtigheden af at gemme rådata. Med flere og bedre data kunne flagermusaktiviteten også analyseres mere detaljeret, for eksempel per time for at modellere natlige forskelle i aktivitet.

Flagermus er meget mobile, og bestandene kan ikke forvaltes på småskala- eller projektniveau. Vekslende intensitet og kvalitet af tidligere undersøgelser forringer mulighederne for at bruge og sammenstille data i nuancerede analyser og modelleringer over en bredere geografisk skala, relevant for større dele af flagermusbestandene. Hvis man vil analysere data på tværs af projekter, bør data være indsamlet, organiseret og opbevares efter en fælles standard. For at identificere hav- og kystområder med høj fouragerings- og migrationsaktivitet hos flagermus og årlige variationer, bør der gennemføres en mere systematisk kortlægning samt etableres et overvågningsprogram for udvalgte lokaliteter uafhængig af enkelte vindmølleprojekter og efterundersøgelser fra vindmøller. Derved sikres robuste, kvantitative data, der understøtter vidensbaseret planlægning og drift af havvindmøller som samtidig kan sikre tilstrækkelig beskyttelse af flagermusbestandene.

Summary

Transitioning to renewable energy is essential to tackle climate change, but it may impose negative effects on the environment and biodiversity. Wind energy poses a major conservation challenge for bats, as turbines increase mortality and degrade habitats. Most research has focused on onshore turbines, but offshore wind turbines also pose a risk to bats that forage or migrate over marine areas. Around Denmark, bat migration and foraging activity have previously been documented over the Baltic Sea, Øresund, and the southern North Sea, but there are no systematic surveys for some seas, e.g. Kattegat.

To better understand and consider nature and environment in the planning process of further wind energy expansion, the Danish Energy Agency in 2022 initiated an environmental mapping and screening of areas for offshore wind in Danish marine waters. The screening included the generation of a sensitivity map for bats based on a literature review of scientific publications and reports from environmental impact assessments. The work revealed several issues with differing methodology and reporting standards, hindering meaningful comparisons between projects based on the reported results.

In recent years, passive acoustic monitoring of bats at sea has been conducted as part of multi-year surveys of proposed wind energy development areas and lifetime extension projects. This report updates the bat sensitivity map through a numerical analysis of offshore activity based on existing data from these surveys, supplied by consultants and energy companies, with support from the Danish Energy Agency.

Offshore bat activity was modelled for the North Sea, northern Kattegat, southern Kattegat, western Baltic, eastern Baltic, and Fehmarn Belt using the following parameters as predictors: area, location, date, distance to shore, temperature, wind speed and direction, precipitation, turbine location and recording height. Activity was summarised and modelled per night as a binary variable (presence/absence), representing the probability of detecting a bat on a given night, to reduce bias from varying data types and quality.

Data on bat activity were not available from all marine areas, so it is difficult to conclude on the sensitivity for bats to wind turbines in e.g. the northern and the southern Belt Sea, Great Belt and Little Belt. As there are no size estimates available for local or flyway populations of bats and no realistic methods to model the effects of wind turbine developments on conservation status of bat populations, the three relative categories of 'low', 'medium' and 'high' sensitivity included in the assessment and map are used to facilitate comparisons between offshore areas. The categories do not translate directly to numerical risks for population effects, but a higher risk, e.g. in the inner Danish waters, must be expected from wind turbines in high sensitivity areas.

The updated sensitivity map based on data analysis largely supports the assessment underlying the initial map, indicating a high sensitivity overall in the inner Danish waters and decreasing sensitivity with increasing distance to the coast in the North Sea. No such effect was observed for the inner Danish waters. The probability of bat activity during a night increased with increasing temperatures, with a clear seasonal difference in temperatures where high bat activity occurred. The probability of bat activity decreased with wind speed.

The predictions for offshore bat activity were generally associated with high levels of uncertainty due to the relatively small sample size. The data quality and type also introduced geographic biases, with raw data provided only for some areas, filtered recordings only from others, and both for a few. Most data from the Baltic, southern Kattegat, and Fehmarn Belt were pre-filtered with the software *Kaleidoscope*, without means to validate the automated processing. For two locations with raw data available, the software performance was tested, showing that *Kaleidoscope* often missed calls from *Eptesicus*, *Nyctalus*, and *Vespertilio*, especially in recordings with considerable background noise. This implies that bat activity in inner Danish waters is further underestimated and that activity differences between the North Sea and inner Danish waters are likely higher than estimated. Declines in activity with higher wind speeds may thus partly reflect call detection performance being affected by noise masking. The findings highlight the need to store raw data. With more and better data, activity could be analysed in finer detail, e.g. hourly, to model nocturnal patterns.

Bats are highly mobile, and population status cannot be managed at a small geographic scale or at the project level. The precision and value of comprehansive analyses of existing data from different surveys and projects are challenged by differences in data type and quality. To identify marine and coastal areas with high foraging and migration activity of bats and annual variation, a more systematic mapping of bats and a long-term monitoring program should be implemented at selected locations independent of individual wind turbine projects. High-quality, quantitative data can promote knowledge-based management to ensure coexistence between offshore wind energy production and adequate protection of bat populations.

1 Introduction

Transitioning from fossil energy to renewable energy sources is regarded as essential to tackle climate change, but the renewable energy production and associated landscape transformation may have severe environmental effects and increase the global biodiversity crisis (Gibson et al. 2017, Thaker et al. 2018, Bennun et al. 2021). Extensive development of wind energy production constitutes a significant conservation issue for bats (e.g. Arnett & Baerwald 2013, Voigt et al. 2015, 2022, Frick et al. 2017, Barré et al. 2022). Understanding habitat use and migration patterns for bats is a key factor for informed spatial planning to enable efficient wind energy production without significant impact on biodiversity and the conservation status of bat populations (Bennun et al. 2021, Friedenberg & Frick 2021, Voigt et al. 2024).

The Danish Energy Agency has initiated a screening of the sensitivity of nature, environmental, wind and hydrodynamic conditions to offshore wind development in Danish waters. The screening aims to find the most suitable sites for offshore wind energy production, considering many environmental parameters and guiding long-term planning efforts of offshore wind turbines. Brinkløv et al. (2025a) reviewed existing knowledge on offshore bat activity and produced an initial sensitivity map for bats in the Danish exclusive economic zone. The map was based on expert assessments informed by scientific literature (e.g. Ahlén et al. 2009, Kruszynski et al. 2020), reports from environmental impact assessments (EIAs) and preliminary reports from strategic assessments of proposed offshore wind development areas (e.g. FEBI 2013, Orbicon 2016, Seebens-Hoyer et al. 2021, COWI 2023, Brinkløv et al. 2024b, WSP 2024b). The review revealed major gaps and inconsistencies in survey effort, methodology, and reporting standards, hindering reliable comparisons and meta-analyses (Adams et al. 2012, Goodwin & Gillam 2021, Asmus et al. 2025). For details, see Brinkløv et al. (2025a).

This report revisits the sensitivity of bats to offshore wind turbine development in Danish waters. It presents an updated sensitivity map based on analysis of data from recent surveys with passive acoustic monitoring (PAM). The surveys were carried out in the project areas as part of strategic assessments of offshore wind farm development areas and life extension of existing offshore wind farms.

The amended European Renewable Energy Directive (EU Directive 2023/2413) targets that 45% of the EU's gross energy consumption must be covered by renewable energy in 2030. To accelerate the development of renewable energy projects, the EU has introduced the "Renewables Acceleration Areas (RAAs)", which are areas where the deployment of renewable energy projects is not expected to have significant environmental impacts (Directorate-General for Energy 2024). The screening project was initiated before the amendment of the European Renewable Energy Directive but the sensitivity maps for environmental parameters to offshore wind farm development may provide an important knowledge-based contribution for the designation of RAAs in the Danish waters.

1.1 Offshore bat activity

All bat species in temperate climates migrate between summer and winter habitats, and some European species embark on long-distance (500-2000 km) flights across Europe (Hutterer et al. 2005, Alcalde et al. 2021, Kruszynski et al. 2021, Merlet et al. 2025). Around Denmark, bats migrating offshore are known from the southern Baltic Sea and the North Sea (e.g. FEBI 2013, Petersen et al. 2014, Rydell et al. 2014, Bach et al. 2017, 2022). Every spring and autumn, relatively large numbers of bats migrate across the southern Baltic to and from their breeding habitats in eastern Denmark, on the Scandinavian Peninsula and further east (Ahlén et al. 2009, Seebens-Hoyer et al. 2021). There is no information on bat migration from Skagerrak, Kattegat and the Belts (see Brinkløv et al. 2025a).

Long-distance migratory species such as Nathusius' pipistrelle (*Pipistrellus nathusii*), common noctule (*Nyctalus noctula*), and parti-coloured bat (*Vespertilio murinus*) are the species most commonly recorded offshore in northern Europe (FEBI 2013, Petersen et al. 2014, Rydell et al. 2014, Ahlén et al. 2009, Seebens-Hoyer et al. 2021). Soprano pipistrelle (*Pipistrellus pygmaeus*), northern bat (*Eptesicus nilssonii*), common pipistrelle (*Pipistrellus pipistrellus*), serotine bat (*Eptesicus serotinus*), Leisler's bat (*Nyctalus leisleri*), and some *Myotis* species may also cross marine areas during their seasonal migration (Table 1.1) (Ahlén et al. 2009, FEBI 2013, Bach et al. 2017, Seebens-Hoyer et al. 2021).

Nathusius' pipistrelle, common noctule, parti-coloured bat, soprano pipistrelle and other species that fly and forage using the open airspace are the species most at risk for collisions with offshore wind turbines. However, all bat species occurring in northern Europe have been found dead under onshore wind turbines (EUROBATS 2023, Voigt et al. 2024).

Tabel 1.1. Bat species observed offshore in Denmark and their migratory behaviour, with their listing on the Habitats Directive (HD Annex) and current conservation status in the relevant biogeographic regions (European Environmental Agency 2025) for bat species occurring over marine waters in Denmark. A map of the biogeographic regions is available here: https://www.eea.europa.eu/en/analysis/maps-and-charts/biogeographical-regions-in-europe-2. ATL: Atlantic biogeographic region, CON: Continental biogeographic region, BOR: Boreal biogeographic region. FV: Favourable, U1: Unfavourable-Inadequate, U2: Unfavourable-Bad, XX: Unknown (EIONET 2025). Updated conservation assessments are expected to be published by the EU in the near future.

Scientific name	Common name	Migratory behaviour	HD Annex	EU conservation status		
				ATL	CON	BOR
Myotis dasycneme	Pond bat	Medium	II + IV	U1	U1	U1
Myotis daubentonii	Daubenton's bat	Short - Medium	IV	U1	U1	FV
Pipistrellus nathusii	Nathusius' pipistrelle	Long	IV	XX	U1	U1
Pipstrellus pygmaeus	Soprano pipistrelle	Short - Medium	IV	FV	U1	XX
Pipistrellus pipistrellus	Common pipistrelle	Short - Medium	IV	U1	U1	XX
Nyctalus leisleri	Leisler's bat	Long	IV	U1	U2	XX
Nyctalus noctula	Noctule	Long	IV	XX	U1	U1
Eptesicus nilsonii	Northern bat	Short - Medium	IV	XX	U1	FV
Eptesicus serotinus	Serotine	Short - Medium	IV	U1	U1	XX
Vespertilio murinus	Parti-coloured bat	Medium - Long	IV	XX	U1	FV
Plecotus auritus	Brown long-eared bat	Short	IV	U1	U1	FV

Migration periods vary with longitude (Roemer et al. 2017, Rydell et al. 2014, Seebens-Hoyer et al. 2021). In Denmark and surrounding waters, the spring migration period spans March into May, and autumn migration from mid-August through October. No long-term monitoring projects have been published to describe potential variations between years and factors causing variations in migration periods and peaks.

Bats are often assumed and documented to fly and migrate at low heights (e.g. below 30 m) on nights with wind speeds below 6 m/s (Ahlén 1997, Brabant et al. 2021, Seebens-Hoyer et al. 2021). Most of these observations of bats were based on direct observations or acoustic monitoring from ground or sea level, where high-flying bats would not be detected due to the quick attenuation of ultrasound in air (Voigt et al. 2021). Acoustic monitoring from masts and wind turbine nacelles, and radio- and GPS-tracking of noctules and Nathusius' pipistrelles have since, although in low sample sizes, documented bats commuting and migrating at height (Roemer et al. 2017, Brabant et al. 2019, Reusch et al. 2022, Lagerveld et al. 2024, Hurme et al. 2025). Bats may select flight altitudes of hundreds of meters during migration to utilise favourable wind directions and speeds (> 10 m/s tailwind) to achieve ground speeds twice their own flight speeds (Lagerveld et al. 2024, Hurme et al. 2025). Offshore bat activity is highest at nights with low wind speeds (below 6-8 m/s), but activity up to 15 m/s is recorded occasionally (Brabant et al. 2019, 2021, Lagerveld et al. 2021, Willmott et al. 2023, Brinkløv et al. 2024b).

Bats have been observed leaving coastlines at peninsulas and headlands like the pattern generally observed in migrating birds (Ahlén 1997). However, bat migration across the southern Baltic is broad-fronted (Seebens-Hoyer et al. 2021), i.e. bats do not fly in straight and well-defined routes between protruding points on the coastlines across belts and seas. Instead, commuting and migrating bats may meander and approach environmental or anthropogenic features (Goldshtein et al. 2024). Wind turbines or other structures offshore could thus serve as beacons for offshore bats, increasing the risk of collisions (Horn et al. 2010, Reusch et al. 2022).

Bats also forage over marine areas during the summer and during the migration periods, particularly over the Baltic Sea and the belts around the Danish archipelago, e.g. soprano pipistrelle, Nathusius' pipistrelles, Daubenton's bats, and noctules (Ahlén et al. 2009, FEBI 2013, Seebens-Hoyer et al. 2021, Brinkløv et al. 2025a). Bats may forage on migrating insects, insects blown offshore and possibly small crustaceans at the water surface (Ahlén et al. 2009). Offshore foraging by bats is not restricted to the migration periods (e.g. Solick & Newman 2021, Lagerveld & Mostert 2023). Bats may also forage at high altitudes offshore (Ahlén et al. 2009, Willmott et al. 2023).

1.2 Wind turbines and bat conservation

Wind turbines have been shown to increase mortality in bat populations. Bats are killed by direct collision with the moving blades or by rapid changes in air pressure near the blades that can damage the lungs and ears (Baerwald et al. 2008, Grodsky et al. 2011). Irrespective of the cause of death, wind turbine-related mortalities from onshore and offshore wind energy production represent an increasing threat to bat populations (Voigt & Kingston 2015, Frick et al. 2017, Barré et al. 2022). Due to methodological shortcomings with documenting bat fatalities and collisions offshore (e.g. carcass searches under the turbines), the risk from offshore wind energy is inferred from knowledge of bats and onshore wind turbines and limited observations from offshore wind turbines. There is bat activity around offshore structures, including wind turbines (Seebens-Hoyer et al. 2021, Brinkløv et al 2025b). Although no collisions were observed, studies with thermal cameras have documented bats flying closely around offshore wind turbines in operation, as observed on onshore wind turbines (Willmott et al. 2023). Until disproven, there is no reason to assume that bats behave differently at offshore and onshore wind turbines, and that bats are not killed at offshore wind turbines.

All bat species have relatively low reproductive rates and long lifetimes (e.g. Altringham 2011). These population dynamic traits make bat populations very sensitive to increased mortality rates and slow their ability to regain viable sizes after population declines. Thus, small changes in annual mortality rates may have a significant impact on the population status of bats (Voigt et al. 2024). Even though the average bat mortality per wind turbine may be low, the cumulative effect of wind turbines may significantly impact the conservation status of bats (Frick et al. 2017, Voigt et al. 2022, 2024). Modelling suggests that the cumulative effects of wind turbines threaten common bat species under all tested development scenarios for wind energy production, even if all wind turbines in the species' distribution range are operated with curtailments, that reduces the mortality by 48% (e.g. a cut-in speed at 5 m/s) compared to the mortality without curtailment (Friedenberg & Frick 2021). Potential spatial variations in mortality risk were not modelled, as it would necessitate explicit data on mortality rates from all parts of the range to include spatial differences in mortality in the population models reliably.

Onshore wind turbines may also cause a significant habitat loss and displacement of bats from suitable habitats, including foraging areas (Millon et al. 2018, Reusch et al. 2023, Leroux et al. 2023, 2024). The exact reasons for the displacement and its relevance in the context of bats offshore are unknown.

1.3 Aim

In recent years, bat surveys offshore in relation to wind farm developments have shifted to a more data-based approach with passive acoustic monitoring in the project area and adjacent waters and coastlines. The present study aims to analyse available data from PAM-surveys in marine areas in the Danish exclusive economic zone.

The goal of the data-based approach is to detail and substantiate the expert-based sensitivity map for bats presented by Brinkløv et al. (2025a) to the extent permitted by the quality and amount of data provided and to give recommendations on how to improve the map further.

2 Methods

We collected existing data and metadata from recent bat surveys offshore from the developers and their consultants (Table 2.1, Figure 2.1). Energinet provided data from the strategic bat surveys from Energy Island North Sea (Brinkløv & Elmeros 2024), Energy Island Bornholm (WSP 2025), the projected North Sea I (Brinkløv et al. 2024, 2025b), and Baltic Sea wind farm areas, including Kattegat, Hesselø, and Kriegers Flak II (WSP 2024b, c, d). Data were also collected from the Energy Agency project in Kriegers Flak I (WSP 2024a), EIA surveys for the Aflandshage project in Øresund (HOFOR, unpubl.), lifeextension of Horns Rev I (Vattenfall AB, unpubl.) and Rødsand I, Fehmarn Belt (Ørsted Wind Power A/S, unpubl.), and a private collection of bat data by Vattenfall in the northern Kattegat (Bjarke Laubek, unpubl.).

Tabel 2.1. Overview of data from bat surveys included in the analyses of offshore bat activity. WT: Wind turbine, WA: Wildlife Acoustics, DC: Duty Cycle. For 'armed' recordings, the detectors were active from sunset to sunrise and were triggered to be saved if ultrasound, i.e. bat calls or noise, was detected above a certain threshold setting. Recorders using a known duty cycling made 5-second recordings followed by a 10-second inactive period from sunset to sunrise, whether bats were present or not within the recorder detection range. Data type: raw means all audio recorded was made available, filtered means only audio considered bat calls by *Kaleidoscope* was made available, mixed means that raw data were available from some detectors and only filtered data from other detectors in the location.

Marine area and location	Station types	Overall survey period	Recorder / microphone	Recording schedule	Data type
North Sea					
Energy Island North Sea	Buoys	Autumn 2022 & Spring 2023	WA SM4BAT FS / SMM-U2	Armed sunset to sunrise	Raw
North Sea I	Buoys	Apr 2023 – Apr 2025	WA SM4BAT FS / SMM-U2	Armed sunset to sunrise	Raw
Horns Rev I	WT	Apr-Nov 2024	SeaBat / n/a	DC (5s on/10s off)	Raw
Horns Rev III*	WT, platform	Apr 2023 – Apr 2025	WA SM4BAT FS / SMM-U2	Armed sunset to sunrise	Raw
Northern Kattegat					
Hirsholmene and Læsø	Buoys	Sep – Nov 2021, Apr 2023 – Nov 2023	WA SM4BAT FS / SMM-U2, SeaBat / n/a	Armed sunset to sunrise / DC (cycle unknown)	Mixed raw and filtered
Southern Kattegat					
Anholt	Buoys	Apr 2023 – Nov 2024	SeaBat / n/a, WA SM4BAT FS / SMM-U2	DC (cycle unknown) / Armed sunset to sunrise	Mixed raw and filtered
Kattegat	Buoys	Apr 2023 – Apr 2025	SeaBat / n/a	DC (5s on/10s off)	Filtered
Hesselø	Buoys	Apr 2023 – Apr 2025	SeaBat / n/a	DC (5s on/10s off)	Filtered
Belts and western Baltic Sea					
Aflandshage, Øresund	Buoys	Aug 2023 – Dec 2024	WA SM4BAT FS / SMM-U2	Armed sunset to sunrise	Raw
Kriegers Flak I	WT	Aug 2022 – Dec 2024	SeaBat / n/a	DC (5s on/10s off)	Filtered (raw autumn 2024)
Kriegers Flak II	Buoys	Apr 2023 – Apr 2025	SeaBat / n/a	DC (5s on/10s off)	Filtered
Fehmarn Belt	WT	Aug – Oct 2024	SeaBat / n/a	DC (5s on/10s off)	Filtered
Eastern Baltic Sea					
Energy Island Bornholm	Buoys	Mar 2022 – Oct 2023	SeaBat / n/a	DC (5s on/10s off)	Filtered

*Part of the North Sea I survey

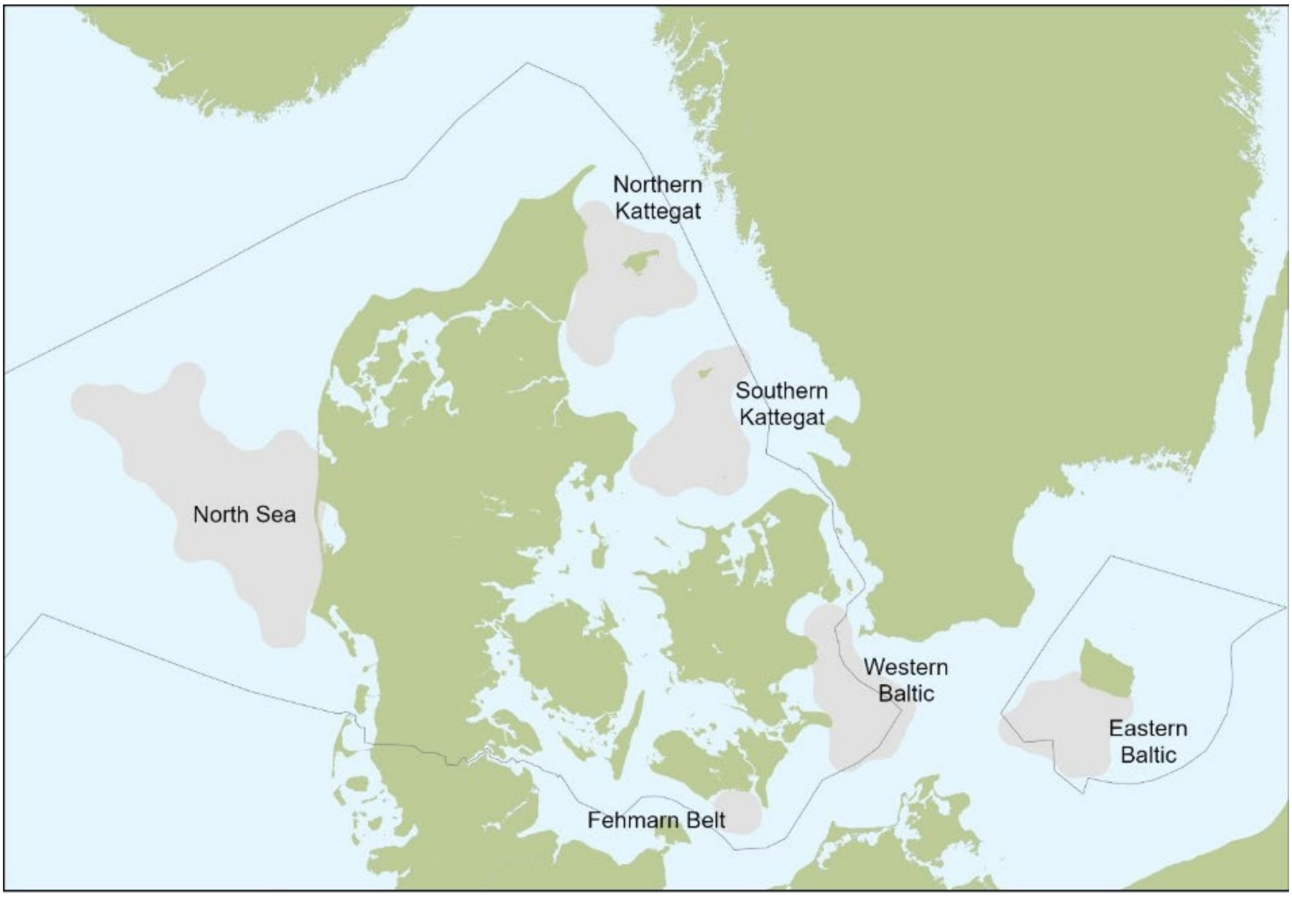


Figure 2.1. Overview of areas included in the study. Monitoring data were obtained from six marine areas (grey) for the modelling of offshore bat activity in the Danish exclusive economic zone (grey line). The areas are indicated as a 10 km buffer around the actual detector site(s). It should be noted that the detection range of individual recorders is less than ca. 100 meters, depending on the species and weather conditions, meaning that much of an area is not actually monitored even if multiple detectors are included.

The general methodology (recorder types, schedule, duty-cycled or triggered activation of data storage, microphone sensitivity check, and data processing) and the type and quality of the data that were available for our analyses differed between projects. See Brinkløv et al. (2024a) for further presentation of the challenges and limitations in comparing acoustic monitoring data sampled using different methods.

We obtained raw data, i.e. all recordings, only from some projects (Energy Island North Sea, North Sea I, Aflandshage, select deployments in northern Kattegat and the 2024 autumn-surveys in Kriegers Flak I and Horns Rev I). Only pre-processed data were available from the other projects and periods (Table 2.1). The latter had been screened for bat calls by commercial software (*Kaleidocope*, Wildlife Acoustics), and only sound files identified as bats by the software were supplied, without the possibility to re-process the raw data. Consequently, there was no way to verify the performance of the software for these deployments, which may misclassify noise detections as bat calls or vice versa and misidentify species. Such verification is essential for all use of automated software for identification and classification (Russo & Voigt 2016, Rydell et al. 2017, Goodwin & Gillam 2021, Asmus et al. 2025).

We grouped data from different projects into six geographical areas: the North Sea, northern Kattegat, southern Kattegat, Fehmarn Belt, western Baltic and eastern Baltic (Figure 2.1).

2.1 Data curation

To standardise the data analysed for the project as much as possible, we curated them according to the same criteria used for the North Sea I offshore baseline surveys for bats (Brinkløv et al. 2025b). Data from this project were therefore included without further curation. Data from Horns Rev I, Kriegers Flak I and the first year of data from Kriegers Flak II had already been curated in the same manner for reanalyses in Brinkløv et al. (2025c). All other data were curated according to the following steps:

1. We excluded recordings from before or on the reported deployment date and from on or after the reported retrieval date.

2. We played back recordings from the first and last day(s) of each deployment at each station and excluded any with clear deck noise, music or speech, indicating the recorder was not at the station. We also excluded dates where we could hear clear deck noise, music or speech on another recorder that was put out during the same servicing trip, unless the metadata clearly stated different deployment dates.

3. If we could hear or deduce, from manual review of the sound recordings and spectrograms, that the microphone was broken in any of the recordings, we listened to a subset of recordings throughout the deployment period and excluded periods of consistent microphone failure.

4. The last night of each deployment was excluded, since these nights were often incomplete (e.g. if a recorder ran out of battery during the night), and only full nights of survey effort were included in the statistical analysis.

2.2 Retraining and validation of detection software

To detect bat calls, we used *Animal Spot* (Bergler et al. 2022), a convolutional neural network optimised to detect and classify animal vocalisations. To make sure the model performed well on the offshore data, we retrained the model from Brinkløv et al. (2025c) on a subset of all included deployments by including two randomly selected recordings per deployment. For data where *Kaleidoscope* output was available, these were supplemented with two randomly selected recordings output *by Kaleidoscope* as containing bat calls and manually verified as such by the external consultant, plus two randomly selected recordings output by *Kaleidoscope* as containing bat calls but manually refuted as such by the external consultant. The training set contained 953 recordings in total, including 273 from the island of Bornholm (collected as part of the dataset for Energy Island Bornholm). The latter were included to boost the training dataset but were not included in the validation set or used for the statistical models, as the high bat activity on Bornholm would potentially mask the resulting offshore patterns. Since Bornholm has resident populations for multiple species, most nights would be expected to have active bats, whereas this wouldn't be the case in any of the offshore locations or smaller islands without resident populations.

For all recordings, we annotated one or multiple noise examples and, if available, also one or multiple bat call examples. This resulted in 5,712 noise examples and 2,780 bat call examples. To make the model more robust, we added 3,399 noise examples based on detections from the model used in Brinkløv et al. (2025c), where the model predicted a bat call that was refuted manually by an observer (false positive). All bat call and noise examples were extracted from the audio recordings as small wave files.

We trained several versions of *Animal Spot* and used an early version of the model to generate more training data by running the model on parts of four different deployments and using 633 noise examples where the model predicted a bat call, that was refuted manually by an observer (false positive). The final model was retrained from the model used in Brinkløv et al. (2025c). Data were split into 70% training data, 15% validation data and 15% test data, where all examples originating from the same recording were used for the same set (as either training, validation or test data). The model achieved 98% accuracy on both the validation and test sets.

The accuracy obtained from the training of *Animal Spot* represents how well the model performs on the examples chosen by an observer. For the full dataset, the model makes predictions on entire recordings using a sliding window. To validate the model performance, we randomly selected one recording per deployment. We supplemented this (if available) with one randomly selected recording output *by Kaleidoscope* as containing bat calls and manually verified as such by the external consultant, plus one randomly selected recording output by *Kaleidoscope* as containing bat calls but manually refuted as such by the external consultant. This resulted in a set of 432 recordings. We manually selected and annotated each detectable bat call in all recordings. Social calls, approach calls and feeding buzzes were excluded from validation, because the main interest was the most species characteristic search phase call. To validate performance, we ran the final model on the set of validated recordings and computed the precision (the proportion of actual bat call detections) and recall (the proportion of the manually annotated bat calls detected by the model). We excluded any calls that were within 20 ms of each other, since these are merged into a single detection by *Animal Spot*, leading to one call being considered 'missed'. However, both calls would still be included in the model output. The model achieved a precision of 93% and a recall of 88% and predicted at least one detection for every single recording that contained bat calls.

2.3 Validation of Kaleidoscope and further validation of Animal Spot

For most of the locations, *Kaleidoscope* had been used to discard sound files that, according to the software, contained only noise before we received the data for analysis. For these locations, it was not possible to reanalyse all recordings with *Animal Spot*. To test how big an effect these discarded data had on the number of nights with bats detected, we validated both models. This would normally involve creating a validation set consisting of randomly chosen files to quantify the detection performance. For offshore recordings, this is often not feasible, as the number of recordings with noise is several magnitudes greater than the number of recordings with bat calls. Like the proverbial needle-in-a-haystack, this makes it virtually impossible to create a random set with enough recordings of bat calls. The upside to the scarcity of recordings with bat calls is that all detections can be manually classified.

To quantify the relative performance of *Kaleidoscope* and *Animal Spot*, we compared their performance on the raw data from six deployments. Two of the deployments were from the transition piece, and two from the nacelle of different wind turbines in Kriegers Flak I during the fall of 2024 using SeaBat recorders (a modified version of Audiomoth – Open Acoustics Devices). The last two deployments were from buoys in the North Sea I during the fall of 2024 using SM4BAT recorders (Wildlife Acoustics). These locations and station types were chosen to represent the species and recording types most common in the current dataset. *Animal Spot* was run on all data, and detections were considered bat calls if given a confidence score (a value produced by Animal Spot to indicate the confidence in the prediction) above 0.5 by the model. All detections were manually annotated. *Kaleidoscope* was also run on all data with default settings with the Bats of Europe classifier (version 5.7.0), including only Danish species. All detections (including NoID, in other words files where the software detected bat calls but couldn't classify them) were manually annotated. We then created a confusion matrix to compare the performance of *Animal Spot* and *Kaleidoscope* for: 1) all deployments, 2) transition piece only, 3) nacelle only and 4) buoy only.

2.4 Reanalysis of audio data

We uploaded all recordings in the curated dataset to Aarhus University's server, ERDA, and ran a script to index the files. The script recorded the location and the duration of the recordings and tested if they were corrupted or contained only zeroes. The output was written to an SQLite database. All functional recordings with a duration greater than zero were then processed on the remote supercomputer LUMI, using the validated *Animal Spot* model. The model predicted if a bat call was present for each 20-ms segment of each recording, with 10-ms segment overlap (e.g. first segment: 0-20 ms, second segment: 10-30 ms, third segment: 20-40 ms). If the model predicted a bat call to be present with a probability above 0.5, the segment was considered a bat call detection. If consecutive segments were considered a bat call detection, they were merged into a single detection. All detections were stored in the database.

For each detection, we created a small audio clip (wave file) containing the detection plus a 10-ms buffer before and after the detection. All these wave files were manually inspected, and all false positives (detections that did not contain a bat call) were removed. All original recordings (11,869 files) with at least one bat call detection were then manually annotated to the following categories: Brown long-eared bat, Nathusius´ pipistrelle, common pipistrelle, soprano pipistrelle, and two species complexes, both including multiple species: *Myotis sp*. (including all relevant *Myotis* species) and ENV (including bats in the genera *Eptesicus*, *Nyctalus* and *Vespertilio*: serotine bat, northern bat, common noctule, Leisler's bat and parti-coloured bat). The ENV and Myotis species complexes were used because the species within could not reliably be distinguished acoustically in a large proportion of the recordings. The species in the ENV complex also have relatively similar flight and hunting behaviours in relation to flight height and hence, similar risk to wind turbine collisions (Schnitzler & Kalko 2001, Denzinger & Schnitzler 2013, EUROBATS 2023). If classification into these categories was not possible, the file was annotated as Chiro sp. These annotations were then added to the database.

2.5 Statistical analysis

We chose to use a binary variable (present/absent) as a proxy for bat activity per night since other representations suffer too much from zero-inflation. Normally, this zero-inflation can be modelled, but due to the missing raw data and metadata, this was not possible. Activity was modelled for bats in general, and for the ENV species complex, the Nathusius´ pipistrelle and the soprano pipistrelle. For the other categories, we did not have enough observations for separate analyses. For locations with raw data, we used the first and last date with recordings as start and end dates for the period modelled. For locations with data filtered by *Kaleidoscope*, we used the first and last date with recordings listed in the id.csv *Kaleidoscope* output file, while following the same criteria for inclusion as in the data curation step (section 2.1).

Weather data were obtained from the ERA5 dataset provided by Copernicus Climate Data Store (https://cds.climate.copernicus.eu/), which is based on reanalysis of satellite and in situ sensor observations. The following meteorological variables were included in the analysis:

- Air temperature at two meters above ground level, converted from Kelvin to degrees Celsius.
- Wind speed (in m/s) at 10 meters above ground level, derived from the eastward and northward wind components.
- Wind direction (in degrees), calculated from the same components used to determine wind speed.
- Precipitation (in mm).

Weather data were retrieved for all locations and dates corresponding to available audio recordings. Weather values were extracted at the time of sunset for each location and date. Sunset was extracted using the function *getSunlightTimes* from the R package *suncalc* (Benoit et al. 2022).

Distance to coast was included as a predictor by calculating the Euclidean distance between each station and the nearest coastal point. This was done using the function st*_distance* from the R package *sf* (v.1.0-19, Pebesma & Bivand, 2023), in combination with coastal data obtained via the function *ne_coastline* from the R package *rnaturalearth* (v.1.0.1, Massicotte & South, 2023).

Other variables included in the analysis were: area (the marine area of deployment, Table 2.1), location (the specific planned or established offshore windfarm, Table 2.1), station, deployment (unique deployment for that station), station type (buoy, transition piece, nacelle, island, bank, mast or light house) and season (spring, summer and fall were defined as follows: spring 01.03. - 15.05, summer 16.05. – 15.08. and fall 16.08. – 31.10). We only included data from the 1st of March to the 31st of October in the analysis, since no or very little activity occurred during winter.

All analyses were performed in R (R Core Team 2021, version 4.1.2). To assess the probability of bat activity per night in the six offshore areas, we fitted several generalised additive mixed models (GAMMs) with a binomial error distribution and logit link function. GAMMs allow for the inclusion of smooth terms, which can be used to model parameters such as date, where multiple peaks of bat activity can be expected (e.g. spring and fall migration). K-values for smooth functions were set to model defaults. The models were implemented with the function *bam* from the R package *mgcv* (Wood 2017), using the function *fREML* for parameter estimation and discrete approximation for efficient computing of large datasets. Model adequacy was assessed via residual and k-index diagnostics, overdispersion and zero inflation testing using the R packages *gratia* (Simpson 2024, version 0.10.0) and *DHARMa* (Hartig F 2024, version 0.4.7). Effects were reported as odds ratios, which quantify how a predictor changes the odds of bat activity (i.e. the probability that there is bat activity rather than none). An odds ratio of one indicates no effect, below one that the predictor decreases the odds of bat activity and above one that the predictor increases the odds.

2.5.1 Seasonal patterns

In the first model, we assessed the probability for bat activity across days of the year for each area, with the bat presence per night as the response variable (present/absent). We included area and an interaction between area and the distance to the coast as fixed factors and an area-specific cyclical smooth term for the day of the year, represented as Julian calendar day (1-366). Since we only included data from spring to fall, we added a knot-range specifier for Julian day from 1 to 366, as an indicator for the beginning and end of the cycle. To account for random variation between days, according to weather conditions or year, we added a random effect of the calendar date (unique for each year, which is different from the Julian calendar day). Additionally, we included random effects of the station type within an area, as well as the deployment nested within station, nested within location. The model was repeated with the bat activity including only one of the three species clusters (i.e. the ENV species, Nathusius´ pipistrelle and soprano pipistrelle). Predictions for the effects of Julian calendar day were made at a fixed distance to the coast of 10 km, excluding random effects. K-checks indicated that k for the Julian day smooth had to be increased for both the model across species and for Nathusius´ pipistrelle to 12, and for soprano pipistrelle to 20. K is the parameter in the model that determines how wiggly the fit can be, and higher k indicates more day-to-day variation.

2.5.2 Seasonal area estimates and effect of distance to coast

In the second model, we assessed the probability for bat activity per season (spring, summer, fall) and the effect of the distance to the coast. The response variable was bat presence per night, and the fixed factors were the area, the season, an interaction of area and distance to the coast and an interaction between the area and season. Random effects were the same as described for the first model (see section 2.5.1). The model was repeated with the bat activity, including only one of the three species clusters at a time. Predictions for seasonal area estimates were made at a fixed distance to the coast of 10 km, excluding random effects.

Given the availability of filtered versus raw data and different equipment use, we decided to update the sensitivity map based on analysis of data solely from the locations Aflandshage and North Sea I. These were not pre-filtered and were recorded using similar PAM equipment and similar settings from buoys at both locations, enabling a direct comparison. For the model, we used the same formula as for the seasonal area estimates described above, but excluded station type as a random factor, as all data were from buoys. Predictions were based on the season with the highest overall bat activity (i.e. fall). The modelled bat activity in Aflandshage was higher than for the North Sea I, so we used the minimum predicted probability in Aflandshage with respect to distance, as well as its lower and upper CI, as a baseline for the high sensitivity category. We then assessed at which distance to the coast at the North Sea I location the probability for bat activity would drop below 10% of the high sensitivity area (defined as medium sensitivity) and below 1% (defined as low sensitivity), by solving for inverse prediction using the base R function *uniroot*. This is in line with the reasoning of the initial sensitivity map, where categories were also relative (but based on expert assessment of all offshore areas). The choice of 10% and 1% is based on the reasoning that a decrease of one order of magnitude represents a change big enough to warrant a new sensitivity category.

2.5.3 Effect of weather

To assess the weather effects of temperature, wind speed, precipitation, and wind direction, we selected data from the three areas with the best data coverage across seasons. Specifically, we assessed bat activity in the North Sea during fall, and in the southern Kattegat and western Baltic Sea during spring and fall. Spring was not included for the North Sea, because almost no activity was recorded. In the GAMMs, the response variable was bat presence per night. Distance to coast, wind speed and precipitation were included as linear effects, station type as a fixed effect, temperature as a smooth term, and wind direction as a cyclic smooth. To capture unexplained daily and spatial variation, we included a random effect of calendar day and a random effect of deployment nested within station nested within location. Predictions for each weather variable were made at a fixed distance to the coast of 10 km, and the effects of wind direction and random effects were excluded. Other variables were fixed at commonly observed values, with temperature fixed according to the respective season (wind speed = 3 m/s, precipitation = 0, fall: temperature = 18 C°, spring: temperature = 10 C°).

2.5.4 Effect of recording height

We assessed the impact of the recorder position (height) on the wind turbine on bat activity. For this model, we selected the activity of the ENV species at the location Kriegers Flak I during the fall at the height of the nacelle (ca. 100 m above sea level) and of the transition piece (ca. 10 m above sea level). Kriegers Flak I was the only location with data from nacelle height, and the ENV was the only species category occurring at this height. The response variable was the ENV species complex presence at night, the fixed factor was recorder position (nacelle versus transition piece), and random factors included the calendar date and deployment nested within station. Predictions for the effect of recording position were made by excluding random effects.

2.5.5 Yearly variation

Lastly, we assessed the impact of yearly variation on bat activity. We selected four locations (i.e. North Sea I, Kattegat II, Kriegers Flak II, and southern Hesselø) where we had data of similar coverage across two years (2023 and 2024). The response variable was bat presence per night, fixed factors were the location and year and their interaction, as well as an interaction between distance to the coast and location. To account for seasonal variation, we included a random smooth of Julian day per location. Random factors included the deployment nested within the station. Predictions for the effect of yearly variation were made at a fixed distance to the coast of 10 km and excluding random effects. Post-hoc comparisons for interactions were performed on estimated marginal means using the R package *emmeans* (v.1.11.2-8, Russel et al. 2025).

3 Results

3.1 Data coverage

The prospected or existing wind farm areas included 2-23 (median = 10) PAM stations (Table 3.1). The number of recordings obtained for this study varied a lot between locations, with only 859 recordings for North Sea Energy Island and ca. 2.5 million for North Sea I. There was a large discrepancy between the number of nights reported as covered and the number of nights that could be included in the study for Energy Island Bornholm, Hesselø/Kattegat island-based, Hesselø, Horns Rev I, Kriegers Flak I, Kriegers Flak II, Kattegat and Fehmarn Belt. The main reason for excluding nights from the study was recorders running out of battery, recorders failing or having settings resulting in no recordings triggered, or microphones failing (recording audio files but either without audio or with loud static noise that would mask bat activity).

Table 3.1. Overview of the data reported, available and included in the analysis for each location. N stations is the number of unique stations (detector sites) deployed. Wind turbine transition piece and nacelle deployments were considered the same station. N deployments is the number of deployments across stations. This might be less than the number of stations if all stations were deployed during the same deployment, or greater than the number of stations, if multiple stations have been deployed multiple times during different deployments. N recordings is the number of functional (not corrupted or all zero) recordings included in the analysis. N nights reported is the cumulative number of nights across stations (e.g. counting a night twice if two stations were reported active) that were either reported in a published report or in the supplied metadata. This number is missing for ongoing projects without intermediate reports. N nights audio is the cumulative number of nights for which we had functional recordings. N nights modelled is the cumulative number of nights that were included in the model. This number can be higher in the case of recordings deleted by *Kaleidoscope* or lower because we removed the last night of recordings for each deployment. Numbers in parentheses represent the number of nights for the first year of the project if a project only had a preliminary report published.

Location	N stations	N deployments	N recordings	N nights reported	N nights audio	N nights modelled
Aflandshage	10	8	28,559	-	2,034	2,190
Anholt	4	4	32,970	-	399	560
Energy Island Bornholm	15	4	40,769	6,420*	935	2,675
Hirsholmene JDM	2	2	97,714	112	96	93
Hesselø/ island	2	4	7,146	- (462)	445 (247)	539 (299)
Hesselø	6	5	1,630	- (794)	297 (95)	1,472 (428)
Horns Rev I	10	2	732,730	1,903	467	1,479
Horns Rev III	16	23	677,063	668	668	668
Kriegers Flak I	15	5	2,423,682	4,759	1,360	3,807
Kriegers Flak II	16	5	9,041	- (2,746)	888	5,430
Kattegat	8	5	4,720	- (1,067)	227 (113)	1,727 (742)
Læsø	5	3	832,957	-	415	482
Fehmarn Belt	10	1	52,405	940	528	569
North Sea Energy Island	9	2	859	600	177	600
North Sea I	23	11	2,531,706	4,786	4,786	4,786

*For this location, it was reported that technical failures occurred in 2022, without specifying how many recording nights were lost and for how many detectors.

3.2 Validation of Kaleidoscope and further validation of Animal Spot

During the validation, *Kaleidoscope* found 33 recordings with bat calls. In contrast, *Animal Spot* found 64, including all recordings found by *Kaleidoscope* (Figure 3.1). *Kaleidoscope* missed about half of the recordings with ENV species, found most of the recordings with Nathusius´ pipistrelle, and missed most of the recordings with soprano pipistrelle, compared to *Animal Spot*. All but one of the missed recordings containing soprano pipistrelle calls were from the same night, which was windy and had considerable noise from turbine blades passing the microphone at transition piece height. Overall, most misses from *Kaleidoscope* were from recordings made from the transition piece (22 misses out of 32 recordings with bats) and the nacelle (six misses out of six recordings with bats). In comparison, *Kaleidoscope* performed better for buoy recordings (three misses out of 25 recordings with bats).

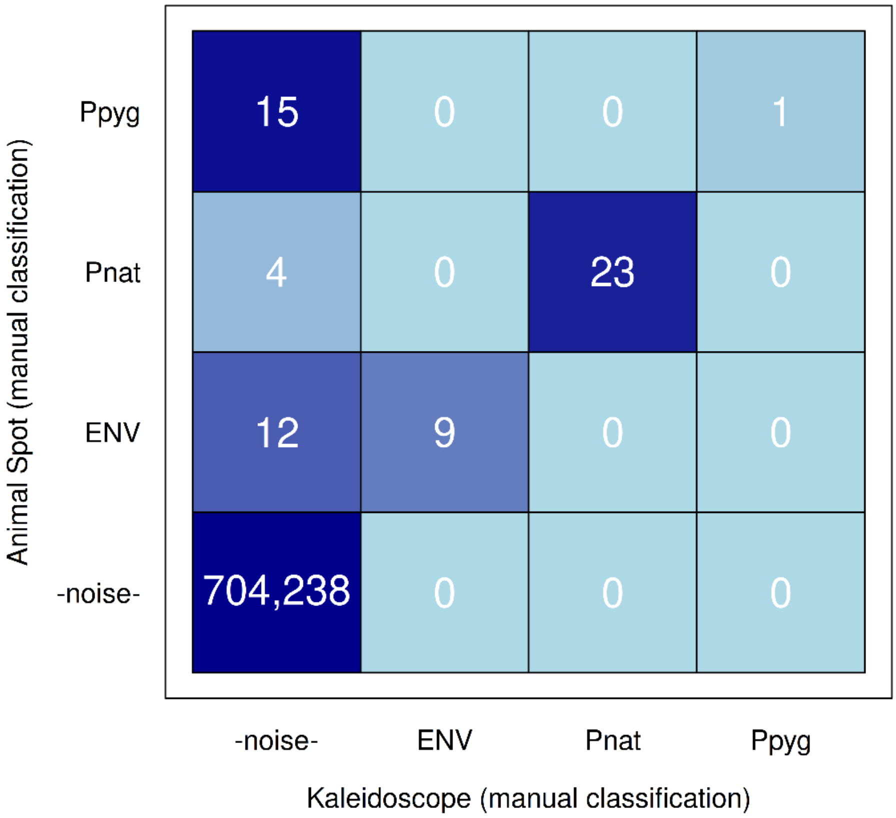


Figure 3.1. Confusion matrix of predictions made by *Animal Spot* and *Kaleidoscope*. Labels on the x-axis represent the predictions made by *Kaleidoscope* with manual classification. Labels on the y-axis represent predictions made by *Animal Spot* after manual classification. Ppyg = soprano pipistrelle *(Pipistrellus pygmaeus)*, Pnat = Nathusius´ pipistrelle (*Pipistrellus nathusii)*, ENV = the species complex of *Eptescicus, Nyctalus and Vespertilio* species. Numbers in the matrix represent the number of files for which a combination of predictions is made. For example, in the top left corner *Animal Spot* predicted Ppyg for 15 files where *Kaleidoscope* predicted noise. In total (summing across rows), *Animal Spot* found 16 recordings of Ppyg, 27 of Pnat, 21 of ENV, and the remaining 704,238 recordings were predicted to contain only noise. Colour indicates the percentage of recordings in the cell out of all recordings in the row, ranging from dark blue = 100% to light blue = 0%.

3.3 Seasonal patterns

Most areas showed a distinct peak in overall bat activity during both spring and fall migration (Figure 3.2). The peak in activity was always more pronounced during fall migration season. The relative magnitude of the spring migration peak varied strongly between areas, with very little spring activity for the North Sea and quite high spring activity for southern Kattegat, although the latter is associated with high uncertainty. In the North Sea, where data was collected up to 125 km from the coast, the effect of distance to coast contributed more to estimated probabilities of bat activity than in the other areas. As a result, the probabilities shown in Figure 3.2, which are based on a fixed distance to the coast of 10 km, are higher for the North Sea than averages of raw data might suggest. The predictions were made at 10 km, to make them more comparable across all areas.

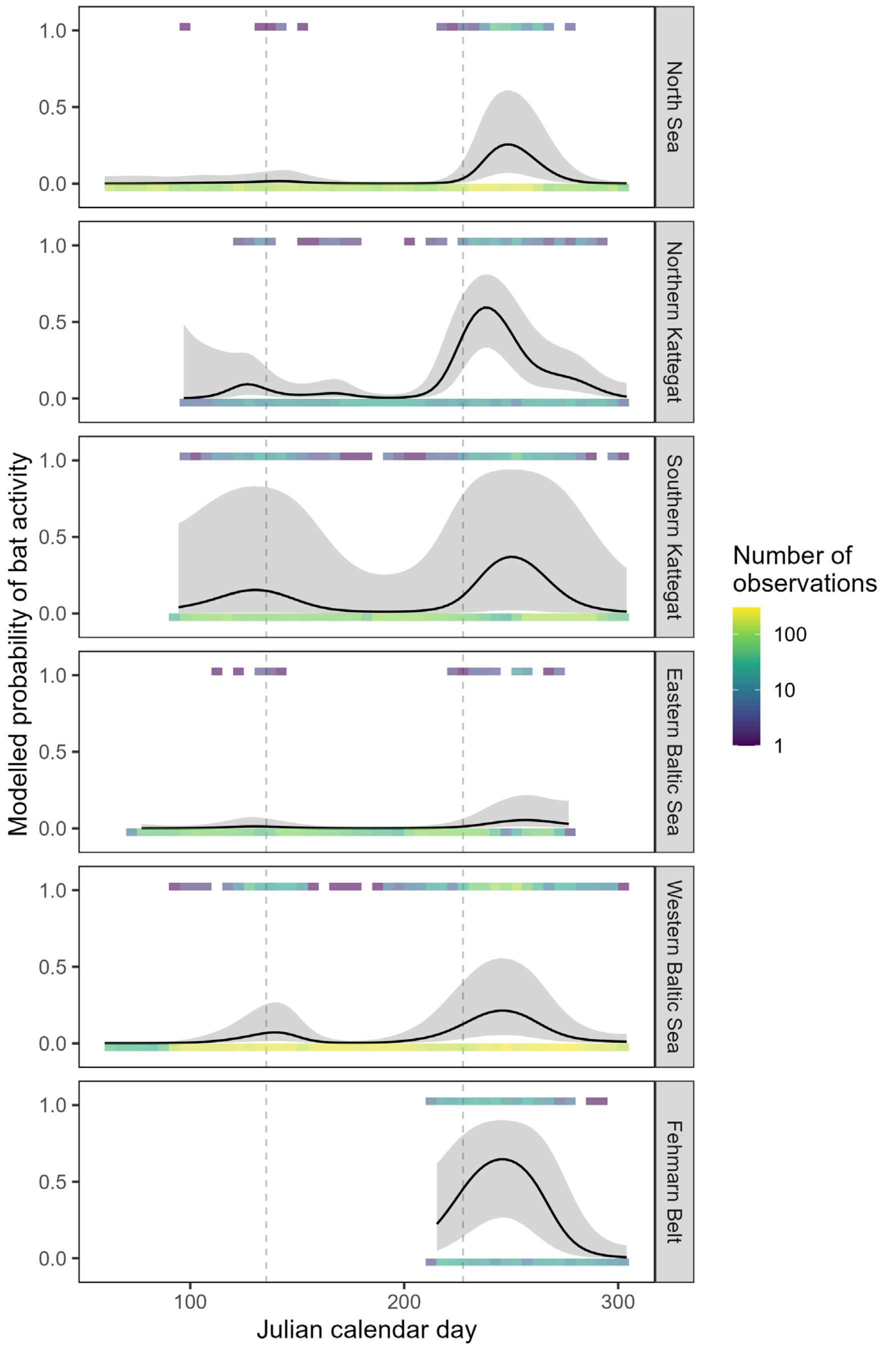


Figure 3.2. Seasonal patterns in overall bat activity. Modelled probability of bat activity (y-axis) across Julian calendar day (x-axis) for all areas (sub-plots). Black lines show the model average; grey areas show the 95% confidence interval. Coloured bars above and below the plots show the observed values summarised as the number of observations per five days (bars above: present = 1, bars below: absent = 0). Grey dashed lines represent the dates separating the seasons used in the model estimating seasonal averages for each area (i.e. 15.05 and 15.08).

Compared to the plots of overall bat activity over the year, the activity of the ENV species was more limited to fall, with the highest peaks predicted for northern Kattegat and Fehmarn Belt. Southern Kattegat and western Baltic Sea retained small activity peaks in spring (Figure 3.3).

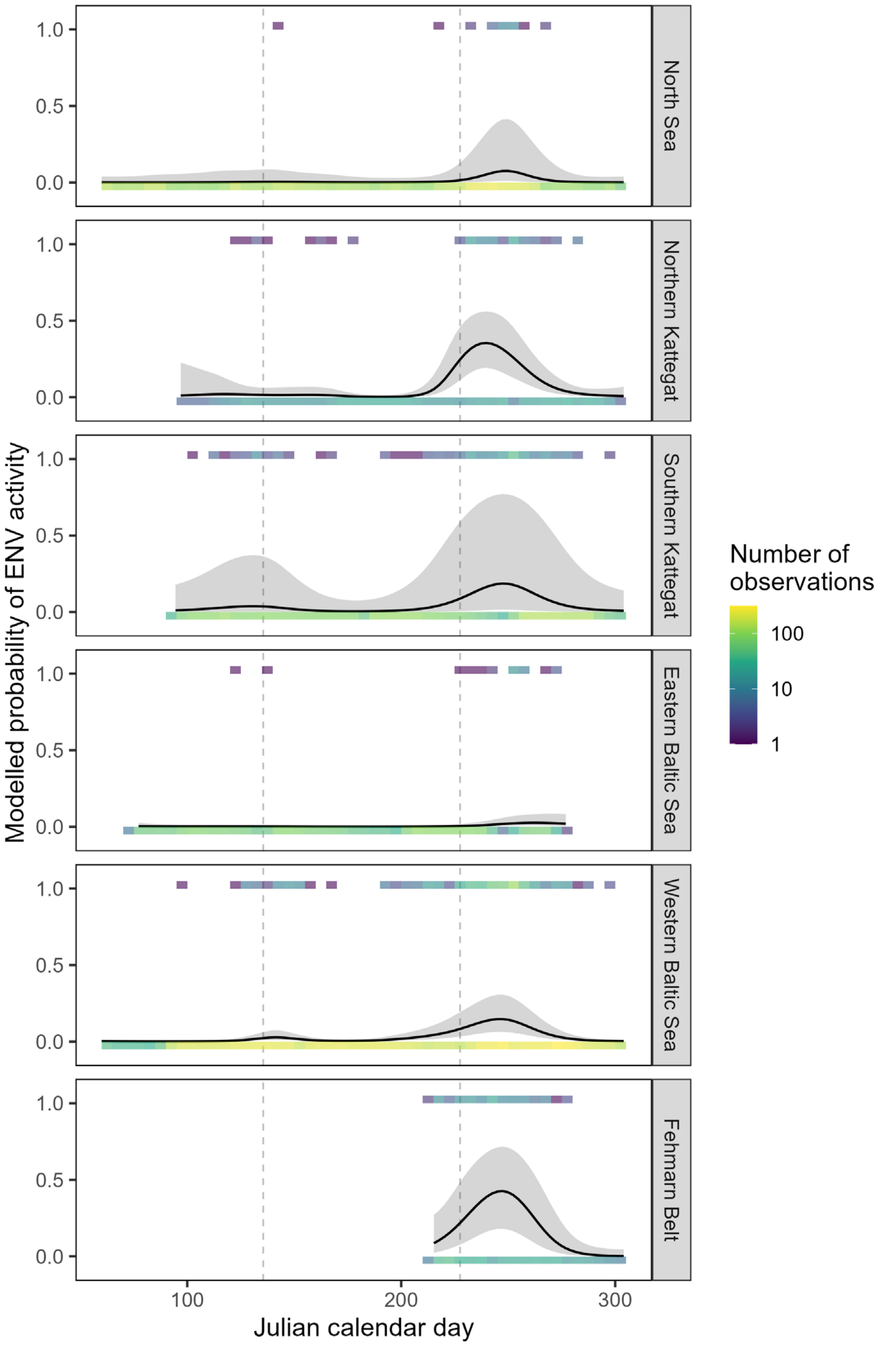
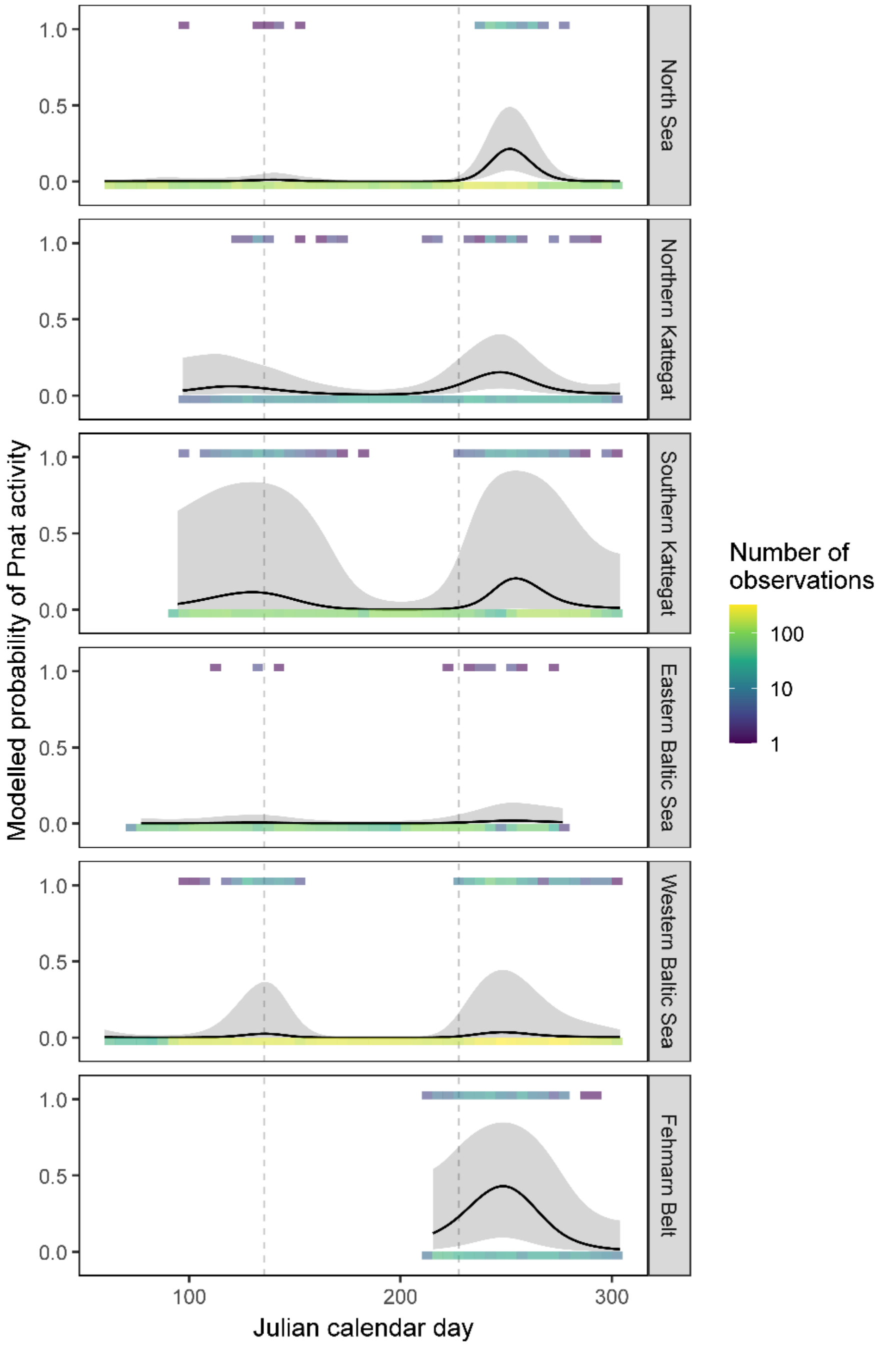


Figure 3.3. Seasonal patterns in activity of bats in the Eptecicus, Nyctalus and Vespertilio (ENV) species complex. Modelled probability of ENV activity (y-axis) across Julian calendar day (x-axis) for all areas (subplots). Black lines show the model average; grey areas show the 95% confidence interval. Coloured bars above and below the plots show the observed values summarised as number of observations per five days (bars above: present = 1, bars below: absent = 0). Grey dashed lines represent the dates separating the seasons used in the model estimating seasonal averages for each area (i.e. 15.05 and 15.08).

The activity of Nathusius' pipistrelle largely followed the patterns of overall bat activity. However, activity was lower across all areas except the North Sea, where activity of Nathusius' pipistrelle during fall was higher relative to most other areas (Figure 3.4). When comparing the overall activity plot (Figure 3.2) and the activity plots of species or species complex (Figures 3.3-3.5) it is evident that most of the overall activity from the North Sea is contributed by Nathusius' pipistrelle. In contrast, overall activity in other areas is contributed either predominantly by ENV species or more evenly by both Nathusius' pipistrelle and ENV species.

Figure 3.4. Seasonal patterns in the activity of Nathusius' pipistrelle. Modelled probability of Nathusius pipistrelle (*Pipistrellus nathusii)* activity (y-axis) across Julian calendar day (x-axis) for all areas (sub-plots). Black lines show the model average; grey areas show the 95% confidence interval. Coloured bars above and below the plots show the observed values summarised as the number of observations per five days (bars above: present = 1, bars below: absent = 0). Grey dashed lines represent the dates separating the seasons used in the model estimating seasonal averages for each area (i.e. 15.05 and 15.08).



The activity of soprano pipistrelles also largely followed the patterns of overall bat activity (Figure 3.5) but was generally low compared to the activity of Nathusius' pipistrelle and ENV species (Figures 3.3 and 3.4). For the western Baltic Sea, however, soprano pipistrelles contributed more to the overall bat activity, and the GAM model resulted in a fall activity peak that occurred noticeably earlier than the corresponding ENV species peak.

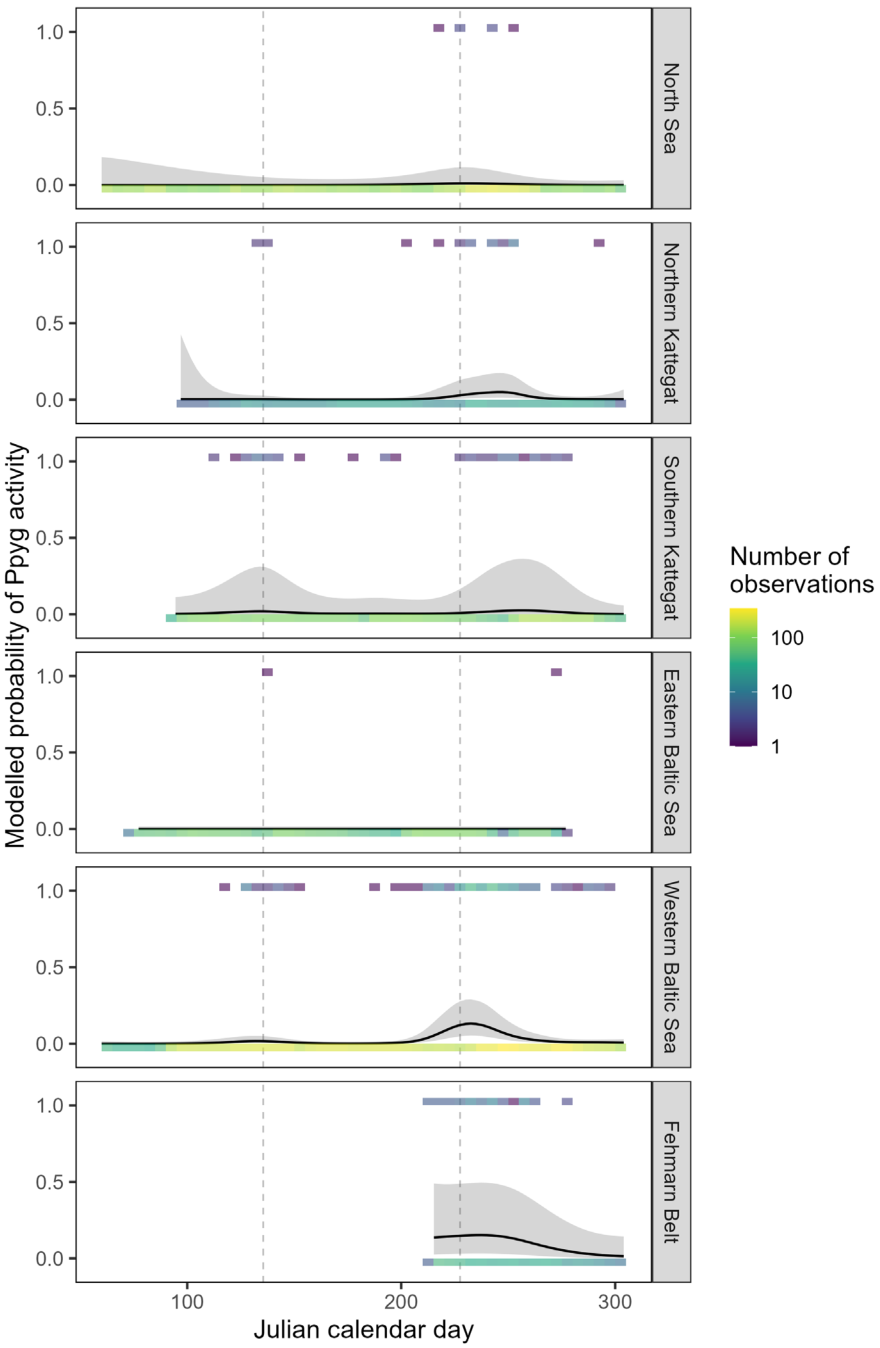


Figure 3.5. Seasonal patterns in activity of the soprano pipistrelle. Modelled probability of soprano pipistrelle (*Pipistrellus pygmaeus*) activity (y-axis) across Julian calendar day (x-axis) for all areas (sub-plots). Black lines show the model average; grey areas show the 95% confidence interval. Coloured bars above and below the plots show the observed values summarised as the number of observations per five days (bars above: present = 1, bars below: absent = 0). Grey dashed lines represent the dates separating the seasons used in the model estimating seasonal averages for each area (i.e. 15.05 and 15.08).

3.4 Seasonal area estimates and effect of distance to coast

Bat activity was higher in the fall for all areas. The highest probability of fall activity was estimated for Fehmarn Belt, and the lowest probability of fall activity was estimated for the eastern Baltic Sea. Most activity present over the North Sea was from Nathusius' pipistrelle, while most activity for the other areas was from the ENV species (Figure 3.6).

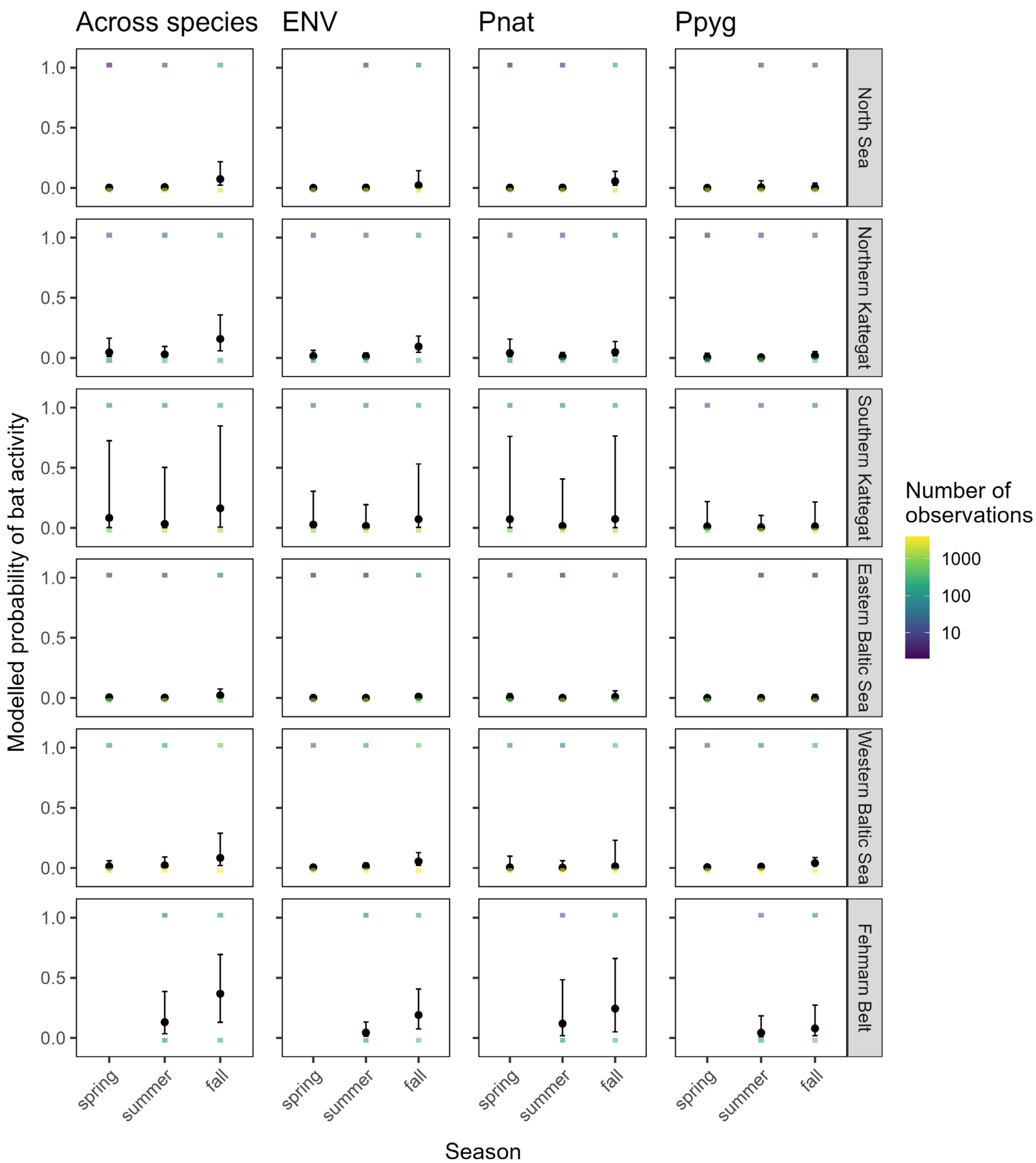


Figure 3.6. Seasonal area estimates of bat activity. Modelled probability of activity (y-axis) across seasons (x-axis) for all bats, ENV = Eptecicus, Nyctalus and Vespertilio species complex, Pnat = Nathusius' pipistrelle (*Pipistrellus nathusii)*, Ppyg = soprano pipistrelle (*Pipistrellus pygmaeus)* (columns) and areas (rows). Black dots show the model average; black lines show the 95% confidence interval. Coloured squares are the observed values (present = 1, absent = 0) summarised as the number of observations per season.

The effect of distance to coast on bat activity was also modelled, but the uncertainty was so high for most of the areas that any observed effects could be spurious, except for the North Sea, where bat activity decreased with increasing distance to the coast (Figure 3.7).

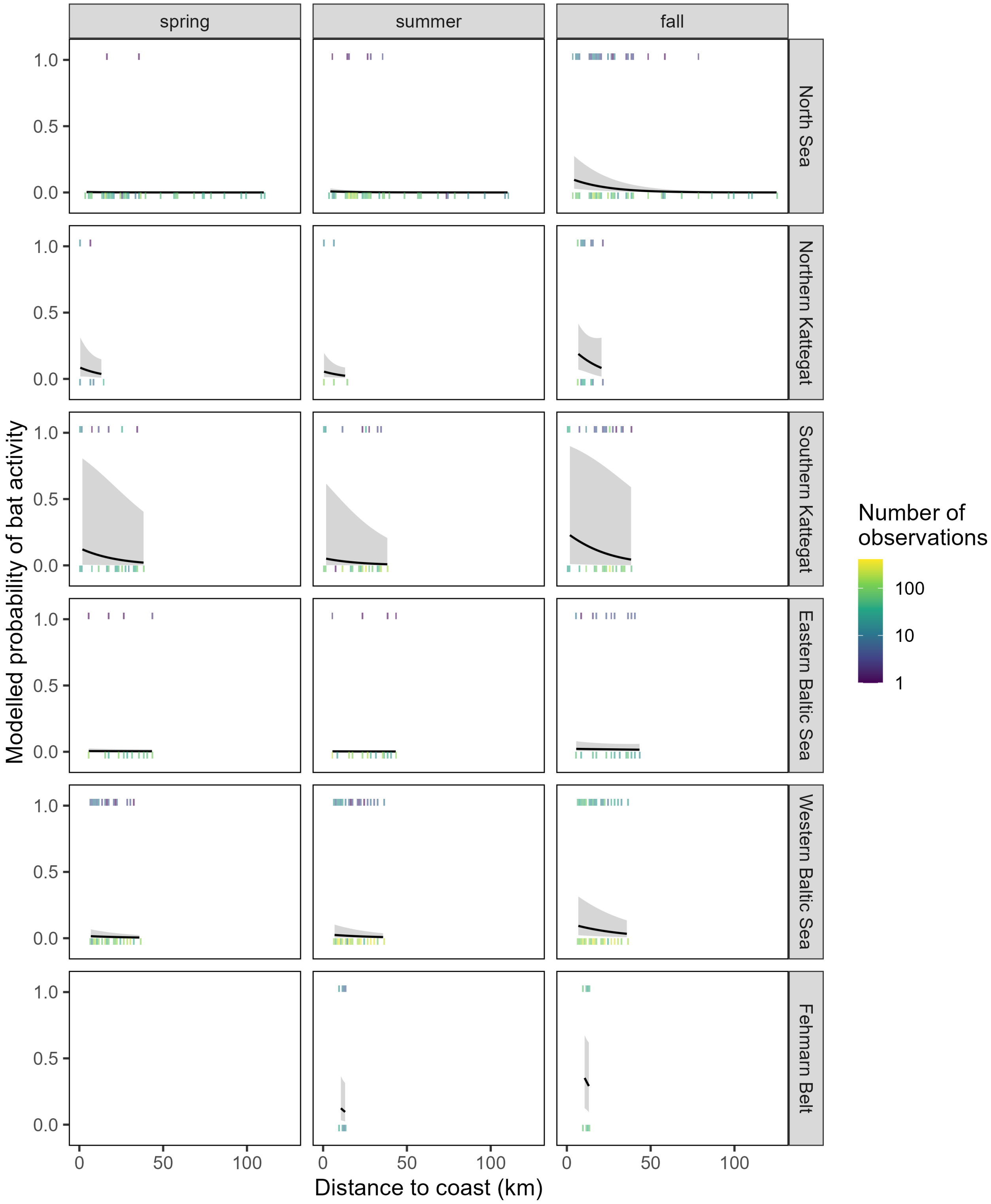


Figure 3.7. Effect of distance to the coast. Modelled probability of bat activity (y-axis) across distance to the coast in kilometres (x-axis) for all areas (rows). Black lines show the model average; grey areas show the 95% confidence interval. Coloured squares show the observed values (present = 1, absent = 0) summarised as number of observations per kilometre.

The boundary between high sensitivity and medium sensitivity (defined as the distance where the modelled probability of bat activity for North Sea I dropped to 10% of the modelled probability of bat activity for Aflandshage) was 21 km (95% CI = [3, 40] km, see also Figure 3.8). The boundary between medium sensitivity and low sensitivity (defined as the distance where the modelled probability of bat activity for North Sea I dropped to 1% of the modelled probability of bat activity for Aflandshage) was 67 km (95% CI = [47, 108] km).

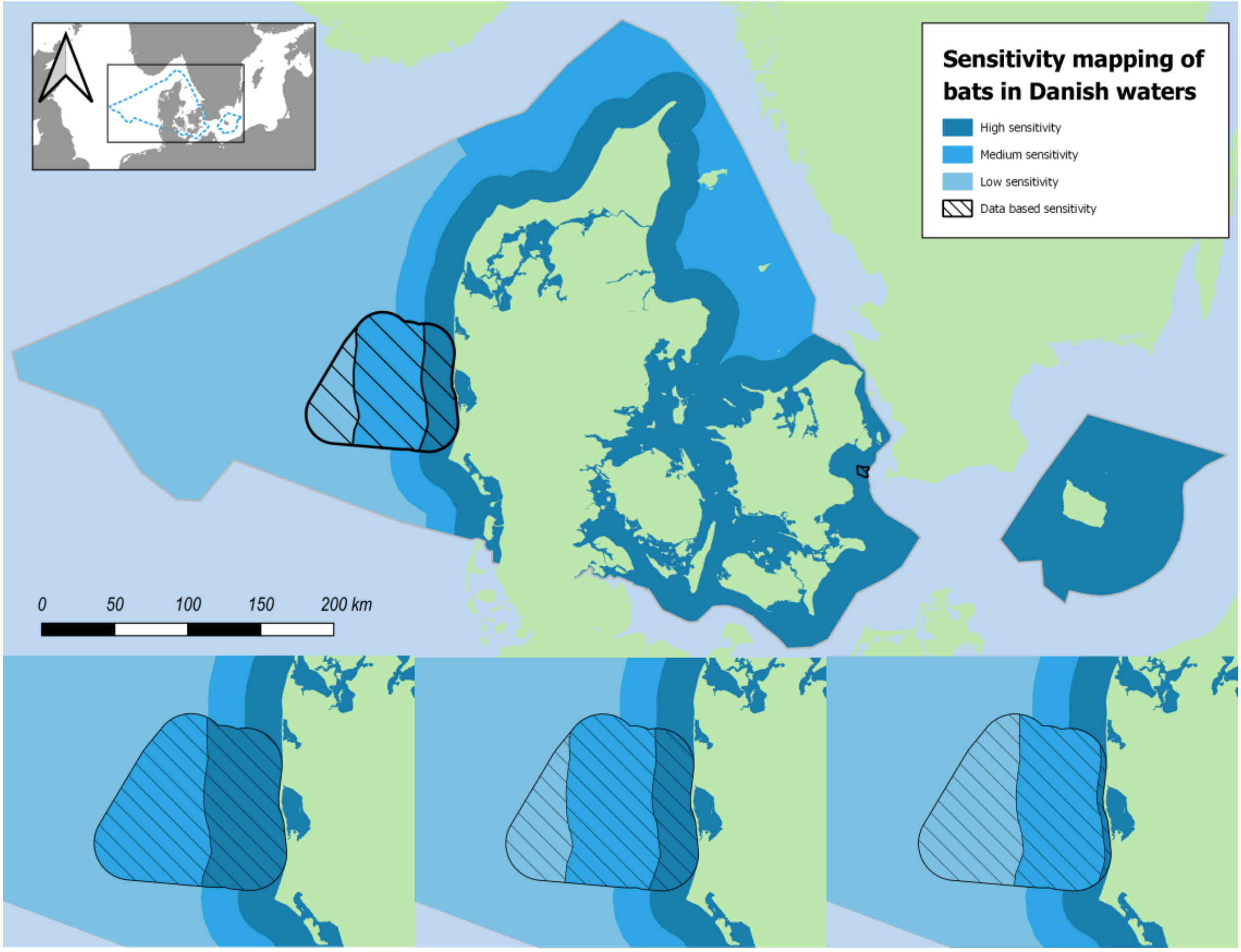


Figure 3.8. Updated sensitivity map. Top panel: original sensitivity map where NSI (left) and Aflandshage (right) are hatched and the sensitivity colouring for North Sea I is updated relative to that of Aflandshage, where the modelled probability of bat activity is assumed to be representative of the modelled probability of bat activity in a general high-sensitivity area. Medium sensitivity for North Sea I starts where the modelled probability of bat activity for North Sea I falls below 10% of the modelled probability of bat activity for Aflandshage. Low sensitivity for North Sea I starts where the modelled probability of bat activity for North Sea I falls below 1% of the modelled probability of bat activity for Aflandshage. For the top panel, these calculations were made for the point estimate of the model. For the lower left panel, the calculations were made using the lower 95% CI, the lower middle is the same as the top panel, and for the lower right panel, the calculations were made using the upper 95% CI.

3.5 Effect of weather

Overall bat activity increased with increasing temperatures (Figures 3.9 and 3.10). Only two areas, the southern Kattegat and the western Baltic, had enough data to estimate weather effects between spring and fall. For the western Baltic, activity started to rise at lower temperatures in spring (5-10 ˚C, Figure 3.10) than in fall (10-15 ˚C, Figure 3.9), although some bat activity was present at lower temperatures in fall for the western Baltic Sea as well. For the southern Kattegat, the spring estimate showed too much uncertainty to make a meaningful comparison between spring and fall.

Wind speed also had a clear effect, with the estimated probability of bat activity approaching zero between 5-10 m/s for all locations.

The effect of wind direction differed between the North Sea and the inner Danish waters. For the North Sea, there was a clear peak in activity for wind blowing away from the mainland during fall (winds including an easterly component). While this could correspond to tailwind for bats migrating along a western/southwestern vector, activity is also elevated for south-eastern tailwind, which does not align with the expected direction of fall migration. Any effects of wind direction on bat activity for the southern Kattegat were too uncertain to predict. The results for the western Baltic Sea suggest alignment with tailwind during migration (northern winds in fall and southern winds in spring). It should be noted that uncertainty was very high, and the model also allowed for no effect of wind direction for the western Baltic Sea.

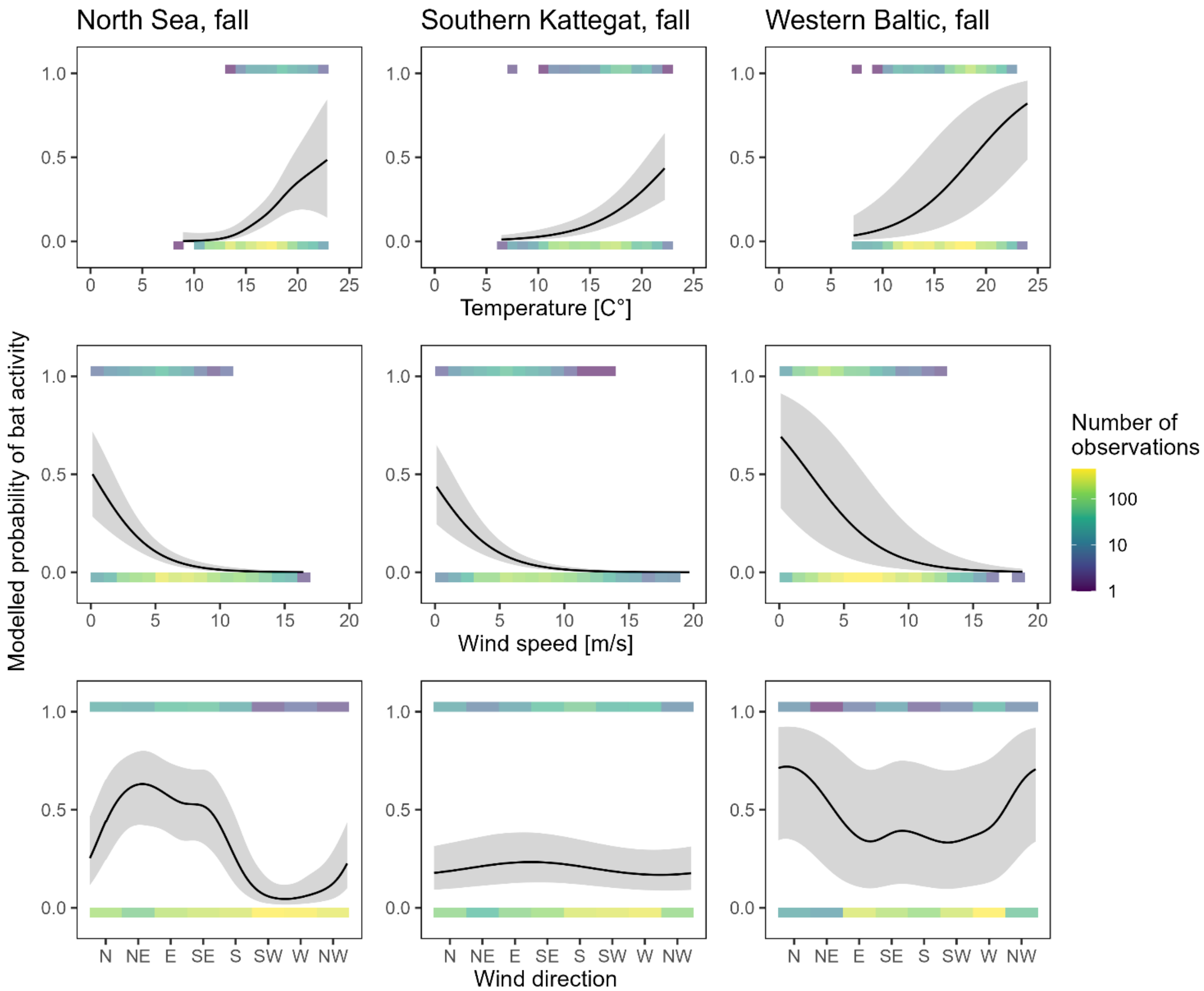


Figure 3.9. Effect of weather on bat activity during fall. Modelled probability of bat activity (y-axis) across temperatures (x-axis, top row), wind speed (x-axis middle row) and wind direction (x-axis bottom row) for North Sea (left column), southern Kattegat (middle column) and western Baltic (right column). Black lines show the model average; grey areas show the 95% confidence interval. Coloured squares show the observed values (present = 1, absent = 0) summarised as number of observations per unit (degree, m/s and 45°).

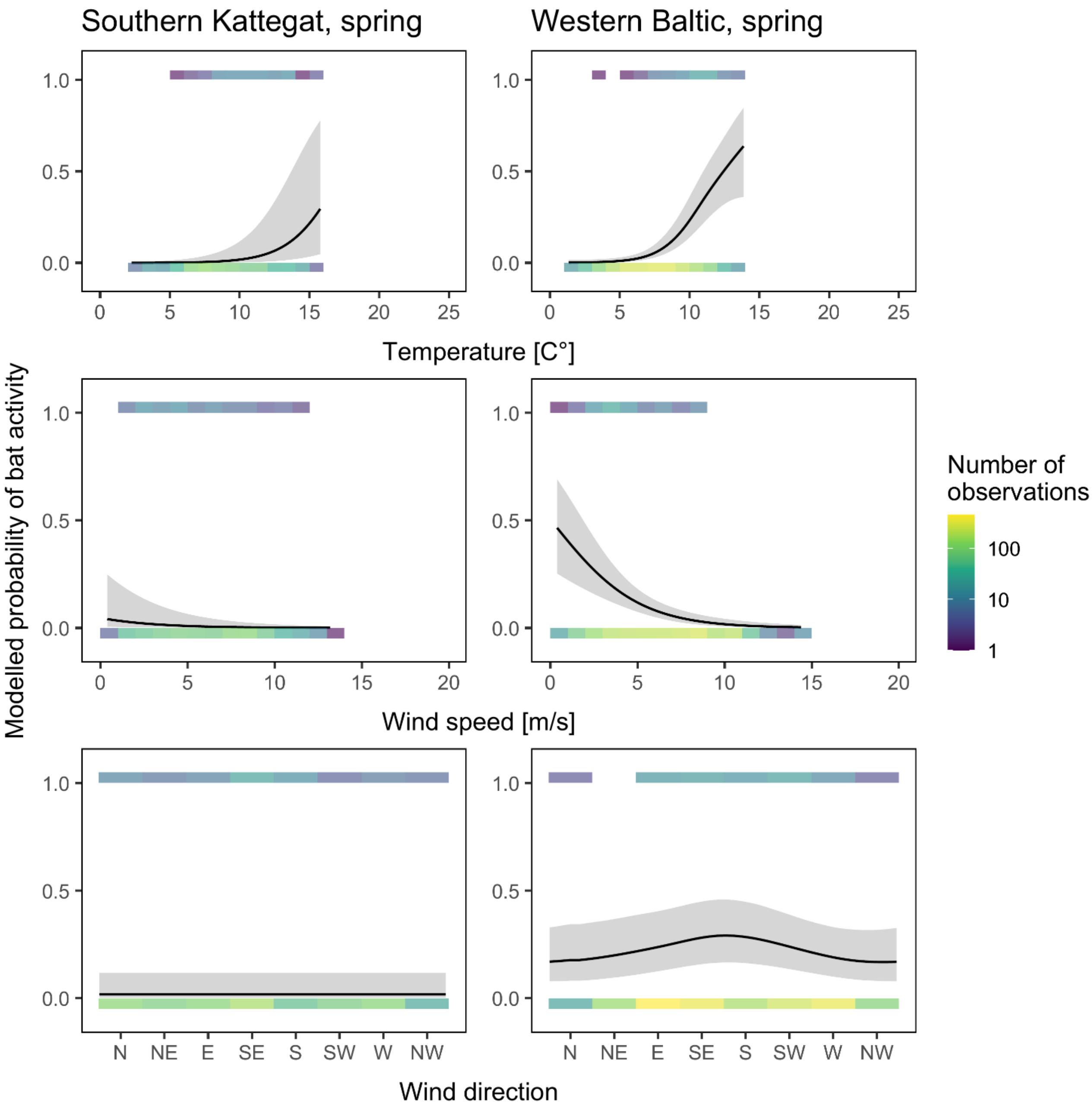


Figure 3.10. Effect of weather on bat activity during spring. Modelled probability of bat activity (y-axis) across temperatures (x-axis, top row), wind speed (x-axis middle row) and wind direction (x-axis bottom row) for southern Kattegat (left column) and western Baltic (right column). Black lines show the model average; grey areas show the 95% confidence interval. Coloured squares show the observed values (present = 1, absent = 0) summarised as number of observations per unit (degree, m/s and 45°).

3.6 Effect of recording height

Only ENV species were detected during fall at nacelle height, and activity at this height was reduced compared to the activity at transition piece height (odds ratio = 4.01, CI = [1.43, 11.25], p = 0.008, Figure 3.11).

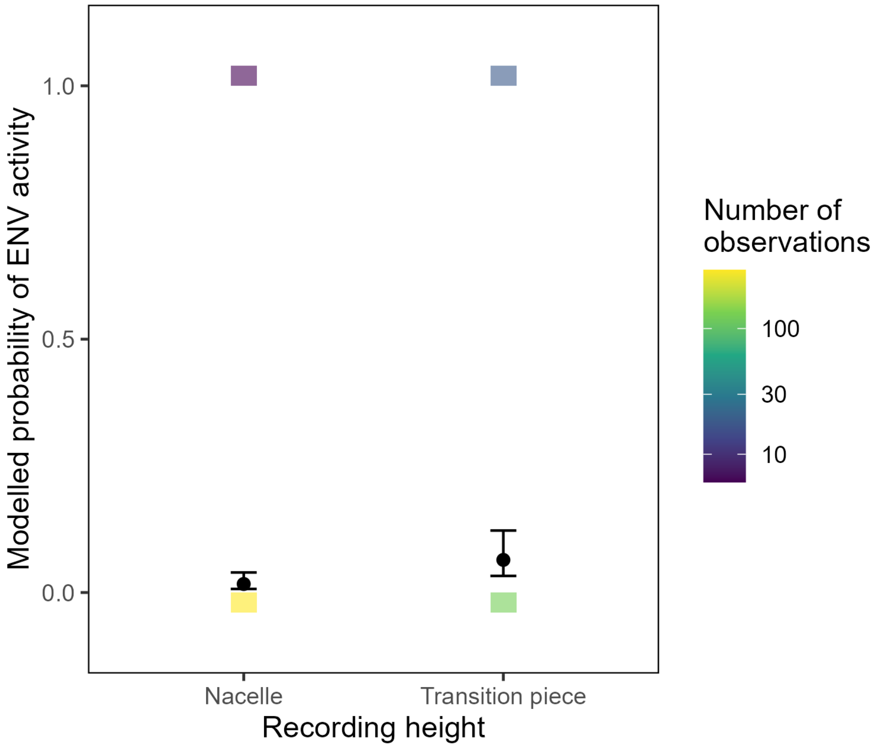


Figure 3.11. Effect of recording height on activity of the Eptecicus, Nyctalus and Vespertilio species complex. Modelled probability of ENV activity (y-axis) for the two different recording heights (x-axis): nacelle versus transition piece. Black dots show the model average; black lines show the 95% confidence interval. Coloured squares show the observed values (present = 1, absent = 0) summarised as the number of observations per recording height.

3.7 Yearly variation

The bat activity across 2023 and 2024 did not vary significantly at the locations North Sea I and southern Hesselø (North Sea I: odds ratio = 0.95, CI = [0.60, 1.49], p = 0.82; southern Hesselø: odds ratio = 1.17, CI = [0.46, 3.02], p = 0.74). For Kattegat and especially for Kriegers Flak II, the probability for bat activity was higher in 2023 compared to 2024 (Kattegat: odds ratio = 1.47, CI = [1.04, 2.07], p = 0.03; Kriegers Flak II: odds ratio = 2.8, CI = [1.40, 5.59], p = 0.004).

4 Discussion

First and foremost, all results presented here must be interpreted with caution. The sensitivity assessment and map for bats offshore is a dynamic tool. The outcomes and the robustness of the statistical analysis should be substantiated and nuanced further over time with more and better data, and initiatives to facilitate this type of overall analysis are vital to avoid time and expenses spent on after-the-fact quality control. Proper organisation of and access to raw data, as well as metadata, should be a standard requirement in baseline and environmental impact assessment surveys.

4.1 Outcomes of the data analysis

Despite the noted associated uncertainties, the comprehensive analysis of the curated dataset was able to:

- Provide a comparison of relative offshore activity between a specific location in the North Sea (North Sea I) and a specific location of the inner Danish waters (Aflandshage), where all data were collected with the same equipment and, to the best of our knowledge, comparable settings. At present, this is the closest to a direct comparison of relative offshore activity between different areas and is now included in the figure with the updated sensitivity map (Figure 3.7).

- Predict a decrease in bat activity with increasing distance from the coast for the North Sea I area, which updated the distance intervals assessed for the entire Danish coastline as high (0-21 km), medium (21-67 km) and low (> 67 km) risk in the initial sensitivity map, including uncertainty estimates for these distances. The resulting updated sensitivity map exemplifies the outcome of a comprehensive analysis and is directly applicable to a small geographical portion of the overall sensitivity map, but it needs further and comparable data from more areas before it can be extended across the entire Danish waters.

- Remove the hatching covering the North Sea in the sensitivity map, indicating it was classified as particularly data deficient. With the data included in this report, the areas data coverage is now comparable to the inner Danish waters.

- Identify a pronounced peak in offshore bat activity during fall consistent for all sites and species for which data were available (Figures 3.2-3.6). For most sites, a secondary, smaller activity peak was identified in spring. This result is not apparent from the updated sensitivity map but highlights the relevance of assessing the risk to bats from offshore wind across time as well as space.

- Document that offshore bat activity occurs during the summer in the inner Danish waters but was not present for the locations in the North Sea. The summer activity outside of the spring and fall migration periods is presumed to reflect offshore foraging activity and supports the overall high sensitivity in the inner Danish waters.

- Show clear species differences in activity between sites in the inner Danish waters and the North Sea, with most offshore activity in the North Sea attributed to Nathusius' pipistrelle and more activity of ENV species and the soprano pipistrelle recorded for sites in the inner Danish waters. This difference points to the relevance of updating the sensitivity map over time with species-specific layers.

4.2 A note on bias and uncertainty

To compare bat activity across the entire Danish waters with the present data foundation is challenging for several reasons, including equipment differences (introducing recorder bias), sampling schedules (introducing sampling bias, e.g. from triggered versus duty cycled data acquisition) and data processing approaches (introducing bias from software performance). These issues are further explained below, in the methods section and outlined in Brinkløv et al. 2025a (see also Adams et al. (2012), Russo & Voigt (2016), Asmus et al. (2025) and Krishna & Lee (2025)). No recording system is perfect and able to document all bat activity in a wind farm area. It should be noted that these issues can potentially cause a bias in the results, i.e. that estimates (including modelled uncertainty) are incorrect. This is different from factors that cause uncertainty (e.g., few data points or imprecise sampling methods), which can be modelled and are shown in the graphs as confidence intervals.

Specifically for the aim of comparing activity across areas, the features and programming of the recording equipment introduce potential biases in the analysis if data is collected with different types of equipment, as not all equipment performs equally. Some recorders are more sensitive than others and will document bat activity more accurately. The temporal coverage may differ depending on the programmed recording schedule (duty cycle versus trigger, etc.). Such differences in performance can largely be accounted for in a comprehensive analysis across a broad geographical scale, if the equipment specifications and settings used are documented and disclosed. Two different recorder types were used to collect the data supplied for the current analyses. A hardware comparison was not carried out as part of the scope for this task, and metadata was incomplete for most data. Therefore, differences in recording sensitivity persist as a bias in the analysis.

Another potential bias is introduced by using automated software to detect and classify bat calls from the raw data recordings. To quantify and account for this type of bias, the performance of different types of software can be compared on the same raw data set of audio recordings. We did so for the two types of automated software used to detect bat calls in the data supplied for the analysis. We subsequently used the most sensitive bat call detector on the entire dataset, where raw audio recordings had been stored. Our comparison revealed a species-specific difference in detection performance between the two software types. The broadly used *Kaleidoscope* (Wildlife Acoustics, Maynard, USA) detected far fewer bat calls of ENV species, especially at nacelle height, where ultrasonic noise overlapping in frequency with these species' calls is more pronounced. This difference in performance creates a bias in the model predictions for activity at different heights (transition piece versus nacelle, Figure 3.11) and adds to the underestimation of activity of ENV species in areas where only data filtered by *Kaleidoscope* were available.

Importantly, if recorder and or software detection performance drops with increasing background noise caused by higher wind speeds, the modelled decrease in bat activity with increasing wind speeds is likely biased, and the estimate of the slope of this effect can therefore not be fully trusted.

The automated analysis approach is indispensable for most PAM bat surveys, and multiple software, open source and commercial, are available for this purpose. Some can be retrained for a specific location (e.g. Bergler et al. 2022, Mac Aodha et al. 2022). Each one comes with pros and cons, and they are not all equally user-friendly. However, the need to validate and document the performance of the chosen automated approach is universal. Classification should only be done at the species level, if this is feasible from acoustic data only, which means the *Myotis* and ENV species complexes should not be split for data recorded in Denmark. Another important step towards transparency about detection and classification performance is the creation of a gold-standard dataset, where a large number of raw data recordings with variable recorders, species present and recording situations have been annotated. These recordings can then be used to directly compare models and versions of models.

It was not possible to recover data from all the survey reports summarised for the initial offshore sensitivity assessment and map for bats (Brinkløv et al. 2025a). The supplied data were curated and quality assured to verify that they only included recordings from actual offshore deployment periods and omitted recordings with obvious microphone failure. This further reduced spatial and temporal coverage, but it is necessary to reduce bias. The data curation process illustrated inconsistencies between the reported and actual temporal PAM coverage. More detailed and accurate reporting of methods and effort, ideally combined with data sharing, is therefore recommended to pinpoint and prioritise data gaps to be filled to support and elaborate on the sensitivity assessment.

Currently, all results from Horns Rev I (except fall 2024), Kattegat, Hesselø, Kriegers Flak I (except fall 2024), Kriegers Flak II and Fehmarn Belt are based on recordings using duty cycling, where only five out of every 15 seconds are recorded, and potentially over half of the ENV species calls are removed as noise by *Kaleidoscope*.

The estimated seasonal patterns and effects of weather parameters on bat activity need to be interpreted carefully. This is largely due to the fact that most locations had data from less than three years, making it difficult to disentangle the temporal autocorrelation of weather and day of the year. For example, for the quantification of seasonal patterns, the model only had a maximum of three samples of each Julian day per year available, creating uncertainty about the exact start and end times of activity peaks.

The biases and uncertainties described above call for more and improved data input to further the comprehensive analysis and, consequently, reveal consistent bat activity patterns offshore, predictable by specific combinations of environmental variables with the used modelling approach. Suggestions for further data input to support and substantiate the analysis and dynamically develop the sensitivity map are given in Chapter 5.

4.3 Temporal coverage and migration periods

We chose to model bat activity as a binary variable per night (present/absent for that night). This is a robust method, and especially useful if the number of individuals cannot be inferred from the data, which is the case for passive acoustic monitoring of bats (i.e. the same individual might fly back and forth in front of the recorder). Another benefit is that uncertainty introduced by variable methods in the different studies is somewhat reduced, since even if a less sensitive method misses some individuals passing the recorder, a single detection is enough to make bats 'present' that night. Some level of zero inflation remains (nights with bat activity being missed due to none of the passes being recorded), especially if both duty cycling and automated, non-validated filtering are used. This would lead to an underestimation of bat activity (Krishna and Lee 2025). A downside of aggregating bat activity per night is that bursts of high activity are not modelled. If many individuals migrate in a single night, all these are lumped as a single night with bats 'present'. This is something we observed for several stations, with, e.g. 1,137 recordings containing bat calls (primarily the ENV species) at Hesselø SE on the 24th of April 2023 and 909 recordings containing bat calls (primarily the ENV species) at Totten on the island of Anholt on the 10th of September 2023. In future studies, nightly activity patterns could be modelled in more detail, using hourly activity or activity minutes. This would require data of better quality, since these models would be more sensitive to zero inflation (recorders missing bat activity). An even more ambitious approach would be to quantify flight patterns at the individual level and use these to estimate the number of individuals based on distance sampling and Monte Carlo simulations (e.g. Baumgartner 2025).

The dates used to separate spring from summer and summer from fall were chosen based on expected migration periods, based on the limited knowledge from literature (Rydell et al. 2014, Seebens-Hoyer et al. 2021). It is notable that the spring activity peak, likely linked to migration, occurred later than expected, near the chosen spring-summer distinction for nearly all species and areas (Figures 3.2-3.5). The opposite was to a lesser degree true for the fall migration, with increased activity predicted for multiple areas already in the first half of August. It is not possible from the PAM data alone to determine if some or all the observed peaks relate to migration or reflect foraging trips offshore not linked to migratory behaviour. However, except for the Fehmarn Belt area, observed and predicted summer activity was generally scarce. Another important point is that due to data scarcity generally and across years, we had to restrict how flexibly the model could fit the seasonal pattern. Allowing more flexibility led to overfitting, with the model capturing short-term peaks each based on very few data points and potentially specific to individual years rather than representing a general seasonal trend. As a result, the current model smooths potential short-term variations due to the data scarcity and therefore cannot reveal whether migration occurred in several brief pulses or over a more extended period, nor can it accurately capture very sharp onsets of migration. When more multi-year data become available, finer detection of temporal dynamics, such as the onset of activity peaks, will be possible.

4.4 Response to weather

Despite potential biases introduced by the causes described at the start, some conclusions about the response of bat activity to weather parameters can be drawn. The temperature at which bat activity started to rise differed between spring and fall. This can be explained by the distribution of available temperatures. Spring did not include days with temperatures above 15 ˚C, probably forcing the bats to be active on the warmest available days, limited to temperatures between 5-10 ˚C in some cases. The response to wind direction differed between the North Sea and the western Baltic Sea, with a clear increase in bat activity during the fall for eastern winds for the North Sea and a less clear increase in activity with northern winds for the western Baltic Sea. Both findings can be a result of migratory behaviour, since an eastern wind would help bats fly away from the North Sea coast, and a northern wind would help bats migrate south. These results also highlight the need for area-specific data collection and analysis. For all weather parameters, it would be valuable to obtain high-quality data across several years for each location. With such data series, predictions will be associated with less uncertainty, allowing the design of curtailment regimes based on live weather data to be tailored to the location and season.

4.5 Sensitivity mapping and extrapolation from pre-construction assessments to mortality risk post-construction

As mentioned in Brinkløv et al. (2025b), the available literature and reports suggest that ranges for high (0-20 km) and medium (20-40 km) sensitivity are conservative but reasonable estimates for bat sensitivity along the entire Danish coastline. For the North Sea I area, this could be updated based on a comparison with Aflandshage. The ranges found are comparable for the high sensitivity area, but the medium sensitivity area extends further offshore. This does, however, not meaningfully impact the overall sensitivity map, since the North Sea is still the only area with a low sensitivity range and the North Sea I area is, therefore, still the location with the lowest sensitivity, when compared to all other offshore locations. It should also be reiterated that these are relative sensitivities, meaning a greater area of the North Sea is now medium in sensitivity relative to Aflandshage, and that this will change once multiple other areas are considered in a comprehensive model, where ranges can be estimated relative to a more solid average activity level. There is no reason to believe that activity levels at Aflandshage are higher or lower than other marine areas at a comparable distance of the coast. The only reason to use Aflandshage as reference point was the lack of data quality in all other areas. We chose not to update any other part of the sensitivity map, since bat activity might differ even within the North Sea.

Although overall the sensitivity on the map might seem high, compared to the actual number of nights where bats were detected, it should be kept in mind that the detection range of each PAM station for ultrasonic bat calls is less than a hundred meter and much less for some species (e.g. Voigt et al. 2021), which is not enough to cover the dimensions of an offshore wind turbine and much less than the distance between the PAM stations at a given location, whether on turbines or on buoys. For this reason, the recorded bat activity across all areas where data are included, regardless of the equipment used, is an underrepresentation of actual bat activity offshore. Bat activity offshore is, however, in general much lower than onshore (Brinkløv et al. 2025a - Tables 3.1 - 3.4, Brinkløv et al. 2025b).

An important, yet open question is how bat activity measured from buoys during a pre-construction impact assessment translates to the actual risk to bats post-construction at offshore wind turbines, as bats seem to be attracted to structures on open waters (Seebens-Hoyer et al. 2021, Brinkløv et al. 2025b). The mortality risk assessments in environmental impact assessments based on short-term pre-construction bat surveys often do not match actual bat fatality rates documented by post-construction carcass searches under onshore wind turbines (Hein et al. 2013, Lintott et al. 2016, Solick et al. 2020). Ahlén et al. (2009) and Lagerveld & Mostert (2023) reported bats foraging over the sea. Noctules were documented more than 20 km from the coast on nightly foraging trips, predominately flying in heights 20-125 m when flying offshore, i.e.

the sweep area for many wind turbines (Lagerveld & Mostert 2023). High temperatures may trigger insect activity and migration, and particularly in late summer/early autumn numbers of migrating insects may drift offshore (Chapman et al. 2004, Drake et al. 2012). Both the fact that the risk to bats is in the rotor swept area and not at buoy height, and that bats are attracted by larger, permanent structures as wind turbines and change their behaviour close to such structures (Horn et al. 2008, Seebens-Hoyer et al. 2021, Willmott et al. 2023), may play a role in the inaccuracy of pre-construction surveys to predict mortality risk for bats.

We only have very preliminary results for the effect of recording height on bat activity estimates (Figure 3.11), with the model accounting for merely 29% of the total deviance and only 16% of the variance in observed probabilities, resulting in high prediction uncertainty for probabilities above 0.1. This is not surprising since we were only able to include five deployments with recordings at nacelle height during fall, and these were characterised by strong background noise when the turbine was active, severely reducing the probability of detecting bat calls. Therefore, the significant p-value for the comparison should not be seen as evidence that bat activity differed between nacelle and transition piece height, but rather that the ability to detect bats differed between these heights. Future studies should increase the post-construction monitoring effort and carefully plan the placement of the microphone to reduce background noise. If background noise levels are not comparable despite this effort, noise levels should be measured, such that detection probability can be modelled and adjusted for (Brinkløv et al. 2023).

5 Conclusions and perspectives

We analysed passive acoustic monitoring data from offshore bat surveys in the Danish exclusive economic zone to compare bat activity in different regions of the zone. Data and metadata from the surveys were obtained from consultants by way of the Danish Energy Agency and the respective wind turbine developers. Raw data were available from some projects, while only pre-processed, filtered recordings were available from others. There was a geographic bias in the type and quality of data that were available for the modelling of offshore bat activity. Raw data were not available from most of the surveys in the Baltic Sea, the southern Kattegat and the Fehmarn Belt. Both types of data were available from a few sites.

Modelling of bat activity in different marine areas, we found that bat activity was higher in the inner Danish waters than in the North Sea, especially for ENV species. We also found a decline in activity with distance to the coast in the North Sea and used this to update the sensitivity for this area. Our analyses also corroborate published knowledge on overall variation in bat activity in relation to wind speed and temperature.

Based on our results, we make the following recommendations for future pre-construction surveys and post-construction monitoring in relation to offshore wind turbines:

- Raw data should always be preserved.
- Recordings should be made from sunset to sunrise (minimum).
- If duty cycling is used, its effect on detection probability should be quantified.
- A trigger can be used, but the threshold should be validated before deployment, ensuring most bat calls will be recorded. Also, a minimum of five seconds should be recorded continuously for each trigger event and periods of low acoustic activity in between calls should not be removed.
- Metadata should include the exact deployment and retrieval data, as well as all settings used (see Appendix I).
- Sensitivity and general functionality of the equipment should be recorded before and after each deployment.
- Automated software can be used to detect and classify bat calls, but for offshore recordings, classification should be verified manually. For any software, performance should always be validated with a representative subset. All raw data should be stored, including files that are classified as only containing noise, to enable future comprehensive analyses.

6 References

Adams AM, Jantzen MK, Hamilton RM, Fenton MB 2012. Do you hear what I hear? Implications of detector selection for acoustic monitoring of bats. Methods in Ecology and Evolution 3, 992–998.

Ahlén I 1997. Migratory behaviour of bats at south Swedish coasts. Zeitschrift für Säugetierkunde 62, 375-380

Ahlén I, Bach L, Baagøe HJ, Pettersson J 2007. Fladdermöss och havsbaserade vindkraftverk studerade i södra Skandinavien. Raport 5748. Naturvådsverket.

Ahlén I, Baagøe HJ, Bach L 2009. Behavior of Scandinavian bats during migration and foraging at sea. Journal of Mammalogy 90, 1318–1323.

Alcalde JT, Jiménez M, Brila I, et al. 2021. Transcontinental 2200 km migration of a Nathusius' pipistrelle (*Pipistrellus nathusii*) across Europe. Mammalia 85, 161–163.

Arnett EB, Baerwald EF 2013. Impacts of wind energy development on bats: Implications for conservation. In: Adams RA, Pedersen SC (eds.). Bat evolution, ecology, and conservation. New York, Springer New York, 435–456.

Asmus J, Frommolt K-H, Knörnschil M 2025. Lost in translation—How transparency can improve comparability and reusability in acoustic bat research. Ecology and Evolution 15, e71883.

Bach L, Bach P, Ehnbom S, Karlsson K 2017. Flyttande fladdermös vid Måkläppen, Falsterbo. Fauna och Flora 112, 37-45.

Bach P, Voigt CC, Göttsche M, Bach L, et al. 2022. Offshore and coastline migration of radio-tagged Nathusius' pipistrelles. Conservation Science and Practice 4, e12783.

Barré K, Froidevaux JSP, Leroux C, et al. 2022. Over a decade of failure to implement UNEP/EUROBATS guidelines in wind energy planning: a call for action. Conservation Science and Practice, e12805

Baumgartner, Mark. "Efficacy of real-time passive acoustic monitoring near wind energy industrial activities for mitigating risks to right whales." Endangered Species Research 57 (2025): 413-430.

Benoit Thieurmel and Achraf Elmarhraoui (2022). suncalc: Compute Sun Position, Sunlight Phases, Moon Position and Lunar Phase. R package version 0.5.1. https://CRAN.R-project.org/package=suncalc

Bergler C, Smeele SQ, Tyndel SA et al. (2022), ANIMAL-SPOT enables animal-independent signal detection and classification using deep learning. Scientific Report 12, 21966.

Boshamer JP, Bekker JP 2008. Nathusius' pipistrelles (*Pipistrellus nathusii*) and other species of bats on offshore platforms in the Dutch sector of the North Sea. Lutra 51, 17-36.

Brabant R, Laurent Y, Jonge Poerink B, Degraer S 2019. Activity and behaviour of nathusius´ pipistrelles *Pipistrellus nathusii* at low and high altitude in a North Sea offshore wind farm. Acta Chiropterologica 21, 341-348.

Brinkløv SMM, Elmeros M 2024a. North Sea Energy Island. Environmental pre-investigations for bats. Technical report. NIRAS & Aarhus University, Danish Centre for Environment and Energy. Commissioned by Energinet Eltransmission A/S.
https://ens.dk/sites/ens.dk/files/Vindmoller_hav/eoen_bats_wp_h_technical_report_v2_final_21082024.pdf

Brinkløv SMM, Smeele SQ, Uebel AS, Fjederholt ET, Elmeros M 2024b. Bat surveys - North Sea I. NIRAS & Aarhus University, Danish Centre for Environment and Energy. Commissioned by Energinet Eltransmission A/S.

Brinkløv SMM, Uebel AS, Fjederholt ET, Elmeros M 2025a. Sensitivity mapping of relative risks to bats from Danish offshore wind energy. Aarhus University, Danish Centre for Environment and Energy.

Brinkløv SMM, Smeele SQ, Uebel AS, Grethen KJ, Elmeros M 2025b. Bat surveys - North Sea I. NIRAS & Aarhus University, Danish Centre for Environment and Energy. Commissioned by Energinet Eltransmission A/S.

Brinkløv SMM, Smeele SQ 2025c. Bat activity offshore – analysis of data from passive acoustic monitoring, weather and turbine operations. Unpublished.

Bennun L, van Bochove J, Ng C, et al. 2021. Mitigating biodiversity impacts associated with solar and wind energy development. Guidelines for project developers. Gland, Switzerland: IUCN and Cambridge, UK.

Chapman JW, Reynolds DR, Smith AD, et al. 2004. An aerial netting study of insects migrating at high altitude over England. Bulletin of Entomological Research 94, 123-136.

COWI. 2023. Lillebælt Syd Vindmøllepark. Baggrundsnotat - Undersøgelse af flagermustræk på det nordøstlige Als i foråret 2022. Bilag B. Lillebælt Vind A/S.

Denzinger A, Schnitzler HU 2013. Bat guilds, a concept to classify the highly diverse foraging and echolocation behaviors of microchiropteran bats. Frontiers in Physiology 4, 164.

Directorate-General for Energy 2024. Guidance on designating renewables acceleration areas (SWD) Guidance on designating renewables acceleration areas. European Commission (https://energy.ec.europa.eu/publications/guidance-designating-renewables-acceleration-areas_en)

Drake VA, Reynolds DR 2012. Radar entomology: observing insect flight and migration. Cabi, Wallingford, UK.

EIONET (European Environment Information and Observation Network) 2025. https://nature-art17.eionet.europa.eu/article17/ (accessed 23/10/2025)

EUROBATS 2023. Report of the Intersessional Working Group on Wind Turbines and Bat Populations. Doc.EUROBATS.AC27.6.Rev.1

European Environmental Agency 2025. https://www.eea.europa.eu (accessed 23/10/2025)

FEBI 2013. Fehmarnbelt Fixed Link EIA Fauna and Flora – Impact assessment. Bats of the Fehmarnbelt Area. Baseline Report No. E3TR0016.

Frick WF, Baerwald EF, Pollock JF, et al. 2017. Fatalities at wind turbines may threaten population viability of a migratory bat. Biological Conservation 209, e172177.

Friedenberg NA, Frick WF 2021. Assessing fatality minimization for hoary bats amid continued wind energy development. Biological Conservation 262, e109309.

Gibson L, Wilman EN, Laurance WF 2017. How Green is "Green" Energy? Trends in Ecology & Evolution 32, 922–935.

Goodwin KR, Gillam EH 2021. Testing accuracy and agreement among Multiple versions of automated bat call classification software. Wildlife Society Bulletin 45, 690–705.

Hartig F 2024. _DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models_. R package version 0.4.7, https://CRAN.R-project.org/package=DHARMa.

Horn JW, Arnett EB and Kunz TH 2008. Behavioral responses of bats to operating wind turbines. The Journal of Wildlife Management 72, 123-132.

Hurme E, Linzi I, Wikelski M, Wild TA, Deckmann DKN 2025. Bats surf storm fronts during spring migration. Science 387, 97–102.

Hutterer R, Ivanova T, Meyer-Cords T, Rodrigues L 2005. Bat migrations in Europe: a review of banding data and literature. Federal Agency for Nature Conservation, Bonn, Germany.

Krishna A, Lee W-J 2025. Influence of duty-cycle recording on measuring bat activity in passive acoustic monitoring. The Journal of the Acoustical Society of America 158, 1892–1903.

Kruszynski C, Bailey LD, Courtiol A, et al. 2020. Identifying migratory pathways of Nathusius' pipistrelles (*Pipistrellus nathusii*) using stable hydrogen and strontium isotopes. Rapid Communications in Mass Spectrometry 35, e9031.

Lagerveld S, Jonge Poerink B, Geelhoed SCV 2021. Offshore occurrence of a migratory bat, *Pipistrellus nathusii*, depends on seasonality and weather conditions. Animals 2021 11, 3442.

Lagerveld S, Mostert K 2023. Are offshore wind farms in the Netherlands a potential threat for coastal populations of noctule? Lutra 66, 39-53.

Lagerveld S, de Vries P, Harris J, et al. 2024. Migratory movements of bats are shaped by barrier effects, sex-biased timing and the adaptive use of winds. Movement Ecology 12, 81.

Leroux C, Le Viol I, Valet N, Kerbiriou C, Barré K 2023. Disentangling mechanisms responsible for wind energy effects on European bats. Journal of Environmental Management 346, e118987.

Leroux C, Barré K, Valet N, Kerbiriou C, Le Viol I 2024. Distribution of common pipistrelle (Pipistrellus pipistrellus) activity is altered by airflow disruption generated by wind turbines. PLoS ONE 19, e0303368.

Mac Aodha O, Balvanera SM, Damstra E, Cooke M, et al. 2022. bioRxiv 2022.12.14.520490; doi: https://doi.org/10.1101/2022.12.14.520490

Merlet M, Soto DX, Arthur L, Voigt CC 2025. The trans-european catchment area of common noctule bats killed by wind turbines in France. Scientific Reports 15, 1383.

Millon L, Colin C, Brescia F, Kerbiriou C 2018. Wind turbines impact bat activity, leading to high losses of habitat use in a biodiversity hotspot. Ecological Engineering 112, 51–54.

Orbicon 2016. Omø Syd kystnær Havmøllepark. VVM - Vurdering af Virkninger på Miljøet og Miljørapport.

Petersen A, Jensen J-K, Jenkins P, Bloch D, Ingimarsson F 2014. A review of the occurrence of bats (Chiroptera) on islands in the North East Atlantic and on North Sea installations. Acta Chiropterologica 16, 169–195.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reusch C, Lozar M, Kramer-Schadt S, Voigt CC 2022. Coastal onshore wind turbines lead to habitat loss for bats in Northern Germany. Journal of Environmental Management 310, e114715.

Reusch C, Paul AA, Fritze M, Kramer-Schadt S, Voigt CC 2023. Wind turbines in forests conflict with habitat use of tree-roosting bats. Current Biology 33, 737–743.

Roemer C, Disca T, Coulon A, m.fl. 2017. Bat flight height monitored from wind masts predicts mortality risk at wind farms. Biological Conservation 215, 116–122.

Russell VL, Piaskowski J 2025. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 2.0.0. https://CRAN.R-project.org/package=emmeans

Russo D, Voigt CC 2016. The use of automated identification of bat echolocation calls in acoustic monitoring: a cautionary note for a sound analysis. Ecological Indicators 66, 598–602.

Rydell J, Bach L, Bach P, et al. 2014. Phenology of migratory bat activity across the Baltic Sea and the south-eastern North Sea. Acta Chiropterologica 16, 139-147.

Rydell J, Nyman S, Eklöf J, Jones G, Russo D. 2017. Testing the performances of automated identification of bat echolocation calls: A request for prudence. Ecological Indicators 78, 416–420.

Schnitzler HU, Kalko EKV 2001. Echolocation by insect-eating bats. Bioscience 51, 557–569.

Seebens-Hoyer A, Bach L, Bach P, et al. 2021. Fledermausmigration über der Nord- und Ostsee. BfN Schriften 631. NABU Mecklenburg-Vorpommern & Bundesamt für Naturschutzt. 211 pp. https://doi.org/10.19217/skr631

Simpson G 2024. Gratia: An R package for exploring generalized additive models. Journal of Open Source Software, *9*(104), 6962. doi:10.21105/joss.06962

Solick DI, Newman CM 2021. Oceanic records of North American bats and implications for offshore wind energy development in the United States. Ecology and Evolution 11, 14341-15454.

Thaker M, Zambre A, Bhosale H 2018. Wind farms have cascading impacts on ecosystems across trophic levels. Nature Ecology & Evolution 2, 1854–1858.

Voigt CC, Popa -Lisseanu AG, Niermann I, et al. 2012. The catchment area of wind farms for European bats: a plea for international regulations. Biological Conservation 153, 80–86.

Voigt CC, Lehnert LS, Petersons G, et al. 2015. Wildlife and renewable energy: German politics cross migratory bats. European Journal of Wildlife Research 61, 213–219.

Voigt CC, Russo D, Runkel V, Goerlitz HR. 2021. Limitations of acoustic monitoring at wind turbines to evaluate fatality risk of bats. Mammal Review 51, 559–570.

Voigt CC, Kaiser K, Look S, et al. 2022. Wind turbines without curtailment produce large numbers of bat fatalities throughout their lifetime: A call against ignorance and neglect. Global Ecology and Conservation 37: e02149.

Voigt CC, Bernard E, Huang JC, et al. 2024. Toward solving the global green-green dilemma between wind energy production and bat conservation. Bioscience 74, 240-252.

Willmott JR, Forcey G, Vukovich M 2023. New insights into the influence of turbines on the behaviour of migrant birds: implications for predicting impacts of offshore wind developments on wildlife. Journal of Physics: Conference Series 2507, 012006.

WSP 2024a. Flagermus ved Kriegers Flak Havmøllepark 2022 og 2023. https://ens.dk/sites/ens.dk/files/Vindmoller_hav/flagermus_ved_kriegers_flak_havmoellepark_2022_2023_maj2024.pdf

WSP 2024b. Kriegers Flak II. Technical report - Bats. Energinet. https://ens.dk/sites/ens.dk/files/Vindmoller_hav/techincalreport-batskriegersflakii.pdf

WSP 2024c. Hesselø. Technical report - Bats. Energinet. https://ens.dk/sites/ens.dk/files/Vindmoller_hav/techincalreport-batshesseloe.pdf

WSP 2024d. Kattegat. Technical report - Bats. Energinet. https://ens.dk/sites/ens.dk/files/Vindmoller_hav/technical_report_-_bats_kattegat.pdf

WSP 2025. Energy Island Bornholm. Technical report – Bats. Version 2. Energinet. https://ens.dk/media/6374/download

Wood, S.N. (2017) Generalized Additive Models: An Introduction with R (2nd edition). Chapman and Hall/CRC.

7 Appendix 1

Copy of requested metadata from each project if the study design and results had not been published. Data was requested for each detector (station) and deployment if parameters had changed during the surveys.

DATA REQUEST	EXPLANATION
Station ID	ID that remains the same across deployments and refers to the specific station
Recorder ID	ID that refers to the device for the given deployment
Coordinates	Latitude and longitude in decimal degrees.
Deployment date	YYYY-MM-DD, date at which recorder was deployed at location, for each redeployment a new deployment date as to be supplied
Recovery date	YYYY-MM-DD, date at which recorder was recovered from the location, for each redeployment a new deployment date as to be supplied
Station type	Please indicate where the microphone was attached, e.g. buoy, base of wind turbine tower, nacelle, transition piece, coastal
Microphone height	Approximate height of microphone above mean sea level or ground
Horizontal microphone orientation	E.g. microphone faces N/NW
Recorder/detector manufacturer & model	*SM3*, *SM4BAT FS* or *ZC*, *SongMeter Miniv. x.x*, *AudioMoth v. x.x*, *D500*, … If exact version is not known, then state *unknown or older than x.x*
Firmware version	Should appear in recorder settings or can be looked up on manufacturer website: *SM4BAT FS vs. 2.4.6*.
Microphone type	This will often be indicated by the type of recording device entered but in some cases several options exist, e.g. *SMM-U1* and *SMM-U2* from Wildlife Acoustics. The same is true for custom recorders or when external microphones are attached, e.g. to AudioMoth. Additional examples: *MEMS*, *Advanced Electret*, *SiSonic*, *US-O V3*
Custom modifications	Please describe, e.g. *commercial recorder with custom coupling to external microphone, any added filters, other* or *none*. Please describe or provide reference to accessible publication describing the modifications in detail.
Was the microphone calibrated or sensitivity verified prior to/during/after deployment?	Yes (*Y*)/ No (*N*) - Calibrated or at least sensitivity of microphone sensitivity tested regularly before and during the survey
Recording schedule	Describe relative to sunset and sunrise, e.g. *set -> rise*, *set+00:30 -> rise-00:30*
Duty cycling	Yes (Y)/ No (N).
If duty cycling describes	E.g. *5 s on/5 s off*. Indicates if the recorder was set to cyclically stop and start recording within nights of recording.
Trigger	Yes (Y)/ No (N). Choose N if all audio is stored during active monitoring periods (either continuous or duty cycle on period)
Specify trigger/recording threshold	Indicate which trigger setting was used: *6 dB, 12 dB,*

Metadata list continued.

DATA REQUEST	EXPLANATION
Anti alias filter	Yes (Y)/ No (N). Helps ensure accurate digital representation of recorded signals
High pass filter	Yes (Y)/ No (N). Determines lower frequency cut-off of recordings
If high pass filter, which frequency	Which setting/ cut-off was used for the high pass filter, e.g. *15 kHz*
Time format	Indicate the time format used in the meta data and the filenames, e.g. UTC, CET, CEST
Analysis flow	
If automated or combined analyses, list software and version used	Indicate name and version of commercial or open source and open access software, e.g. *SonoChiro v. x.x.x*, *Kaleidoscope v. x.x.x.* and a short description or reference to publication of how automated detections and classifications were verified
State which data is available	(1) raw wav files (as saved on the SD card), (2) other files as config, summary and dump files as saved on SD-card, (3) sorted wav files (from *Kaleidoscope* or other software) and (4) software output (Kaleidoscope id.csv, *Sonochiro* database file or similar depending on software used)

MODELLING OFFSHORE BAT ACTIVITY OVER DANISH WATERS

Wind turbines pose a risk for bat populations. Even offshore wind turbines may pose a risk for bats, as they forage and migrate over marine areas. We modelled offshore bat activity for different Danish seas. Activity was summarised and modelled per night as a presence/absence variable. The analyses indicate a relatively higher probability for bat activity in the inner Danish waters compared to the Danish North Sea. Activity decreased with increasing distance to the coast in the North Sea, but no such effect was observed for the inner Danish waters. Bat activity increased with increasing temperatures, with a clear seasonal difference in temperatures where high bat activity occurred. Offshore bat activity decreased with wind speed.

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