



Observing pelagic fish over longer periods of time using stationary acoustics

Phase 1 of Monitoring, Research, Nature Enhancement, Species Protection (MONS)

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Contents

Samenvatting	4
Summary	5
1 Introduction	6
2 Objectives	7
3 Methods	8
3.1 Locations	8
3.2 Frames and acoustic settings	9
3.3 Deployment and retrieval	10
3.4 Gillnet fishing	10
3.5 Analyses	11
4 Results	14
4.1 Gillnet fishing	14
4.2 WBAT	15
4.3 Acoustic data	15
4.4 Simulation	21
4.5 Fish identification	22
5 Discussion	25
5.1 WBAT failure	25
5.2 Species	26
5.3 Perspectives on prey aggregation and potential seabird response and WBAT as a monitoring tool	27
5.4 Scale and Spatial Distribution and potential placement of WBAT stations	28
5.5 Diel Pattern	29
5.6 Behaviorally-Informed Modeling and use of WBAT as a tool for improvement	29
5.7 Interpretation of Simulation Results	31
5.8 General discussion and future WBAT applications	31
6 Conclusions	33
7 Quality Assurance	34
References	35
Justification	37

Samenvatting

Dit rapport presenteert de resultaten van het MONS-pilotonderzoek naar het potentieel van stationaire echoloodinstrumenten (WBAT) voor langetermijnmonitoring van de beschikbaarheid van pelagische vis en hun relevantie voor foeragerende zeevogels in de zuidelijke Noordzee. De Nederlandse kustzone in de zuidelijke Noordzee wordt over het algemeen beschouwd als een ecologisch belangrijk gebied voor zeevogels die afhankelijk zijn van het in hoge dichtheid voorkomen van aan het oppervlak zichtbare visscholen. Echoloodinstrumenten werden ingezet in de windparken Borssele (zuidelijke Nederlandse kust, nabij de Belgische grens) en Hollandse Kust Noord (ter hoogte van Noord-Holland). Helaas zijn de analyses, vanwege een technische storing in de dataverzameling op de locatie Hollandse Kust Noord, beperkt tot Borssele.

Pelagische vissen worden hier beschouwd als een component van het middentrofische niveau, die energie overdragen als een belangrijke prooi. Ze vormen een essentiële voedselbron voor een breed scala aan zeezoogdieren, zeevogels en grotere roofvissen. De foerageerstrategieën van toproofdieren variëren afhankelijk van de beschikbaarheid en toegankelijkheid van prooien (die zelf variëren met seizoenen, diepte, tijdstip van de dag, enz.). Voor zeevogels is de overvloed aan prooien belangrijk, maar de locatie van prooien op geringe diepte in de waterkolom kan van groter belang zijn voor zeevogels, met name die met beperkte duikmogelijkheden. Met behulp van de WBAT-gegevens van windpark Borssele werd een methode ontwikkeld om tijdreeksen van beschikbare visbiomassa voor zeevogels af te leiden. Eerst werd een analyse uitgevoerd van tijdelijke veranderingen in de dichtheid van pelagische vissen. Vervolgens werd een ruimtelijke simulatie uitgevoerd om de verspreiding en toegankelijkheid te schatten van vanaf het oppervlak zichtbare prooiplekken. De afstanden tussen deze plekken werden gebruikt om de potentiële foerageerinspanning van zeevogels af te leiden.

De soortidentificatie van vis werd ondersteund door vangstgegevens uit de buurt van de WBAT. Deze bevestigden dat sprot (*Sprattus sprattus*) de dominante soort was die bijdroeg aan de akoestische reflectie. De gebruikte vangstgegevens waren afkomstig van de International Bottom Trawl Survey (IBTS), die inzicht gaven in de bredere structuur van de visgemeenschap in het Borssele-gebied. Er werden voor dit project ook specifiek kieuwnetmonsters genomen, maar de resultaten hiervan werden als niet-representatief beschouwd.

WBAT-gegevens, met verticale en diagonale resolutie, kunnen helpen de kloof te overbruggen tussen het foerageergedrag van zeevogels op locatieniveau en de beschikbaarheid van prooien, en bieden empirisch bewijs om deze zwakke verbanden in realtime te testen. Stationaire echoloodsystemen blijken krachtige instrumenten te zijn voor het vastleggen van de dynamiek van visbiomassa en diepteverdelingen op een fijne tijdschaal. Dit type gegevens is met name relevant bij het beoordelen van de voedselbeschikbaarheid van visuele foerageerders zoals zeevogels. De gegevens tonen duidelijk aan dat WBAT's, wanneer ze worden geïntegreerd met ruimtelijke simulaties en strategisch worden ingezet over ecologische gradiënten, kunnen dienen als robuuste indicatoren voor de ecosysteemfunctie en de beschikbaarheid van prooien.

Akoestische onderzoeken met behulp van schepen leveren gegevens op met een fijne ruimtelijke verdeling, soortenidentificatie door middel van trawlvisserij en aanvullende ecosysteemobservaties zoals de aanwezigheid van zoöplankton en zeevogels. Dergelijke onderzoeken zijn echter momentopnames en kostbaar. In die context zijn stationaire echoloodsystemen complementair aan monitoring met een fijne tijdsresolutie. Door beide methoden te combineren, kan de dynamiek van pelagische vissen zeer effectief worden gemonitord. Een hybride monitoringstrategie wordt aanbevolen, waarbij jaarrondgegevens van WBAT's worden gecombineerd met periodieke onderzoeken met behulp van schepen voor ruimtelijke kalibratie en ecosysteemcontext. Op basis van dit en gerelateerd onderzoek zou een optimaal netwerk ongeveer 6-10 WBAT's omvatten, verspreid over belangrijke habitattypen – zoals estuaria, getijdenfronten, offshore zandbanken en windenergiegebieden – om de ruimtelijke variabiliteit vast te leggen die relevant is voor zowel prooien als roofdieren.

Bovendien neemt de kracht van WBAT's aanzienlijk toe wanneer hun uitkomsten worden gecombineerd met andere milieudatasets, waaronder primaire productiviteit, zoöplanktondichtheid, tracking van zeezoogdieren en vogels, hydrografische kaarten, troebelheid, waterstratificatie en zelfs geluidsvervuiling. Deze geïntegreerde aanpak verbetert de mogelijkheid om ecologische patronen en factoren te identificeren, wat informatie oplevert voor ecosysteem gebaseerde beheer- en beschermingsstrategieën voor zeevogels en mariene voedselwebben langs de Nederlandse kust en de bredere zuidelijke Noordzee.

Summary

This report provides the results of the MONS pilot investigation on the potential of stationary echosounders (WBAT) as a tool for long-term monitoring of pelagic fish availability and their relevance to seabird foraging in the southern North Sea. The Dutch coastal zone along the southern North Sea in general is considered an ecologically important area for marine birds that rely on locating surface-visible, high-density fish schools. Echosounders were deployed inside the Borssele (southern Dutch coast, near the Belgian border) and Hollandse Kust Noord (offshore from North Holland) wind farms. Unfortunately, due to technical failure of data collection at the Holland Kust Noord site, analyses are limited to the Borssele deployment.

Pelagic fish here interpreted as a mid-trophic level component, transferring energy as an important prey item. They are a vital food source for a wide array of marine mammals, seabirds, and larger predatory fish. Foraging strategies of top predators vary depending on prey availability and accessibility (itself varying with seasons, depth, time of day, etc). For seabirds, prey abundance is important but the location of prey at shallow depths in the water column may be more critical, especially for those with limited diving capabilities. Using the WBAT data from the Borssele wind farm, a method to derive time series of available biomass to seabird was developed. First, an analysis of temporal changes in density of pelagic fish was conducted. Then, a spatial simulation was conducted to estimate the distribution and accessibility of surface-visible prey patches. Nearest-neighbour distances between these patches were used to infer potential foraging effort by seabirds.

Species identification was supported by trawl samples collected near the WBAT, which confirmed sprat (*Sprattus sprattus*) as the dominant species contributing to acoustic backscatter. Gillnet sampling also occurred, though results were considered non-representative. Additional context was drawn from the International Bottom Trawl Survey (IBTS), which helped interpret the broader fish community structure in the Borssele area.

WBAT data, with vertical and diel resolution, can help bridge the gap between patch-level seabird foraging behaviour and prey availability, offering empirical evidence to test these weak associations in real time. Stationary echosounders proved to be powerful tools for capturing fish biomass dynamics and depth distributions at a fine temporal scale. This type of data is particularly relevant when assessing food availability of visual foragers like seabirds. The data clearly show that when integrated with spatial simulations and deployed strategically across ecological gradients, WBATs can serve as robust indicators of ecosystem function and prey availability.

Vessel-based acoustic surveys provide data at a fine spatial distribution, species identification through trawling, and additional ecosystem observations such as zooplankton and seabird abundance. However, such surveys are snapshots in time and are costly. In that context, stationary echosounders are complementary with monitoring at a fine scale temporal resolution. Combining both methods allows one to monitor the dynamics of pelagic fish very effectively.

A hybrid monitoring strategy is recommended, combining year-round data from WBATs with periodic ship-based surveys for spatial calibration and ecosystem context. Based on this and related work, an optimal network would include approximately 6–10 WBATs distributed across key habitat types—such as estuaries, tidal fronts, offshore sandbanks, and wind farm zones—to capture spatial variability relevant to both prey and predators.

Moreover, the power of WBATs increases significantly when their outputs are combined with other environmental datasets, including primary productivity, zooplankton density, marine mammal and bird tracking, hydrographic maps, turbidity, water stratification, and even noise pollution metrics. This integrated approach enhances the ability to identify ecological patterns and drivers, informing ecosystem-based management and conservation strategies for seabirds and marine food webs along the Dutch coast and broader southern North Sea.

1 Introduction

Maintaining the marine environment in a “healthy” condition is an important political and societal objective, which has to be achieved while the marine environment is already under pressure by anthropogenic activities, especially in the southern North Sea. The renewable energy transition introduces extra complexity into the activities in the marine environments, hence, complicates the implementation of such objectives. The North Sea Agreement (NSA) states that the planned transition should comply with the carrying capacity of the North Sea. The NSA outlines the need for an integrated and systematic research and monitoring program that forms the base for knowledge about the functioning of the North Sea.

The Monitoring-Research-Nature Recovery-Species Protection (MONS) program aims to answer the central question of how the changing use of the North Sea fits within the ecological capacity of the North Sea. The program should provide the knowledge needed for achieving a healthy and resilient ecosystem in which nature, the generation of sustainable wind energy and profitable food production go hand in hand. This knowledge is necessary to be able to determine how the transitions can be implemented in such a way that ecosystem functioning is not jeopardized, nature objectives are achieved, fisheries are ready for the future and remain within the carrying capacity of the North Sea.

To this end the MONS program developed an integral and systematic monitoring and research program that focuses on the physical, chemical, and biological parameters for the functioning of the ecosystem and on (the variation of) the occurrence of birds, bats, benthic animals, fish, and marine mammals. This forms the framework for research that is planned to be carried out over a ten-year period in order to be able to answer the knowledge questions as formulated in the NSA (OFL 2020, Asjes et al. 2021).

As part of the MONS program, a monitoring component was designed directed at (small) pelagic fish species in the North Sea (Couperus et al. 2022). This component considers pelagic fish as a source of food for higher trophic levels, mainly seabirds. It consisted of two parts: 1) temporal and spatial distribution of pelagic fish in the offshore open waters, and 2) temporal distribution of fish in the surf zone. The following activities of the proposed monitoring program (Couperus et al. 2022) were granted:

- 1) A coastal hydroacoustic survey in January and June
- 2) Connection of these coastal surveys with international surveys
- 3) Sampling of the surf zone throughout the spring and summer season
- 4) Stationary year-round sampling: WBAT (pilot)
- 5) Gill net sampling near the stationary sampling

The results of activities 1-3 were reported in Couperus et al. (2024) showing the timing of arrival and growth of juvenile fish in the surf zone and a winter and summer snapshot of the distribution of small pelagic fish, mainly sprat (*Sprattus sprattus*) in the Dutch coastal waters (~10 m water depth to 20 nautical miles offshore). The activities 4 and 5 were delayed owing to permit and permission processes. The details and results of these delayed activities are provided here, with particular focus on analysing the findings in the context of MONS' knowledge questions (Asjes et al. 2021), especially how they relate to the food availability and its implications for bird populations.

2 Objectives

The overall objective of MONS is to collect and analyse data of the North Sea ecosystem in order to understand and assess the potential impacts of anthropogenic activities. The monitoring designed for pelagic fish must contribute to this overall objective by providing data on the temporal and spatial distribution of (small) pelagic fish. The central knowledge questions over a period of 10 years that the pelagic fish monitoring program should answer are:

- 1) *What is the distribution of small pelagic fish species in Dutch waters, by season and from year to year?*
- 2) *How can these geographical and temporal distributions be explained by the knowledge on life history of the species involved, in terms of behaviour and habitat requirements?*

These questions cannot be answered based on a single year of data collection and a single method of monitoring. Therefore, a multi-year monitoring program including different methods was proposed (Couperus et al. 2022). In Couperus et al. (2024), the results of the first monitoring year using the common, traditional synoptic acoustic methods of monitoring pelagic fish were reported and discussed. Here, in addition to the reported results of the traditional method, the results of the innovative technique using stationary autonomous echosounders are reported.

The traditional acoustic surveys on a vessel provide a snapshot in time of the geographical distribution of pelagic fish. In MONS two snapshots in a year (winter, and early summer) are made this way, and therefore a knowledge gap exists with regards to the temporal distributions of pelagic fish in between.

The objective of the stationary monitoring is to provide insight in the temporal distribution of the pelagic fish over a longer time in addition to the large geographical scale snapshots. Additionally, this method provides knowledge on the dynamic processes occurring over longer and finer temporal scales. The expectation is that knowledge on the diurnal and schooling behaviour, and the position of the pelagic fish in the water column can be gained (Holliday et al. 2010, Solberg 2017). This could provide insight in the accessibility of the fish for their predators. Ultimately, the idea has been suggested that a network of stationary acoustics could replace the expensive ship-based monitoring, providing temporal and geographical data.

When the first plans for the MONS pelagic monitoring were developed, the stationary acoustics weren't in use in Dutch water yet. Since then, some studies in different environments were done, for example, in the Marsdiep, inlet to the Wadden Sea (Maathuis et al. 2024b), or near wind farms (Kok et al. 2021). Deployment in the open sea for a longer period, however, still had to show its value. Therefore, this study was a pilot with measurements done on two locations combined with test fishing for species identification using gillnets. The main objective of this pilot study is the evaluation and discussions on its further use in answering the MONS questions.

3 Methods

3.1 Locations

The pilot study assumed the placement of two stationary acoustic landers in the Dutch coastal waters. The specific location was not of direct importance. Putting landers out in the open sea poses threats, i.e. bottom trawl fishing and requires legislative approval. Placing them within windfarms was considered to reduce the threats of fishing and other shipping activities. It however required permission of the windfarm operators and still legislative approval. Talks on the permissions and approval resulted in a location in the Borssele windfarm and a location in the Hollandse Kust Noord (Hk(n)) windfarm, one in the south close to the Belgium border and the other offshore in front of the coast of Noord Holland (Figure 3-1).

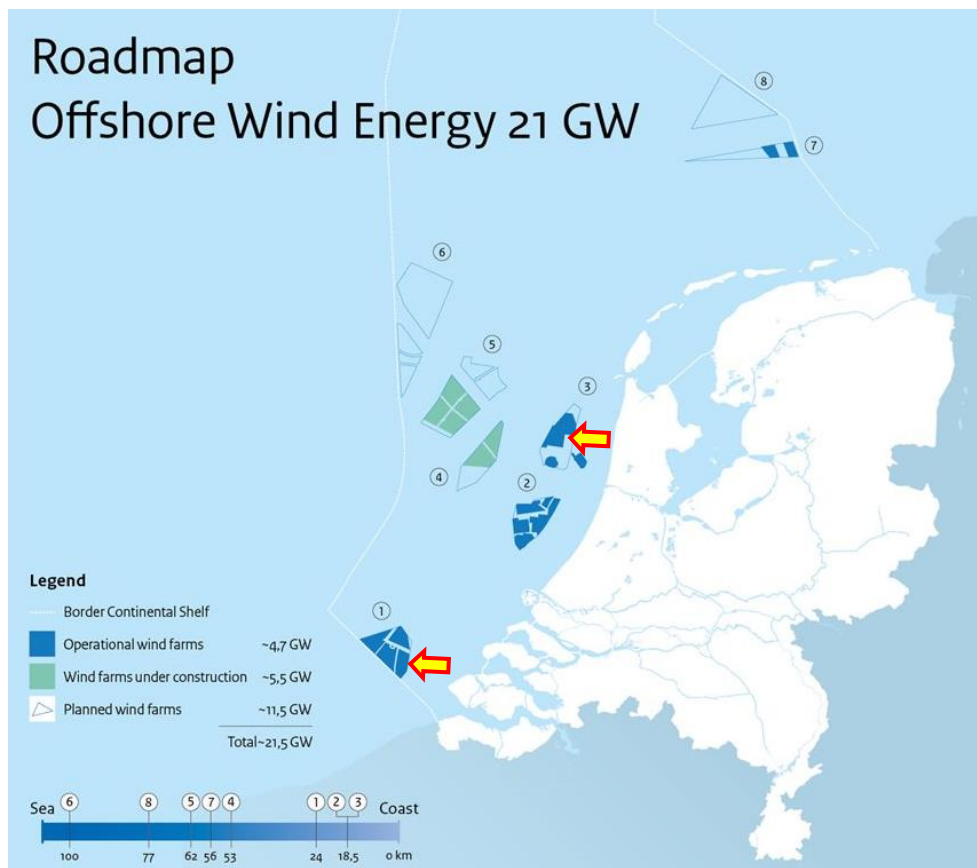


Figure 3-1: Locations of the current and planned wind farms in the Dutch exclusive economic zone. Number 1 and 3 are respectively the Borssele and Hollandse kust Noord windfarms in which the landers were placed (Figure from Noordzeeloket).

Both windfarms are divided in areas for multi-use (mariculture, nature development, static gear fishing, generation of sustainable energy). The areas assigned for static gear fishing were considered the most appropriate to place the landers (Figure 3-2) as the use of static gear near the landers to catch fish for species identification was also part of the plans. The landers were placed on the sandy seafloor away from the monopiles and the hard scour beds. The lander in Borssele was placed at N 51° 37' 43.4316 E 3° 4' 50.6856 (WGS84) and in Hk(n) at 52° 39' 30.2616 E 4° 14' 57.876 (WGS84).

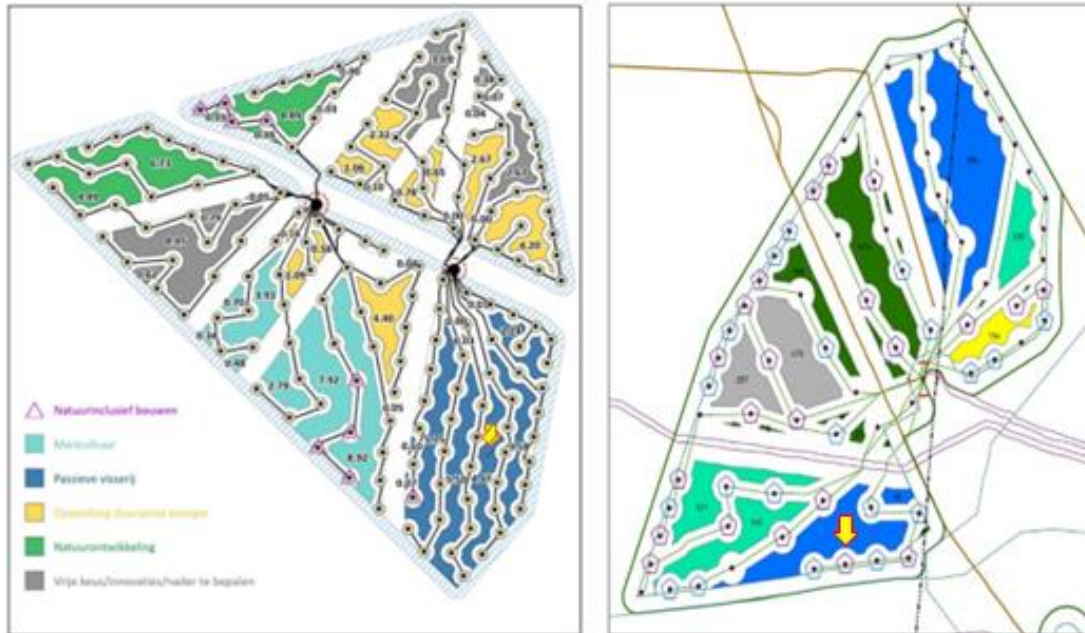


Figure 3-2: On the left is Borssele wind farm and on the right the Hollandse kust Noord (Hk(n)) wind farm. In both farms areas are assigned for multiuse purpose, with the blue areas indicating locations for static gear fisheries. The yellow arrows show the locations of the landers with acoustic equipment (Figure from Noordzeeloket).

3.2 Frames and acoustic settings

Data were collected using a bottom-mounted wideband autonomous transceiver (WBAT) echosounder attached to a stainless-steel frame (Figure 3-3). The battery powered Simrad EK80 WBATs were equipped with a 18° split-beam transducer at 38 kHz, and a 7° single beam at 200 kHz. The WBATs were programmed to transmit 1024 μ s pulses in wideband mode at a ping interval of 0.64 seconds, using a transmission power of 113 W. Wake-up intervals were set at 1.5 hours, with 12 short recordings (approximately 5 minutes each) and 4 long recordings (12 minutes each) conducted per day. Statistical analysis indicated that short recordings produced mean backscatter values comparable to those from long recordings, though longer recordings increased the likelihood of capturing aggregation characteristics. Shorter pulse durations were implemented to help conserve battery life.

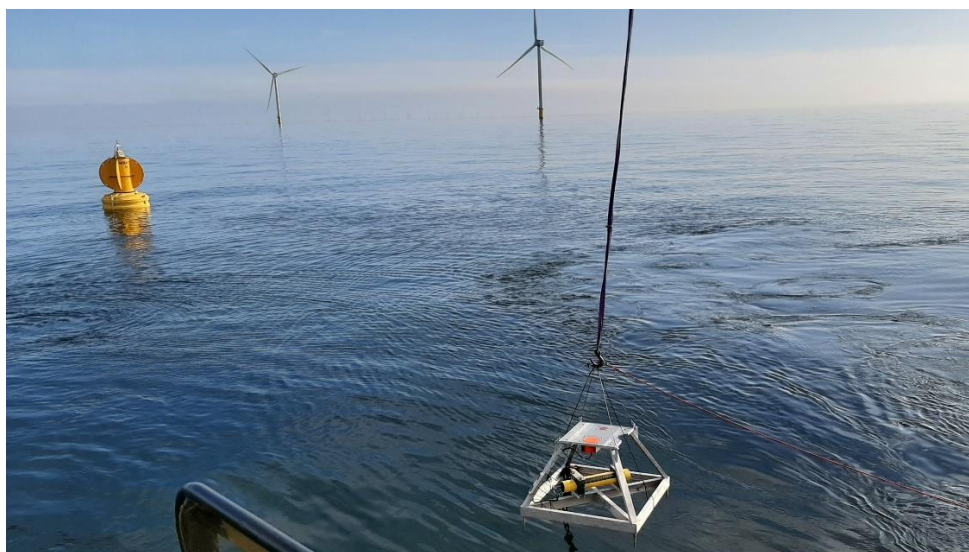


Figure 3-3: Frame with WBAT (yellow) and the two receivers (orange) during deployed in Hk(n), with in the background the yellow demarcation buoy.

3.3 Deployment and retrieval

The deployment of the frame was done from a Buoyage vessel of the shipping company of RWS. First a concrete block of 1000 kg is lowered to seafloor, attached to this block a demarcation buoy is attached (Figure 3-3). A 50 m chain is extended from the concrete block to which the frame with the WBAT is attached. The frame in Borssele was deployed on 18 September 2024 and retrieved on 11 February 2025 after almost five months on the seafloor. The frame in Hk(n) was deployed on 18 October 2024 and retrieved on 13 March 2025, also almost five months.

3.4 Gillnet fishing

The strength of the acoustic signals gives some indication of species type. However, to be certain of the occurrence of species in the surrounding of the landers another method is required. Active fishing in the windfarms was expected to be not allowed, therefore static gear fishing using gillnets was proposed. Earlier activities in a wind farm showed that variety of species in a range of length classes could be caught using multi-mesh gillnets (van Hal et al. 2017). These gillnets placed on the seafloor targeted demersal species. As here pelagic species in the water column were the target, in consultation with local gillnet fishermen, the demersal multi-mesh gillnets (Figure 3-4) were altered such that they would be floating about two meters of the seafloor, while being anchored on the seafloor with on each side a 15 kg Bruce anchor and marked on both sides with buoys (Figure 3-5).

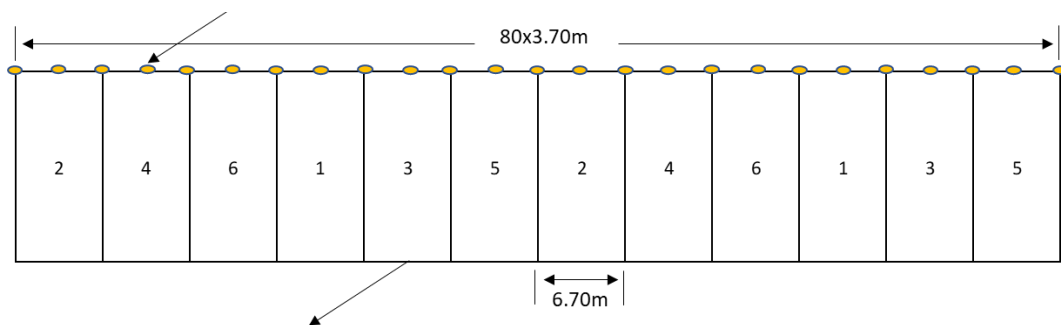


Figure 3-4: Configuration of the multi-mesh panels of the gillnets. 1 = 65mm 1.5 x 3 multimonoofil, 2 = 34mm 0.33 monofil, 3 = 40mm 0.20 monofil, 4 = 55mm 1.5 x 3 multimonoofil, 5 = 12mm 210/4 nylon, 6 = 48.5mm 0.20 monofil.

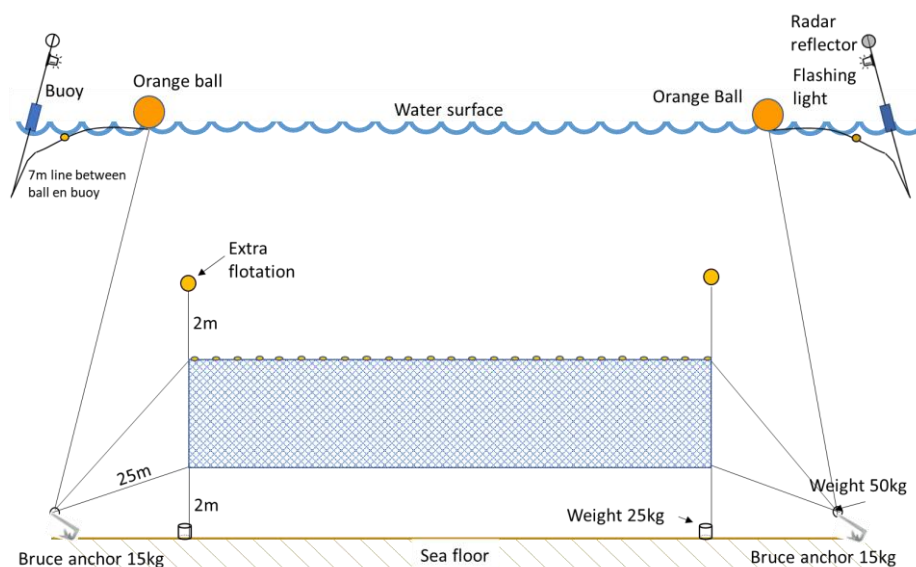


Figure 3-5: Schematic of the placement of the multi-mesh gillnet.

At both locations two gillnets would be placed each month, depending on the weather conditions. In Borssele the nets were placed and retrieved by the local gillnet fishermen D. Zoetewij with the vessel YE152, and in Hk(n) this was done by P. Zaaier with the vessel IJM7. The nets were placed during the day and retrieved after a full night in the water on the next day. The catches were collected and sorted to species level by panel of the net and then measured to the cm-below (10-10.9 cm is considered 10 cm).

3.5 Analyses

Raw acoustic data analysis

All acoustic analyses presented in this study were based exclusively on data collected at 38 kHz, a frequency commonly used for detecting pelagic fish such as sprat due to its sensitivity to swimbladder-bearing species. WBAT data were imported into Echoview software for processing. Initial pre-processing was to remove undesired reflections and noise, particularly since the upward looking measurements causes reflections associated with the water surface. This surface reflection is often contaminated with bubble-induced noise, which can penetrate deeper into the water column when wind and wave energy increase (De Robertis and Higginbottom 2007).

To address this, an automated algorithm in Echoview was applied to detect and remove surface noise artifacts. However, surface noise removal via automation is not always reliable; the algorithm may mistakenly exclude fish schools located near the surface or, conversely, include detached bubble layers that do not represent biological targets. To compensate for these limitations, visual inspection was conducted across the echogram using three-to-four-day time windows. This step allowed for the manual refinement of surface boundary layers, and the removal of bubble interference and sediment-related disturbances originating near the seabed—issues known to degrade data quality if left uncorrected (Ryan et al. 2015). After this manual curation, the cleaned dataset was exported from Echoview with a resolution of 1-meter vertical intervals and 1.5-hour temporal intervals to balance precision with manageable data volume. Regions around extreme backscatter values were visually re-checked to ensure that no residual noise was falsely interpreted as fish echoes. Only after confirming data integrity were automatic fish school detection algorithms applied, along with frequency response analysis for potential species discrimination (MacLennan et al. 2002). Because the primary aim of this study was to assess the likelihood and spacing of high-density surface-visible fish aggregations, rather than to characterize full school morphology, analyses focused exclusively on areas of intense backscatter and did not include broader aggregation metrics such as school shape or layering.

A total of 2335 separate wake-up cycles were recorded, using a combination of 5-minute and 12-minute sampling intervals. Of these, 2227 cycles (approximately 95%) were deemed of good quality. The remaining 5% were excluded due to acoustic interference caused primarily by adverse weather conditions (e.g., surface wave action), which degraded signal quality throughout much of the water column. Daylight conditions were determined for each cycle based on geographic coordinates of the WBAT deployment, using sunrise and sunset data from SunEarthTools.com. Of the high-quality recordings, 820 cycles (37%) occurred during daylight hours, while the remaining 63% took place during twilight or nighttime conditions.

Temporal Patterns in Fish Density and Ground-Truthing with Trawl Data

To assess diel variation in pelagic fish density, acoustic backscatter measurements collected by the WBAT over a five-month deployment period were analyzed with a focus on high-density fish aggregations. Acoustic data were processed into Nautical Area Scattering Coefficient (NASC) values. To ensure the analysis targeted biologically relevant and visually detectable fish schools, values corresponding to densities below approximately ten individuals per square meter—roughly the backscatter equivalent of 8–10 cm sprat (*Sprattus sprattus*)—were filtered out.

Hourly trends in fish presence were visualized using boxplots for each 1.5-hour interval, with NASC values log-transformed to account for the skewed distribution of acoustic intensities. A locally estimated scatterplot smoothing (LOESS) curve was applied to highlight overall temporal trends in fish density across the diel cycle. This approach has been previously applied in diel fish behavior studies using stationary acoustics (De Robertis et al. 2003, Klevjer et al. 2012).

To provide biological context and aid interpretation of the acoustic data, trawl samples from the NS-IBTS (North Sea International Bottom Trawl Survey) were obtained from ICES' DATRAS database for Quarter 3 of 2024 and Quarter 1 of 2025. These samples were filtered to include only those collected near the WBAT deployment site in both space and time. A total of three relevant samples were selected: one from the Danish survey team in September 2024 and two from the French team in January 2025. For consistency with the acoustic focus, only pelagic fish and gelatinous zooplankton were retained in the analysis. These data were used to assist in the ecological interpretation of the backscatter patterns observed in the WBAT dataset, especially in understanding the species composition associated with high-density surface layers.

Simulation based on WBAT measurements

To evaluate how surface-visible fish schools affect seabird foraging in the southern North Sea our spatial simulation was designed using a 320-point grid (20 × 16) with 400 m X 400 m spacing across the Borssele Wind Farm zone (Figure 3-5). Each node in the grid represented a potential site for surface-exposed schools, which are critical for visual predators such as marine birds. Using observational probability data derived from the stationary echosounder, an experimental range of surface exposure probabilities from 0.001 to 0.15 was assigned to each grid point. In practical terms, a probability value such as 0.15 means that in 15% of the observation windows (e.g., daytime periods), a near-surface, high-density fish aggregation (NASC > 1000 within 0–5 m) was detected at that location.

We assumed that this location, where the WBAT was deployed, is broadly representative of the spatial dynamics within the wind farm area at the scale of our grid (8 km × 6.4 km). This assumption is supported by the relative known homogeneity of the site, although we acknowledge that finer-scale differences in bathymetry, hydrodynamics, or fish behaviour may exist. Rather than extrapolating acoustic data directly, we used the WBAT-derived surface school occurrence probabilities to parameterize a probabilistic model across the grid. Each grid point was treated independently and assigned a randomly drawn presence/absence outcome using a binomial trial based on the shared input probability. This method does not create spatial structure directly from the WBAT data but instead allows the generation of randomized but ecologically plausible spatial scenarios, informed by the observed rate of school occurrence, and constrained by the known patchiness of distributions (particularly sprat). While the simulation lacks explicit spatial structure, each grid point was treated independently using a probability derived from a single WBAT location, the primary aim was to demonstrate the potential of using WBATs for monitoring surface-exposed pelagic fish relevant to seabird feeding. This proof-of-concept shows how stationary acoustic instruments can inform probabilistic spatial models, even in the absence of dense spatial coverage. Currently, this approach does not capture spatial autocorrelation or the natural clustering of prey, which are key features in our study area. However, with data from multiple WBATs or integration of vessel-based acoustic survey data, it would be possible to estimate spatial covariance parameters and incorporate them into more advanced simulation frameworks. This would allow for modelling of spatially structured pelagic fish occurrence and support more refined assessments of bird foraging dynamics.

We simulated whether a school was present using a binomial trial for each point—a method that realistically captures the patchiness and variability of prey seen in marine acoustic data (Fauchald and Tveraa 2006, Benoit-Bird et al. 2013). The southern North Sea exhibits considerable environmental heterogeneity—from nearshore fronts to offshore wind farm influence zones—that modulates prey availability (Camphuysen and Leopold 1994, Peschko et al. 2024). From simulation outputs, we identified the set of grid points with a positive (“present”) draw. We then computed pairwise nearest-neighbour distances among these sites using the Haversine formula to estimate minimum flight distances needed for seabirds to encounter successive foraging patches. While the metric used in the simulation does not guarantee visibility to birds, it serves as a reasonable proxy for potential prey availability within their visual detection range. Travel distances are a critical foraging constraint in central-place foragers like sea birds during chick provisioning (Wanless et al. 2005). These distances help estimate foraging effort and energy budgets in relation to prey spatial structure, integrating spatial simulation with trophic dynamics for ecosystem monitoring.

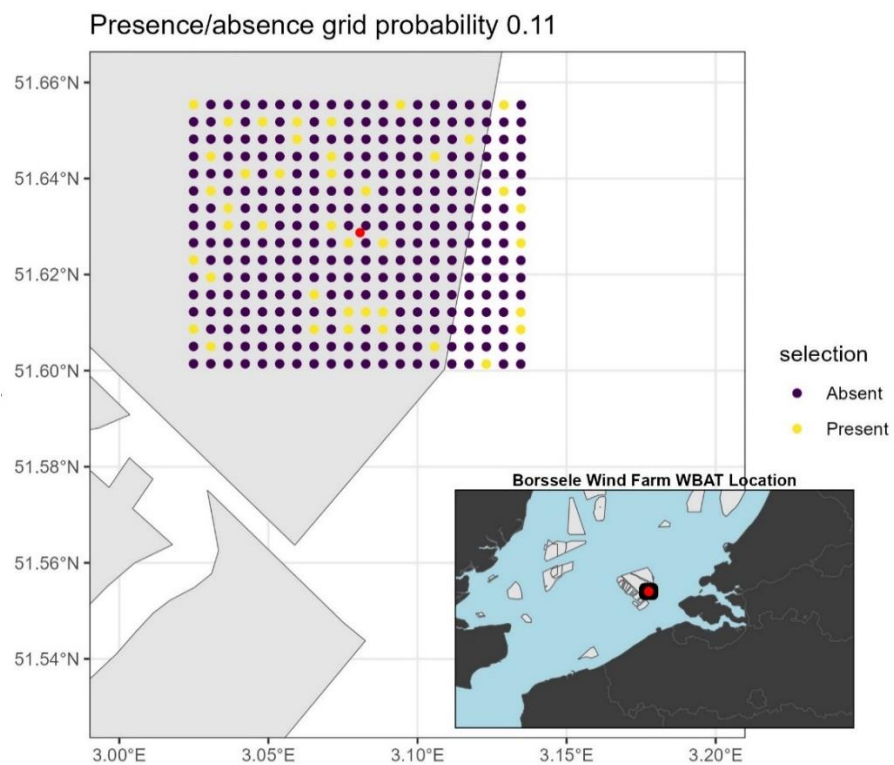


Figure 3-6: Example probability map showing presence (coloured) and absence (uncoloured) grid points based on a binomial threshold of 0.11. The background displays the Borssele Wind Farm area, providing spatial context to the grid placement.

4 Results

4.1 Gillnet fishing

The gillnet fishing depended on the weather conditions and the availability of the fishermen and WMR-field workers. In total six fishing activities in Borssele and two in Hk(n) have taken place. The first activity in Borssele took place already in July 2024 and in August 2024 in Hk(n), in both cases this was prior to the deployment of the frames, as expected deployment of the frames was delayed.

The fishing activities with the gillnet were a failure. Already, in the first deployment in Borssele the gillnets became heavily damaged. Large amounts of jellyfish were clogged in the nets (Figure 4-1), which ripped, due to the pressure, the meshes during retrieval. In Hk(n) the jellyfish resulted in less damage to the nets. Consultation with the fishermen brought to light that due to the strong currents in Borssele retrieval had to be done very fast. Owing to the local conditions there was no clear solution to reduce damage during retrieval in Borssele. During the second deployment in Hk(n), one of the two nets, became entangled making the deployment invalid.

The damage to the nets was not the only issue. The bigger issue was the limited catches, except for jellyfish (*Chrysaora hysoscella*, *Mnemiopsis leidyi* and some *Rhizostoma pulmo*). In Hk(n) only a single horse mackerel (8 cm) and a single mackerel (28 cm) were caught with the first deployment, and with the second deployment only a single horse mackerel (12.5 cm) was caught. In Borssele, some catches were larger, but then the catch was dominated by the benthopelagic species whiting, supplemented with some flatfish (plaice, dab and sole) (Table 4-1). These were not the pelagic species targeted and expected. The presence of these demersal species indicated that the gillnets were likely laying down on or close to the seafloor during the strong tides.



Figure 4-1: Retrieval of the multi-mesh gillnet in wind farm Borssele (19 July 2024). Even though, most jellyfish fall out of the net during retrieval, the net was still clogged with *Chrysaora hysoscella*.

The length of the species caught in Borssele was 10 – 35 cm. The exceptions were the smooth hounds (*Mustelus asterias*) and twait shad (*Alosa fallax*) of 47 cm. It was expected that the smaller pelagic fish (sprat, herring, and anchovy) would get entangled in the 12 mm mesh size, at least some had been caught in the multi-mesh gillnets in the wind farm Egmond aan Zee (van Hal et al. 2017). The only small fish were caught on the 28th of august, which included horse mackerel (*Trachurus trachurus*) of 10 -11 cm and a single sandeel of 12 cm. The catches in both areas indicate the presence of the pelagic species horse mackerel and mackerel (Table 4-1), and whiting which as a benthopelagic species might be occurring in the acoustic observations close to the transducers.

Table 4-1: Number of fish caught per multi-mesh gillnet deployment (two nets each deployment) in Borssele in 2024.

Species	19th July	28th Aug	5th Oct	31st Oct	5th Nov	13th Dec
Horse mackerel	11	5				
Mackerel	1	1	1			
Wijting			3	56	2	62
Bib					1	
Plaice	1		3	2		5
Dab		2		4	1	1
Sole	1		1			
Turbot			1			
Tub gurnard			1			1
Striped red mullet				1		
Starry smooth-hound			2			
Rock gunnel	1					
Sandeel sp.		1				
Twait shad		1				

4.2 WBAT

The Hk(n) deployment took place from 18 October 2024 to 13 March 2025. However, due to an internal error in the HKN WBAT, no data were collected at that site. As a result, the analyses presented here focus solely on the data from the Borssele wind farm. The Borssele unit was deployed on 18 September 2024 and successfully collected data until its recovery on 11 February 2025. In total 2335 separate wake-up cycles (5 and 12 minute) were recorded. 95% (2227) were considered of good quality. The discarded 5% was mainly due to bad weather, e.g. wave action affecting a large part of the water column impacting the acoustic observations. Of the good quality recordings, 820 wakeup cycles corresponded to daylight hours making 37% (Data acquired from "SunEarthTools.com" based on geographic location of the WBAT in Borssele), the other 63% is considered twilight or nighttime.

4.3 Acoustic data

MONS WBAT observations

The WBAT deployment at Borssele revealed occasional occurrences of fish densities far exceeding those observed during the MONS vessel-based acoustic surveys (Couperus et al. 2024). For example, Figure 4-2 shows an echogram from November 17, 2024, around 13:30 UTC, where an exceptionally dense aggregation appears—estimated at nearly 5,800 individual fish per square meter. In contrast, recordings from before and after this event show only 1–2 individuals per square meter. This highlights the highly patchy nature of small pelagic fish aggregations.

Due to very limited spatial coverage and relatively short temporal coverage, it is not realistic to derive a meaningful fish density estimate for a constrained area based on these observations. However, the

occurrence of high-density aggregations is a meaningful metric from the perspective of monitoring effort as it can be linked to food availability for the birds and other top predators. Such dense, transient schools likely attract predators, as they provide easier foraging opportunities. Since such high-density fish aggregations are relatively rare, detecting these events often requires either luck or increased sampling effort. This is a clear example where high-frequency measurements over longer periods, using fixed WBAT echosounders, become especially valuable —capturing temporal dynamics and rare events that cannot be resolved by traditional vessel-based surveys.

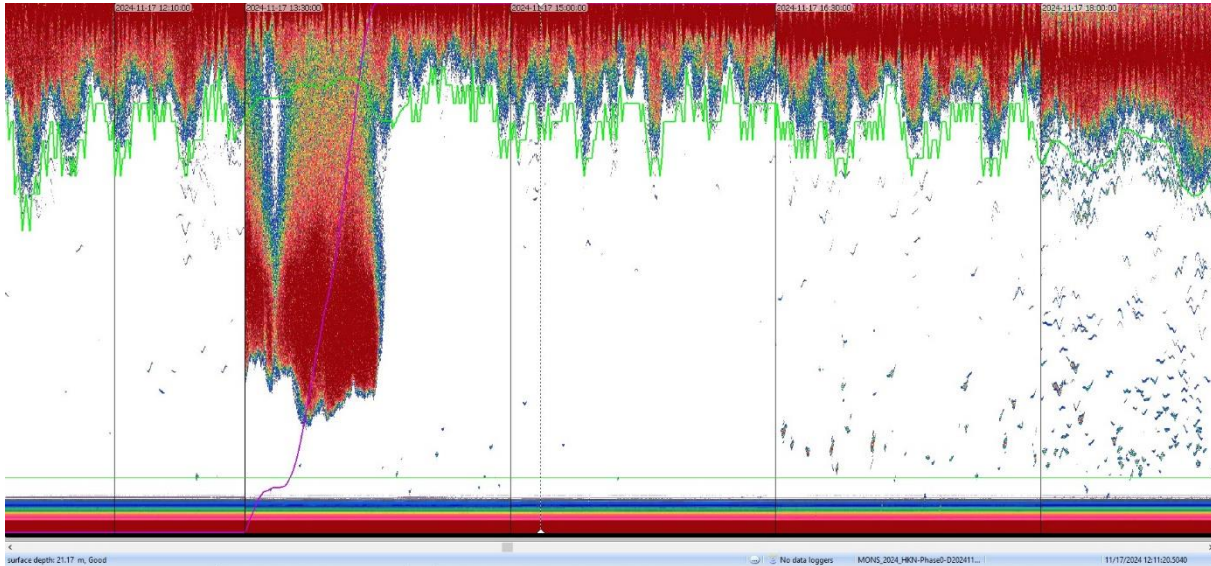


Figure 4-2: Echogram from November 17, 2024, with five recordings, the recording that started at 13:30 UTC shows an exceptionally dense fish aggregation ($\sim 5,800$ fish/m²). The dense red on the top of the images is the reflection of the surface in which wave action is visible. The green line automatically demarks this zone and excludes it for further analyses. Parts where automatic identification fails, such as in this subsurface school, a manual edit is performed based on visual judgement. The purple line is an integration line showing the point in the echogram where density jumps to a high value. This high-density aggregation illustrates the patchy and transient nature of small pelagic fish schools. The last two recordings show individual fish.

While such high-density aggregations are mainly expected to be seen during the daylight hours, the observation on January 18, 2025, around 19:30 UTC (Figure 4-3) occurred during the dark period of the day—when fish schools typically disperse and form looser layers. Nevertheless, the aggregation remained so tightly packed that it still resembled a typical daytime school. This suggests that, when packing density reaches to certain intensity, these aggregations can still be detected during nighttime hours. This finding suggests that when estimating probability of occurrence of these events, the nighttime observations can be potentially included.

The two panels on Figure 4-3 show the same aggregation observed with the 38 kHz (upper panel) and 200 kHz (lower panel). The fact that the observed intensity is similar in both echograms suggests that this was a fish with swim bladder and considering its characteristics it was most likely sprat. In the North Sea sprat occurs mainly in coastal waters, often in fjords or along the coastlines, at depths of 10-40 meters.

Additional examples of such dense fish aggregations can be observed in the WBAT data. On October 24, 2024, around 06:00 UTC, a notable early morning aggregation was recorded (Figure 4-4). Similarly, Figure 4-5 shows another dense school captured on October 30, 2024, around 18:00 UTC. These events further underscore the sporadic yet intense nature of pelagic fish schooling, particularly for sprat in this area, which, although occasionally detected by vessel-based surveys, often occur outside the typical observation windows of such traditional surveys. Frequency of occurrence of such high-density schools positioned close to the surface can be used to estimate food availability for the marine birds in different seasons.

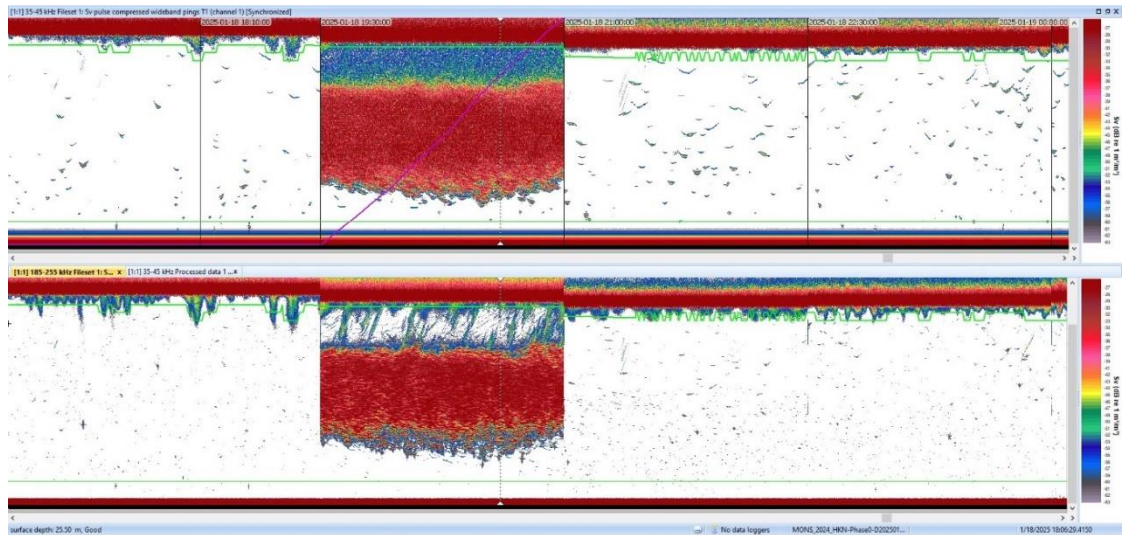


Figure 4-3: Echogram from January 18, 2025, at 19:30 UTC showing a dense nighttime fish aggregation detected at both 38 kHz (upper panel) and 200 kHz (lower panel). The similar signal intensity across frequencies suggests the presence of swim-bladdered fish, likely sprat (*Sprattus sprattus*).

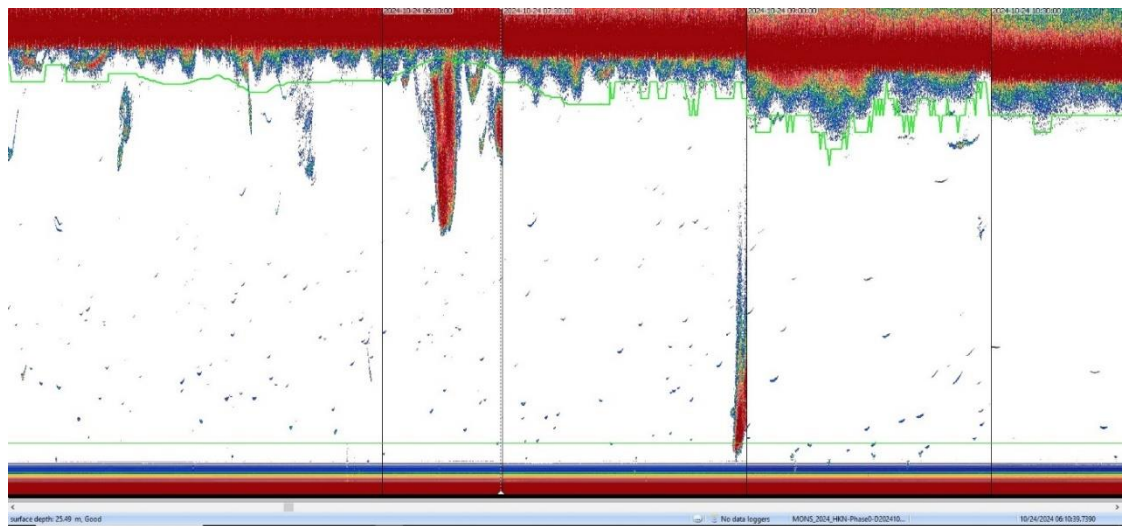


Figure 4-4: Example of a dense fish aggregation recorded on October 24, 2024, at 06:00 UTC. This further illustrates the sporadic yet intense nature of pelagic fish presence.

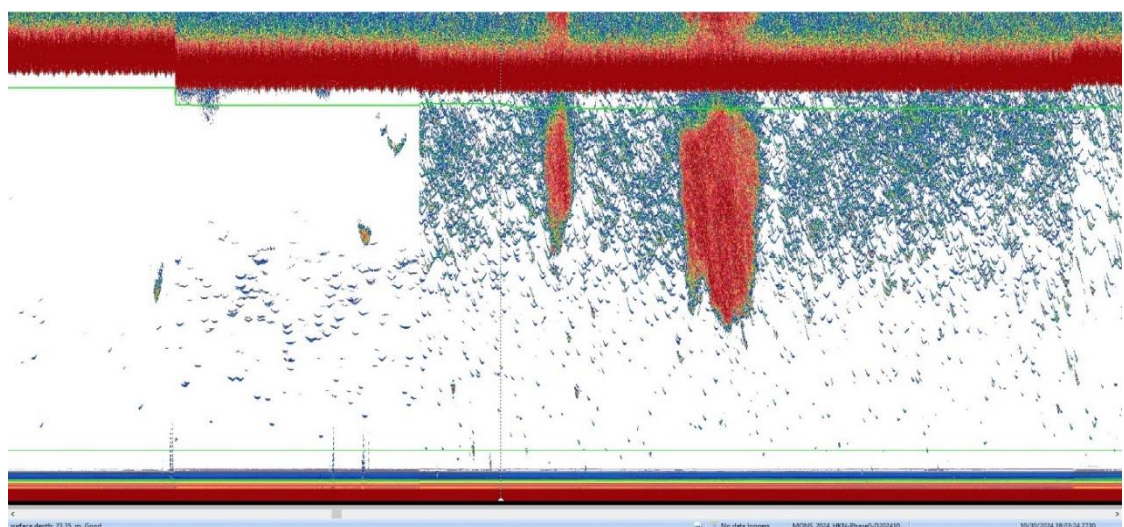


Figure 4-5: Another high-density aggregation observed on October 30, 2024, around 18:00 UTC. Such events emphasize the temporal variability in fish distribution.

The diel pattern aggregated for the five months of WBAT data shows on average higher acoustic backscatter density (NASC) during daytime (Figure 4-6), indicating daytime schooling behaviour. A distinct increase in fish density is shown from early morning, peaking between approximately 10:00 and 14:00, and gradually decreasing into the evening and night. The outliers, e.g. the highest density schools, however, show that equally high densities were observed at day and nighttime.

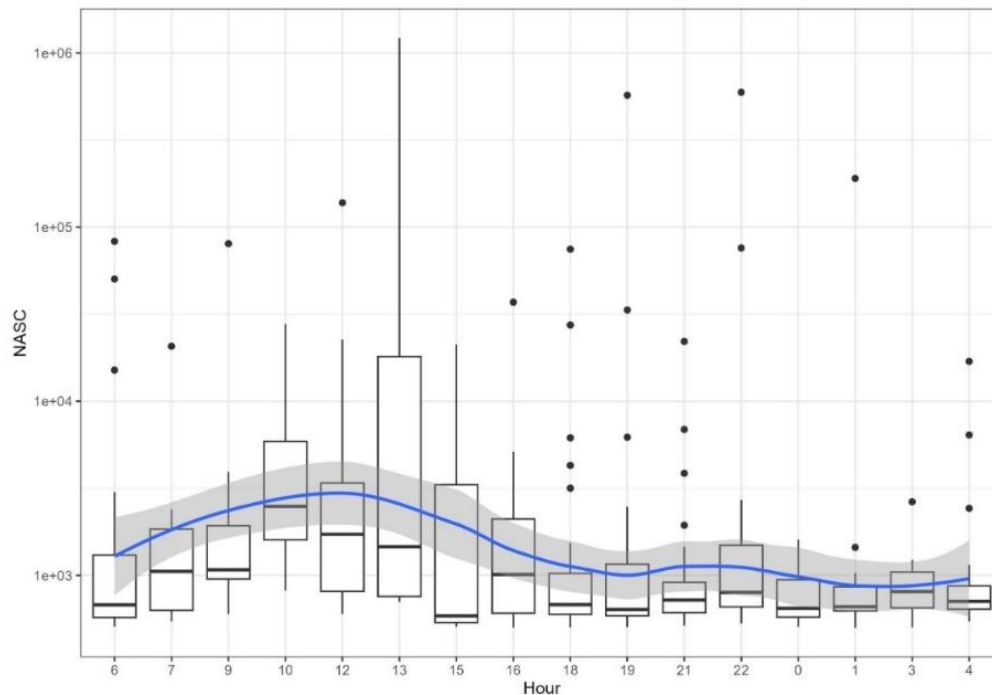


Figure 4-6: Hourly distribution of acoustic backscatter density (NASC) from five months of WBAT data, focusing on high-density fish observations. The y-axis shows NASC values on a logarithmic scale, and the x-axis represents the time of day. Boxplots show 1.5-hour intervals, with a LOESS curve indicating a daytime peak in fish density (10:00–14:00). This pattern suggests increased prey availability for visual predators like seabirds during daylight hours.

The full time series of acoustic backscatter measurements from the Borssele WBAT, separated by month from September 2024 to February 2025, shows high density fish aggregations near the surface in late October and November (Figure 4-9). Regular vertical shifts near the surface indicate tidal influences. Additionally, some events in December and January show elevated densities extending from depth to the surface, further highlighting potential access to prey for surface-feeding predators (Figure 4-9).

These episodic high-density fish aggregations, as illustrated in Figure 4-2 to Figure 4-5 and the overall trend in Figure 4-7, highlight the patchy and transient nature of small pelagic fish distributions in the Dutch offshore wind farms hence potentially marine birds access to dense fish schools greatly enhances foraging efficiency. The rare occurrence of these aggregations suggests that prey availability may be less predictable than previously assumed based on daytime surveys alone. These findings underscore the importance of continuous acoustic monitoring with stationary echosounders – WBATS – in revealing fine-scale temporal patterns that can influence the feeding behaviour and distribution of marine top predators.

The occurrence of dense fish aggregations located within 5 meters of the surface during daylight hours, conditions particularly relevant for surface-foraging predators, were identified and characterized (Figure 4-8). Although the 5-meter depth threshold was selected somewhat arbitrarily, it was guided by average underwater visibility estimates based on Secchi disk measurements from the MONS surveys, which typically ranged between 3.5 and 7 meters in these offshore areas. After filtering the data to retain only quality observations and defining the “day” period based on specific hourly intervals, high-density events ($\text{NASC} > 1000$) were isolated occurring in the shallower section. These events are rare, and their frequency is quantified by an occurrence factor (inverse of the number of observations per timestamp), then aggregated at daily and weekly scales. The resulting time series reveal when such near-surface fish aggregations are

most likely to occur. The final plots indicate a clear temporal structure in these events, with certain weeks, the weeks from 41 to 48 (From October 7th to November 25th) showing markedly higher occurrence, suggesting that prey availability for marine birds at a specific location may not be evenly distributed throughout the five months period but rather concentrated during specific periods.

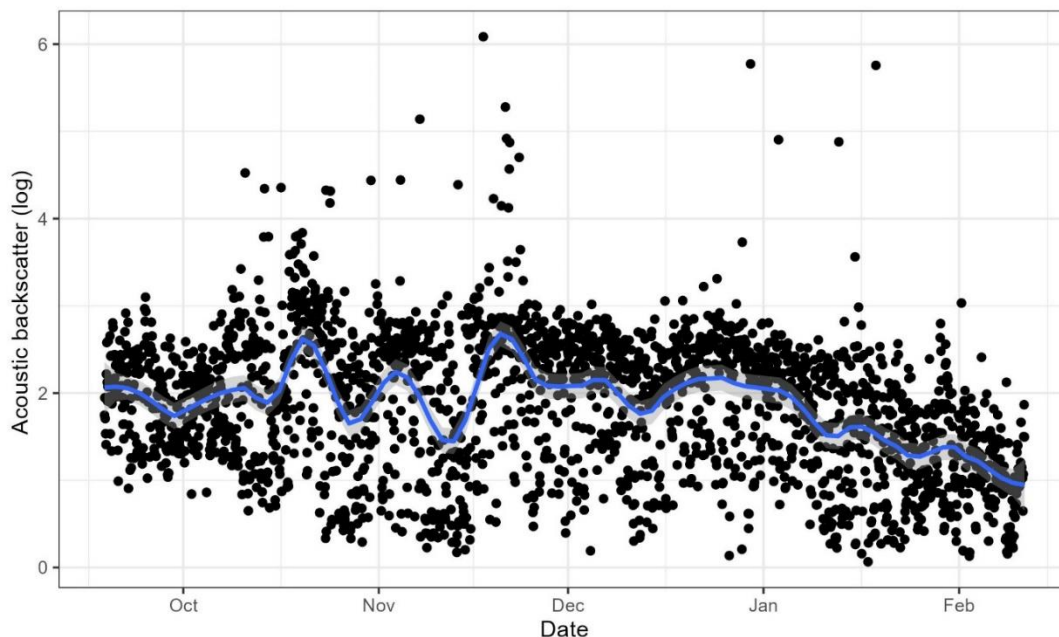


Figure 4-7: Integrated fish density per 1.5-hour duty cycle over the entire deployment period, shown on a logarithmic scale. Periodic fluctuations may reflect tidal and seasonal cycles, while the overall pattern likely relates to temperature changes and fish migration.

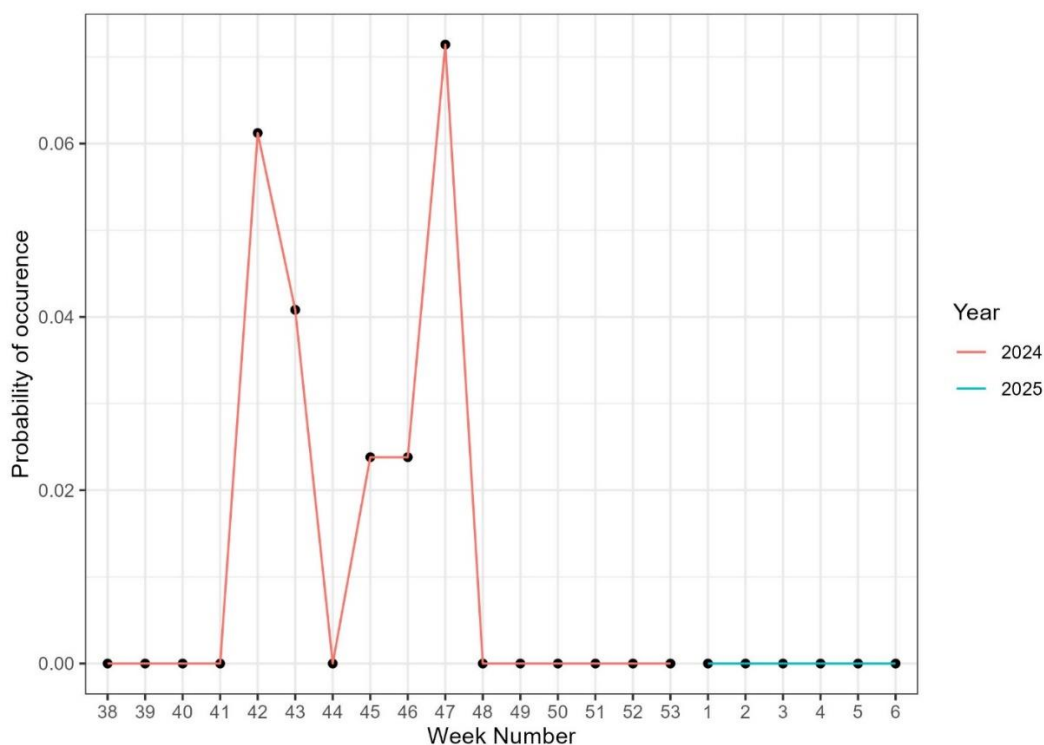


Figure 4-8: Occurrence of high-density fish aggregations (<5 m depth, NASC > 1000) during daylight hours at the Borssele site from September 2024 to February 2025. Points show daily maximum occurrence frequency; lines indicate weekly trends. Daylight information is acquired from "SunEarthTools.com" based on geographic location of the WBAT in Borssele and specific times of the wake-up cycles. Daylight recordings consisted of 37% of the data.

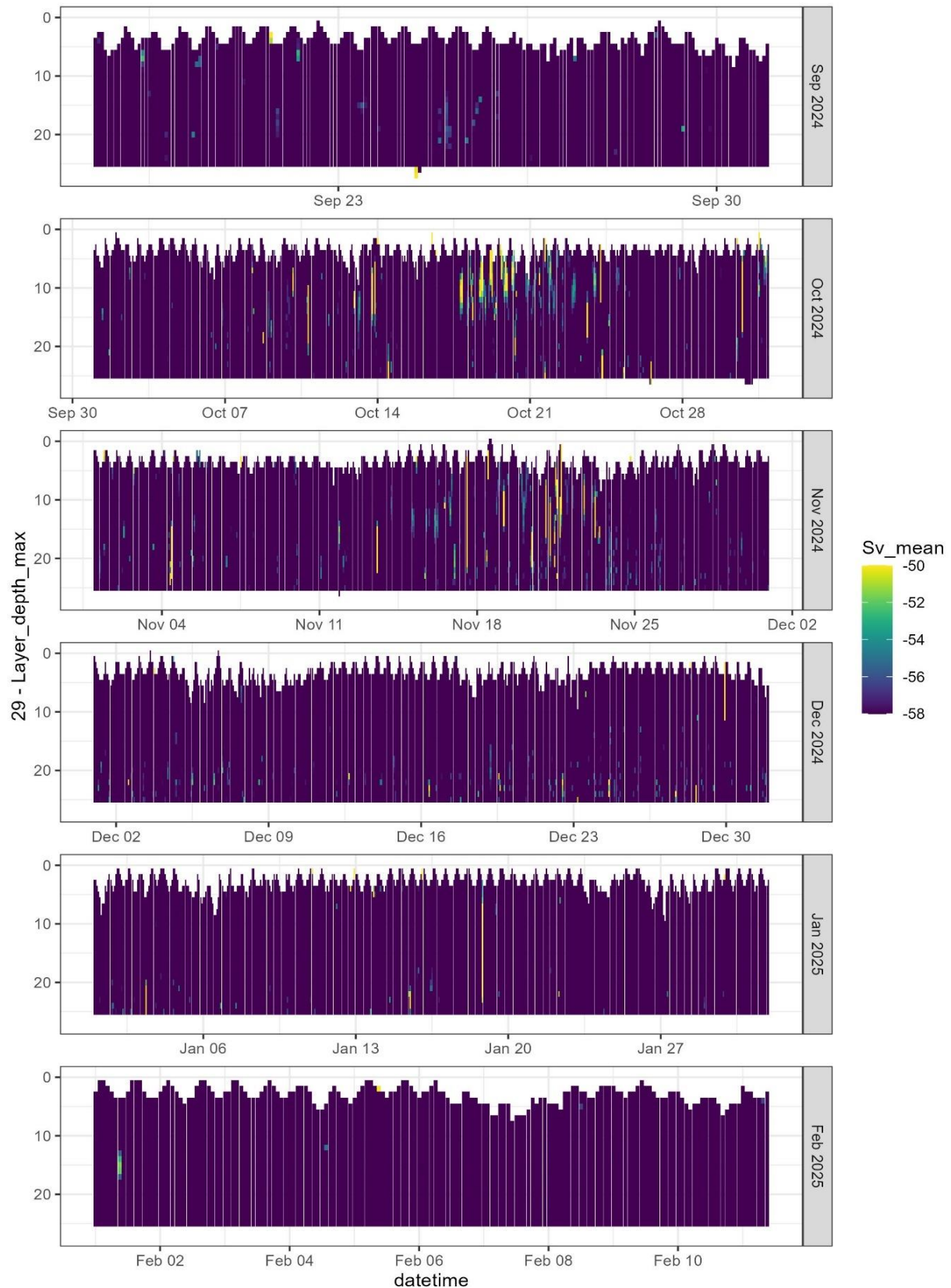


Figure 4-9: Monthly time series of acoustic backscatter from the Borssele WBAT (Sept 2024–Feb 2025). Higher fish densities (yellow) are shown; values below ~ 10 fish/m² (8–10 cm sprat) were filtered out. The measurements have a temporal resolution of 1.5 hours and a vertical resolution of 1 meter.

4.4 Simulation

Simulated Fish School Distribution

The spatial simulation generated various distributions of surface-exposed fish schools across the 320-point (20×16) grid within the Borssele windfarm, representing potential foraging patches for marine birds. For each simulated scenario, based on an assigned observational probability ranging from 0 to 0.15, we identified a unique set of grid points where fish schools were present. The binomial trial captured the inherent patchiness and variability characteristic of marine prey distributions (Figure 3-6). For example, at a probability of 0.05, the simulation typically resulted in approximately 16 out of 320 grid points indicating a fish school presence (i.e., $320 \times 0.05 = 16$ schools), though the exact spatial arrangement varied due to the stochastic nature of the binomial draws. Visual inspection of these simulated maps confirmed that lower probabilities yielded more sparse distributions of schools, while higher probabilities resulted in a greater number of available patches, reflecting the environmental heterogeneity of the southern North Sea (Figure 3-6). This method does not directly map observed WBAT data across space. Instead, it uses the observed surface-school probability from the WBAT as an input parameter to simulate plausible spatial scenarios. Each point on the grid was treated as a potential location where a fish school could be visible. Although this approach lacks explicit spatial structure, it serves to demonstrate the potential value of WBAT observations for informing spatial models of predator-prey interactions.

Seabird Foraging Distances and Effort

Following the identification of "present" fish school locations, we calculated the pairwise nearest-neighbour distances among these simulated foraging patches using the Haversine formula. These distances represent the minimum flight effort required for seabirds to travel between successive foraging sites. For example, across all simulations, the mean nearest-neighbour distance varied depending on the simulated probability of school presence. Scenarios with lower probabilities neighbour distances (e.g., average $1.2 \text{ km} \pm 0.3 \text{ km}$ standard deviation) compared to scenarios with higher probabilities (e.g., $p=0.10$) showed substantially shorter travel requirements (e.g., average $0.4 \text{ km} \pm 0.1 \text{ km}$ standard deviation, Figure 4-10). This inverse relationship highlights how the spatial structure of prey directly influences the potential foraging effort of central-place foragers. The distribution of these nearest-neighbour distances was generally right-skewed, indicating that while many patches were relatively close, some required substantially longer flights. These computed distances provide crucial estimates of the foraging effort and energy budgets needed by marine birds during critical periods such as chick provisioning, integrating the simulated prey field with trophic dynamics for ecosystem monitoring.

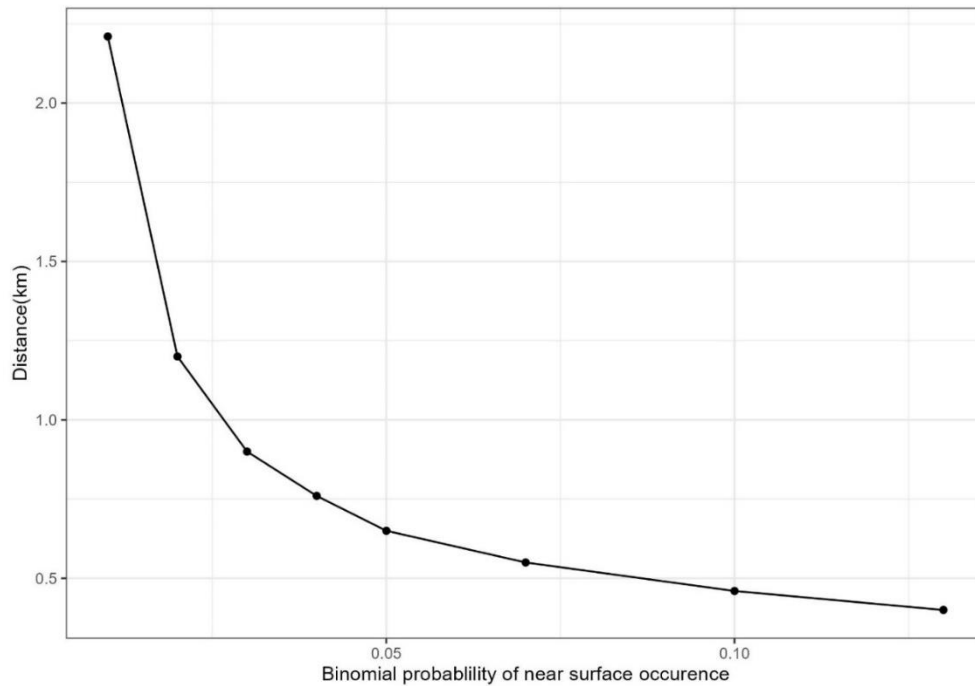


Figure 4-10: Relationship between the probability of fish school presence and the mean nearest-neighbour distance. The plot illustrates an exponential decrease in mean nearest-neighbour distance (km) as the probability of a fish school being present increases, indicating reduced foraging effort with higher prey availability.

4.5 Fish identification

Based on the acoustic data alone, it is hard or even impossible to determine which species were observed as reflections. Based on the reflection strength and shape of the school some species or species groups can be distinguished but still data on the actual occurrence of species in the area at the time of the acoustics measurement provides insight on the most likely species being observed.

The gillnet data presented in paragraph 4.2 provide some indication, however due to described issues less than we had expected. Therefore, we looked at other available data giving insight in pelagic species in the vicinity of the WBAT. The NS-IBTS Q3 2024 and Q1 2025 took place when the WBAT was in the water. Also, the MONS pelagic survey in February took place, however during this survey unfortunately no fishing hauls in the vicinity of the WBAT in Borssele were performed.

The NS-IBTS, fishing with the GOV-net with a net height of ~5m, catches pelagic fish especially in the shallow waters of the southern North Sea. In Couperus et al. (2024) a comparison between the GOV-net and the MONS-pelagic net showed clearly overlapping catch compositions. Three relevant NS-IBTS samples were identified: one by the Danish participant in September 2024 and two by the French participants in January 2025 (Figure 4-11). Only data on pelagic fish and gelatinous organisms from these catches were retained for further analysis.

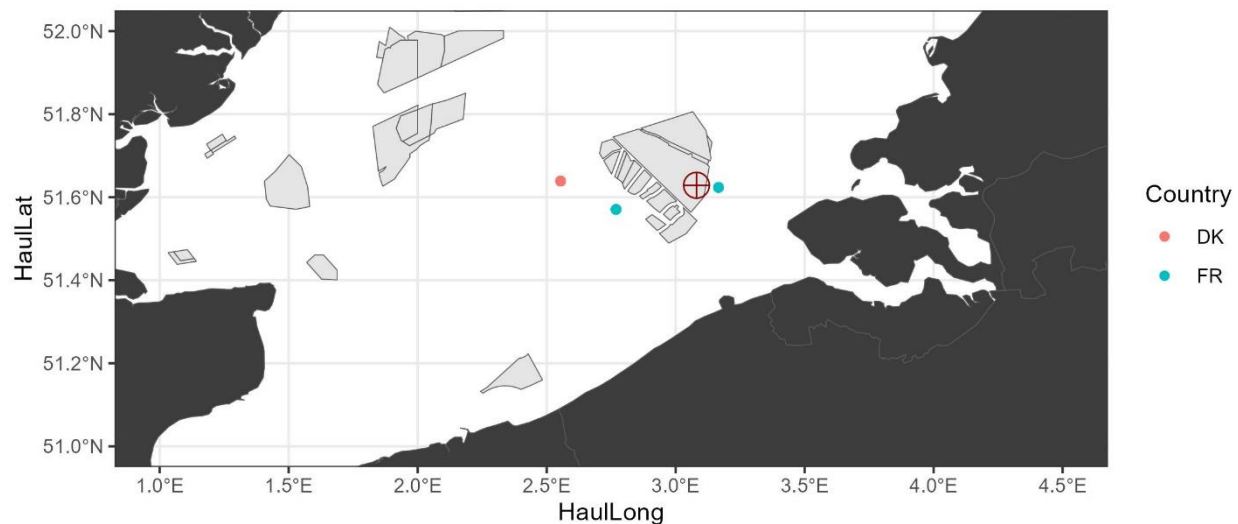


Figure 4-11: Map with the WBAT in Borssele and the nearby Danish NS-IBTS Q3 2024 (orange) and French NS-IBTS Q1 2025 (greenish) stations (Data: ICES DATRAS database).

The selected fish species included sprat (*Sprattus sprattus*), Atlantic herring (*Clupea harengus*), European pilchard (*Sardina pilchardus*), anchovy (*Engraulis encrasicolus*), Atlantic horse mackerel (*Trachurus trachurus*), Atlantic mackerel (*Scomber scombrus*), and sandeel (*Ammodytes* spp. and *Ammodytes marinus*). Gelatinous organisms included compass jellyfish (*Chrysaora hysoscella*), moon jellyfish (*Aurelia aurita*), and sea gooseberry (*Pleurobrachia pileus*).

The sandeel, which lack swimbladders, are poor acoustic targets and no significant backscatter matching their characteristics was observed, making them unlikely contributors to the detected high-density layers observed with the WBAT. While this does not confirm their absence, it suggests that sandeels were unlikely to be a major contributor to the prominent pelagic aggregations that were used in the analysis. This focus for the main analysis and the interpretation was on the species producing stronger acoustic signals, such as herring or sprat. Semi-pelagic or benthic species such as whiting (*Merlangius merlangus*) were also disregarded, as their typical distribution and lack of midwater schooling behaviour did not align with the patterns observed in the WBAT data.

The Danish sample from September 2024 yielded two relevant pelagic species: sprat and herring. In this single station, 58 sprat with a mean length of 9 cm, corresponding to two-year-old individuals, and four herring with a mean length of 15 cm, suggesting juvenile individuals, were caught (Figure 4-12). The French samples in January 2025 were dominated by sprat, with approximately 15,000 individuals estimated from a 155 kg sample, and a mean length of 11 cm suggesting a mature, adult population. Herring were present as well, with 31 individuals totalling 2.6 kg and a mean length of 20 cm, and two pilchard length 23 cm were caught (Figure 4-12).

These IBTS catches align well with observations from the MONS survey conducted in January 2024 aboard RV Tridens, where sprat dominated all catches and herring appeared only rarely (Couperus et al. 2024). The two individuals of European pilchard suggest that while it is important to consider their presence as a candidate, the low number indicates that this species can be neglected.

The French trawl samples also reported the presence of small numbers of the gelatinous species *Pleurobrachia pileus*, but these can also be considered negligible due to their very small size and weak target strength. Taken together, these opportunistic datasets support the interpretation that the high-density acoustic backscatter layers observed by the WBAT system are most likely formed by aggregations of sprat. Sprats are a commonly expected species in the coastal zone of the North Sea and are typically found in dense aggregations higher in the water column, making them likely candidates for the midwater backscatter observed in the WBAT data. While it is not uncommon for juvenile herring to co-occur with sprat, especially in nursery areas, their low numbers in the sample suggest that small pelagic fish present in the area during late summer to early autumn were predominantly sprat (Maathuis et al. 2024a).

Since gelatinous organisms were reported from the French samples and the gillnet sampling, interpretation of weak individual acoustic targets is difficult as they could be jellyfish or small fish swimming individually.

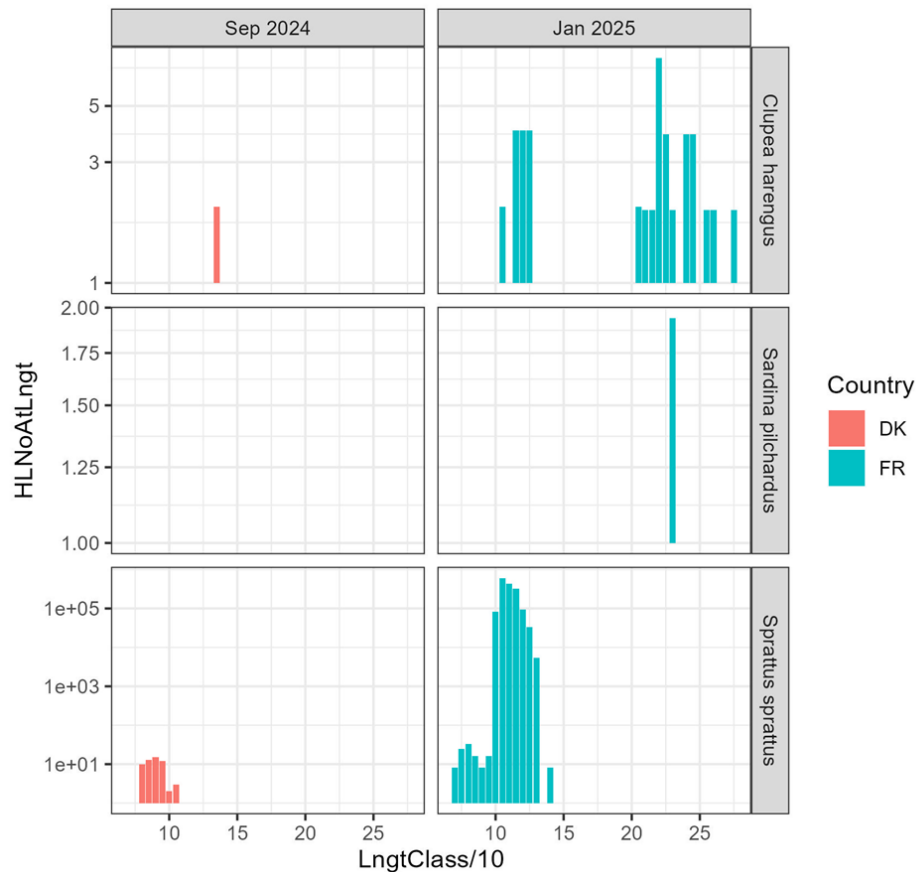


Figure 4-12: Length distribution of three pelagic fish species—sprat (*Sprattus sprattus*), Atlantic herring (*Clupea harengus*), and European pilchard (*Sardina pilchardus*)—based on IBTS trawl samples collected near the Borssele WBAT deployment. The plots are organized in a 2-column by 3-row layout, with columns representing sampling periods (September 2024 and January 2025) and rows corresponding to species. Barplots show the number of individuals per length class on a logarithmic ($\log_{10}$) scale to accommodate the wide range of observed counts. The figure highlights the dominance of sprat in both periods, particularly in January 2025, and provides comparative size distributions for other potential acoustic targets.

5 Discussion

This pilot study explored the use of stationary echosounders (WBATs) to monitor pelagic fish density as an ecosystem indicator, focusing on prey availability for top predators, particularly seabirds in the southern North Sea. As primary interpretation method, we simulated spatial distributions of fish schools based on empirical surface exposure probabilities calculated from the acoustic data collected over five months within the Borssele Wind Farm. A binomial sampling framework and nearest-neighbour distance analysis were applied to estimate foraging effort under varying prey visibility scenarios. Literature on seabird foraging ecology and diel fish behaviour was reviewed to contextualize these patterns, highlighting the ecological importance of surface-layer prey availability. The analysis supports the complementary use of stationary echosounders alongside traditional vessel-based surveys. While vessel surveys remain essential for broad spatial coverage, species identification via trawls, and ecosystem context through zooplankton and bird observations, WBATs can complement the scope of ship-based surveys. Together, these tools can enhance long-term monitoring of coastal ecosystems, offering improved temporal coverage and ecological relevance for indicators such as seabird foraging success. WBAT data, with vertical and diel resolution, can help bridge the gap between patch-level seabird foraging behaviour and prey availability, offering empirical evidence to test these weak associations in real time. While a single WBAT, as in the case of this work, provides valuable temporal insights, spatial limitations necessitate a network of sensors across ecological gradients for broader ecosystem interpretation.

Autonomous acoustic systems, moored or on unmanned autonomous vessels, have emerged as powerful tools for long-term ecosystem monitoring, particularly in contexts where high temporal resolution is required. De Robertis et al. (2018) tested whether a bottom-moored echosounder array could provide an index of fish abundance comparable to traditional vessel-based acoustic surveys. Using moored echosounders deployed in the Gulf of Alaska during a NOAA survey, they measured fish backscatter continuously and compared the data to ship-based survey estimates. Data from the stationary systems correlated well with ship-based estimates when averaged over time, indicating their potential for monitoring abundance. They also show that longer deployments help reduce temporal variability and improve comparability. Their study highlights the growing role of moored echosounders in capturing continuous acoustic data over weeks to months, enabling the detection of temporal dynamics that are missed by traditional vessel-based surveys. Their synthesis reinforces the complementary role of WBAT in monitoring fine-scale vertical and diel fish distributions and supports its integration into hybrid observation strategies, especially in remote or logistically constrained environments such as offshore wind farms.

Understanding seabird foraging behaviour in patchy marine environments requires models that reflect both the distribution and predictability of prey. In this context, the WBAT-based spatial simulation, linking surface exposure probability with nearest-neighbour distance, serves as a valuable proxy for seabird foraging constraints. Similarly, prey availability could be investigated for marine mammals through a multi-variate analysis that accounts for preys in specific part of the water column. Integrating acoustic data with biologically informed models offers a promising direction for evaluating ecosystem resilience and functional prey availability under changing marine conditions. Here we discuss the highlights of the findings, their relevance to the MONS monitoring program as well as challenges that were faced during the pilot project.

5.1 WBAT failure

After retrieval of the WBAT in Hk(n) it was found out that only error messages were saved on the memory, while the settings and the mission plan used were similar as for the WBAT in Borssele. The manufacturer, confronted with the issue, hinted that might had been a hardware malfunctioning. However, after done some of the test proposed by the manufacturer no issues could be found. Testing the same settings and mission plan did not result in error messages again. So, it is still unclear what has caused the issue.

This failure speaks for more often checking the settings in the field. Originally, in field checks of the WBAT were planned. Recent other deployments of the WBAT had shown its capability of staying in the field for longer periods of time. Additionally, the placement in the wind farms combined with the obligated demarcation buoys made retrieval and checking a complicated activity requiring the large Buoyage vessel, making it difficult to plan and expensive. As the recent deployments were so convincing, it was decided to take the risk.

Of course, it is unfortunate that this WBAT did not collect data, but it is part of the risks of field work at sea especially of a pilot study. The single WBAT data from Borssele was still relevant to analyse, however missing the second location hampers interpreting the observed results. Synchronized observations at two (or more) locations could have provided support for the currently observed patterns, which now have reduced strength as they might be only local behaviour related to the local environmental conditions. Relying on measurements from a single WBAT observation point limits the spatial representativeness of detected aggregations, especially given the dynamic and patchy nature of pelagic fish distributions.

Deploying multiple WBAT stations across different locations enhances spatial coverage and increases the probability of detecting these rare events. This distributed sampling strategy not only improves the reliability and statistical robustness of the observations but also allows for spatial comparisons across habitats or environmental gradients. As a result, the patchiness can be resolved for better understanding and modelling of the prey availability.

5.2 Species

The integration of stationary acoustic monitoring from the Borssele WBAT deployment with opportunistic biological data from nearby DATRAS trawl samples has provided additional information on likely composition of pelagic fish aggregations. This is useful as an alternative, due to failure in the initially planned gillnet sampling as an independent data source to interpret the acoustic backscatter signals.

The trawl data revealed a consistent presence and seasonal shift in the size structure of sprat (*Sprattus sprattus*), supporting its identification as the dominant contributor to the observed high-density acoustic layers. In September 2024, Danish trawl data showed a relatively small sprat population (mean length 9 cm), likely representing one to two-year-old individuals in nursery areas. A small number of juvenile Atlantic herring (*Clupea harengus*, mean length 15 cm) were also present, though in much lower abundance. The species' known tendency to co-occur with sprat in nursery habitats suggests a mixed juvenile community, but the dominant biomass was clearly attributed to sprat.

By January 2025, French trawl samples indicated a marked increase in sprat abundance and size (mean length 11 cm), consistent with adult individuals forming larger overwintering schools. The significant biomass (~155 kg, estimated ~15,000 individuals) provides strong evidence that sprat aggregations are responsible for the dense midwater backscatter detected acoustically. This seasonal progression from juvenile-dominated nursery aggregations in late summer to dense adult overwintering schools aligns with known sprat life history and distribution patterns in the North Sea. Herring remained present but scarce (47 individuals, mean length 20 cm), further reinforcing the dominance of sprat in both seasons.

European pilchard (*Sardina pilchardus*) appeared only in small numbers and at limited sizes in both periods, suggesting they play a minimal role in the acoustic signal composition. The presence of gelatinous organisms, such as *Pleurobrachia pileus*, was recorded only in the January French samples and in very small amounts. Given their weak acoustic reflectivity and low abundance, they are unlikely contributors to the observed backscatter.

Species such as sandeels (*Ammodytes* spp.), which lack swimbladders and are therefore poor acoustic targets, were excluded as plausible sources of the high-density aggregations observed with the WBAT. Similarly, semi-pelagic or benthic species like whiting were disregarded, as their typical non-schooling and bottom-associated behaviours do not match the midwater schooling patterns seen in the WBAT data.

The bottom trawl samples in the same area also indicated a high abundance of whiting (*Merlangius merlangus*), being a benthopelagic species, they may contribute to the recorded acoustic backscatter at near bottom depths. This interpretation is supported by the depth-resolved characteristics of the WBAT data, which consistently showed distinct patterns within 3-5 meters range above transducer. Whiting typically remain close to the seafloor and exhibit limited vertical movement during the day (Stensholt et al. 2002),

normally reducing their detectability in upward-facing acoustic measurements unless they form dense pelagic layers. In our case, such pelagic layers may explain some of the above-bottom marks observed in this dataset.

Demersal species are among the first to colonize new hard structures in the North Sea (Todd et al., 2020). Ecosystem simulations by Sayer et al. (2005) around artificial reefs in Scottish waters show that the addition of hard substrate, especially designs that maximize edge habitat, can lead to increased fish abundance and shifts in species composition, particularly favouring demersal and benthic-associated species. While it could be assumed that our WBAT data might reflect similar artificial reef-driven aggregations, this influence is likely minimal. The WBAT was deliberately deployed at a distance from hard substrates to avoid such effects. Furthermore, whiting is currently one of the most abundant species in the southern and central North Sea, supported by both survey results and commercial catches, likely due to recent strong recruitment events coinciding with similar trends in other gadoids such as haddock.

Overall, the high-density, diel-migrating acoustic signatures of sprat remain prevalent, while whiting exhibited lower-density, bottom-oriented echoes consistent with demersal schooling. This acoustic discrimination ensures that WBAT effectively isolates pelagic fish dynamics. Overall, the combined evidence from acoustic monitoring, trawl sampling, and size distribution analysis provides a coherent interpretation pointing to sprat as the primary source of midwater acoustic backscatter observed near the Borssele site.

5.3 Perspectives on prey aggregation and potential seabird response and WBAT as a monitoring tool

Temporal changes in pelagic fish densities and their vertical distribution, as detected by WBAT, provide key insights into seabird foraging behaviour in the southern North Sea. Several seabird species, including common and Sandwich Terns (*Sterna hirundo*, *Thalasseus sandvicensis*), northern gannets (*Morus bassanus*), and black-legged kittiwakes (*Rissa tridactyla*), depend heavily on spatially aggregated, high-density prey patches during their breeding and post-breeding periods. This reliance on prey-rich zones is well documented in Camphuysen and Leopold (1994), which presents ship-based seabird distribution data from 1987 to 1993. The atlas highlights consistent hotspots of seabird activity, particularly of guillemots and terns, along oceanographic frontal systems such as the Friese Front, Doggersbank, and Terschellingerbank. These areas are known for enhanced mixing and productivity, indicating a strong spatial association between seabirds and pelagic fish aggregations. During the chick-rearing period, Sandwich Terns display tightly clustered, prey-driven foraging behaviour focused on nearshore waters, often returning with high-energy fish such as sprat, herring, or smelt (van Bemmelen et al. 2022). These foraging efforts tend to concentrate in productive marine areas like tidal inlets and shallow banks, where stratification and tidal mixing promote prey availability. Given this ecological context, WBAT provides a crucial monitoring tool by capturing the fine-scale vertical and temporal dynamics of pelagic fish aggregations that directly influence seabird foraging success in these productivity hotspots.

Environmental conditions further mediate foraging success. Baptist and Leopold (2010) demonstrated a non-linear relationship between water transparency and prey capture success in Sandwich Terns, with optimal foraging occurring at moderate clarity (1.5–2 m Secchi depth). Capture rates declined under both very clear and very turbid conditions. Importantly, the study also revealed behavioural plasticity: terns adapted their foraging techniques, switching from full plunge dives to partial or surface dipping, depending on visibility. Together, these findings emphasize the importance of coupling prey field observations with environmental data. WBAT is particularly suited to this task, as it can continuously monitor vertical prey structure under varying turbidity conditions, such as those commonly found along the Dutch coast. The broader ecological context offered by van Bemmelen et al. (2022) through analysis of Sandwich Tern diet, spatial behaviour, and responses to offshore wind farms. Their GPS-tracking and diet analyses show temporal shifts in prey use and habitat preference, an example to the patterns that WBAT's high-resolution acoustic data can help to interpret. The degree of overlap between tern foraging areas and prey availability near wind farms may be critical in assessing whether habitat displacement or foraging constraints arise from offshore development.

Goyert et al. (2018) demonstrated that seabird distributions are strongly influenced by a combination of prey availability, habitat features, and interactions with other marine predators. Specifically, surface-feeding plunge-diving seabirds showed increased density around marine mammals, suggesting their foraging success is enhanced by subsurface predators forcing fish upward. These findings underscore the necessity of monitoring vertical prey structure and ecological interactions in developing predictive models of seabird foraging. By capturing fine-scale vertical dynamics and prey layer availability, WBAT can fill critical data gaps in understanding such community-level drivers. Especially in offshore wind farm areas where seabirds and other marine predators interact within complex trophic environments. Thresholds in prey density are important to characterise seabird feeding behaviour, as fish densities determine whether birds will forage on them. Research suggests that birds often ignore low-density prey patches, as the energetic return may not justify the effort (Yurek et al. 2024). Instead, they tend to exploit areas where fish schools reach a critical biomass threshold—both in terms of vertical packing and spatial extent—that allows efficient prey capture. This behaviour creates a non-linear relationship between prey density and predator response, where birds may only aggregate and feed when prey concentrations exceed a certain threshold. Understanding these thresholds is crucial for interpreting patterns observed in integrated seabird and acoustic monitoring data, as apparent mismatches between bird presence and acoustic fish signals may reflect sub-threshold prey densities rather than true absence of prey. Garthe et al. (2011) tracked GPS-equipped northern gannets across two years with distinct prey fields. They found that in years dominated by dense, shallow capelin layers, gannets engaged in deeper, prolonged U-shaped dives within compact foraging ranges. Conversely, during years when prey was sparser or deeper their dives were shallower and less frequent, and their foraging ranges expanded by over 30-fold. This demonstrates that vertical prey distribution—not just abundance—encourages seabirds to flexibly adjust foraging behaviour. WBAT’s capability to resolve vertical prey structure over time makes it suited to detect and explain such inter-annual behavioural adaptations, particularly in colony-associated waters and human-impacted zones. Boyd et al. (2017) used an individual-based model to show that for central-place foraging seabirds, prey depth distribution is the primary driver of foraging outcomes, followed by overall prey abundance and spatial patchiness. Their results highlight that birds locating prey at shallower depths achieve significantly higher foraging success rates. This underlines the importance of vertical prey accessibility something WBAT is able to measure. By resolving prey layers relative to seabird diving depths, WBAT enhances the ability to predict foraging success and evaluate ecological risk in colony-proximate and potentially human-impacted areas.

WBAT’s capability to continuously monitor vertical fish distributions complements biollogger-derived seabird data by enabling the detection of fine-scale prey availability dynamics, crucial for using seabirds as ecological sentinels, as reviewed by “Tracking Cairns” (Brisson-Curadeau et al. 2017). Boyd et al. (2015) demonstrated that seabird diving behaviour is guided more by the depth distribution of prey than by total abundance. Their resource selection models, based on GPS and dive data from two seabird species, showed that the probability of diving increased sharply with shallow prey presence, while overall abundance had a lesser impact. The finding that seabird foraging success is tightly linked to prey density and availability near the surface, is a conclusion that is also supported by Benoit-Bird et al. (2013), who demonstrated strong correlations between predator distribution and acoustic signals indicating prey aggregation. Prey density thresholds have been shown to determine the likelihood of diving behaviour for species such as gannets and kittiwakes, both of which are regular users of Dutch coastal waters during the breeding and post-breeding seasons (Peschko et al. 2024). WBATs, capable of high-frequency, high-resolution vertical sampling, are particularly suited for detecting such fine-scale prey dynamics, including surface-layer schooling that may only occur under certain tidal or diel conditions. By capturing the vertical accessibility of prey, stationary echosounders provide insights into how dynamic prey fields structure predator behaviour and reproductive performance along the Dutch coast.

5.4 Scale and Spatial Distribution and potential placement of WBAT stations

In the southern North Sea, particularly off the Dutch coast, physical and hydrographic features such as tidal mixing zones, freshwater inflow gradients, and offshore sandbanks create predictable hotspots of prey concentration. These zones influence seabird foraging distributions and aggregation intensity (Camphuysen

and Webb 1999). For example, common terns and sandwich terns breeding in the Wadden Sea frequently forage in the littoral zone - areas of shallow bathymetry, typically within the coastal shelf where light reaches the seabed – where frontal activity and other oceanographic features support pelagic fish abundance. Such fine-scale prey distributions are key drivers of seabird spatial patterns during the breeding season. Spatially resolved foraging models have shown that prey field heterogeneity significantly influences seabird movement decisions and area-restricted search behaviour (Fauchald and Tveraa 2006). Fauchald and Tveraa (2006) showed that marine predators use nested search strategies—locating large-scale prey fields before switching to fine-scale area-restricted searches when encountering smaller aggregation patches. These hierarchical dynamics are potentially similar in the prey structure in the North Sea, where frontal zones contain dense vertical aggregations. WBAT's continuous, vertically resolved data can identify both the broader prey field and embedded micro-patches, helping to explain shifts in seabird search behaviour and foraging efficiency across scales. In the Dutch sector, telemetry and observational data confirm that foraging is often concentrated within 10–30 km of colonies, matching zones of recurring prey availability (van Bemmelen et al. 2022). van Bemmelen et al. (2022) used GPS tracking to show that Sandwich Terns breeding in the Netherlands typically forage within 15–25 km of their colonies, though some individuals occasionally range up to 40 km or more—particularly when local prey availability is low. These insights could help strategic placement of WBATs: deployments should ideally be situated near key hydrographic features or within known foraging ranges of seabird colonies to capture ecologically relevant prey dynamics. Additionally, deploying WBATs along spatial gradients—from inshore estuaries to offshore banks—would improve representation of ecosystem variability. Such a network would help identify shifts in prey field structure due to environmental changes or human activity, including offshore wind farm development. As such, metrics like nearest-neighbour distances between prey patches, derived from spatially distributed acoustic stations, can serve as effective indicators of foraging efficiency and ecosystem condition.

5.5 Diel Pattern

Many pelagic fish species, including sandeels and sprat, exhibit diel vertical migration, a behaviour characterized by movement closer to the surface at night or during crepuscular periods. This diel variation in fish vertical distribution is a key factor shaping prey accessibility for surface-feeding seabirds. In the southern North Sea, species such as sprat, herring, and juvenile sandeel have been observed to migrate vertically over diel cycles, often surfacing during dawn and dusk (Couperus et al. 2016). These cycles are tightly coupled to predator avoidance and feeding strategies, creating critical windows of availability for seabirds. Upward movement increases their availability to surface-feeding seabirds for limited periods (Holliday et al. 2010, Klevjer et al. 2012).

WBATs are particularly suited to detect these short-period behaviours due to their high temporal resolution. Analysis of the diel pattern over five months of data from the WBAT shows, on average, higher densities of fish during daytime hours. These higher densities indicate daytime schooling behaviour, which may enhance prey availability for visual predators such as seabirds if the schools occur within the birds' diving depth (Dänhardt and Becker 2011).

5.6 Behaviorally-Informed Modeling and use of WBAT as a tool for improvement

Understanding seabird foraging behavior in the complex and often patchy marine environment requires models that accurately reflect both the distribution and predictability of their prey. Traditional random search models often underestimate foraging efficiency in such heterogeneous systems (Miramontes et al. 2012). More recent efforts, such as those along the Dutch coast, have integrated telemetry data from guillemots and kittiwakes to calibrate models with realistic prey field structures and predator responses (Peschko et al. 2024). In the southern North Sea, prey patch dynamics are shaped by tidal cycles, spawning aggregations, and wind-driven mixing—factors that influence the spatial consistency of prey availability. Within this context, WBAT-based spatial simulations that combine surface exposure probability with nearest-neighbor distance offer a useful proxy for evaluating seabird foraging constraints. The integration of acoustic data with

biologically informed models presents a promising direction for assessing ecosystem resilience and the functional availability of prey under changing marine conditions.

Although stationary acoustic devices have inherent limitations, they have been proven effective for detecting relative fish densities and behaviors over time (Benoit-Bird and McManus 2014), especially when used in conjunction with vessel-based surveys. Benoit-Bird and McManus (2014) demonstrate the importance of short-lived, diel-scale vertical prey dynamics in structuring predator–prey interactions—from zooplankton and micronekton to top predators—using moored acoustic sensors. Their findings highlight a 30-minute dusk window when zooplankton layers, prey ascent, and predator foraging coalesce. This shows the value of continuous, high-resolution vertical monitoring—like that provided by WBAT—to detect critical ecological pulses that shape seabird foraging behavior and prey accessibility in pelagic systems. In other regions, such as the California Current and the Norwegian Sea, moored echosounders have successfully tracked seasonal trends in fish availability and assessed prey accessibility for top marine predators. Urmy et al. (2012) investigated the vertical distributional variability of pelagic fauna in Monterey Bay using a stationary upward-facing echosounder deployed over several months. Their study also revealed pronounced diel and seasonal patterns in the vertical distribution of organisms, driven by both biological behavior (e.g. diel vertical migration) and environmental variability.

Seabird foraging behavior in the North Sea is tightly linked to pelagic fish distributions. Fauchald et al. (2011) showed that responses occur at multiple scales: strong, synchronous responses at the interannual scale; high response diversity across habitats due to niche segregation; and more diffuse, multispecies foraging aggregations at the local patch scale, where associations with prey are weaker. Their work underscores the importance of scale in interpreting predator-prey interactions—insights that align with the multi-scale, high-resolution capabilities of WBAT for monitoring vertical and temporal prey dynamics.

Temporal variability in prey availability has also been identified as a critical driver of predator behavior. Green et al. (2020) found that mesoscale variability in modeled mesopelagic prey fields was more predictive of predator activity than mean biomass. While these insights were derived from large-scale, model-based data, WBAT offers a complementary empirical approach that captures fine-scale, sub-daily dynamics otherwise inaccessible through traditional surveys. This makes WBAT particularly valuable in ecologically sensitive and human-impacted areas, such as offshore wind farms.

Fauchald et al. (2011) highlighted the complexity of seabird responses at local patch scales—the same scale at which WBAT operates—where foraging behavior is influenced by flocking, facilitation, and behavioral plasticity. High-resolution, continuous monitoring of prey fields is therefore essential to uncover fine-scale ecological patterns. WBAT's ability to detect the formation, depth, and persistence of vertically structured prey aggregations can help explain how seabirds partition foraging niches in space and time, particularly among prey types such as sandeels, sprat, and herring. Couto et al. (2022) demonstrated how physical drivers like tidal flow can structure pelagic fish distributions and directly influence seabird foraging. In a North Sea tidal-stream environment, predator presence tracked prey concentrations which were detected by echosounder, and varied with tidal phase. This indicates a tight coupling between hydrodynamics, prey accessibility, and predator response. These findings reinforce the value of high-frequency, fine-scale acoustic monitoring, like that provided by WBAT, for understanding dynamic predator-prey relationships in marine environments undergoing increasing anthropogenic pressure.

Overall, stationary platforms provide higher temporal resolution and are especially valuable for detecting short-term ecological events, such as diel migrations or tidally driven fish aggregations. By continuously monitoring a single location, these studies reveal important diel and seasonal patterns that are often missed by traditional vessel-based surveys. On the other hand, Huse (2016) emphasizes the importance of broad spatial coverage, showing that herring population dynamics are shaped by large-scale movements across spawning, feeding, and overwintering areas, often guided by socially learned migratory routes. Together, these studies highlight that while stationary echosounders are essential for capturing local temporal dynamics, understanding population-level processes also requires coupling such high-resolution temporal data with spatially extensive survey data to account for the complex horizontal structure of pelagic fish distributions.

5.7 Interpretation of Simulation Results

To evaluate how surface-visible fish schools affect seabird foraging in the southern North Sea a spatial simulation was conducted for estimating occurrence of surface-exposed schools, which are important for visual predators during the breeding season (Cairns 1987, Camphuysen and Leopold 1994). Using empirical surface exposure probabilities derived from WBAT data, probabilities ranging from 0.001 to 0.15 were assigned to grid points. A binomial draw determined school presence at each point, effectively simulating prey patchiness and spatial heterogeneity typical of marine environments (Fauchald and Tveraa 2006, Benoit-Bird et al. 2013). The southern North Sea's dynamic physical structure, from coastal fronts to anthropogenic influences, strongly modulates this variability (Camphuysen and Leopold 1994, Peschko et al. 2024). From the simulations, the minimum travel required for seabirds to reach successive prey patches were estimated. The resulting patterns provide insight into foraging effort and landscape-level prey accessibility under different prey availability scenarios.

The simulation yielded realistic spatial patterns of fish school presence based on the empirical exposure probability. Nearest-neighbour distances reflect the likely spacing between visible prey patches. These distances can be interpreted as the minimum travel cost for seabirds moving between feeding opportunities. With a surface exposure probability of 13%, the average spacing of high-density surface-visible schools may still be several hundred meters, especially under patchy conditions. This can significantly affect foraging efficiency of the birds and chick provisioning success.

5.8 General discussion and future WBAT applications

This pilot study illustrated both the promise and the limitations of stationary echosounders (WBATs) for ecosystem monitoring. While even a single WBAT offers detailed temporal insights into pelagic fish behaviour and closeness to the sea surface relevant to seabird foraging, it introduces spatial bias by failing to represent the broader heterogeneity of the Dutch coastal zone. To address this, deploying a spatial network of WBATs across ecologically distinct environments—such as estuaries, offshore sandbanks, and frontal mixing zones—would enhance spatial generalizability and improve estimation of prey availability. Ideally, 6–10 stations would capture key ecological gradients, particularly in proximity to seabird colonies where foraging pressure is highest. The simulation results highlight the utility of such a network in estimating foraging distances and assessing ecosystem function through prey accessibility. Additionally, expanding the monitoring period beyond the current five-month window to cover a full annual cycle would allow alignment with seasonal patterns in fish spawning, migration, and seabird breeding. Although WBATs cannot entirely replace vessel-based surveys—especially for species identification and broad-area coverage—they offer valuable long-term data and behavioural resolution. A hybrid monitoring approach combining vessel surveys for calibration and spatial context with stationary echosounders for high-resolution temporal tracking represents the most robust framework for ecosystem-based monitoring in the southern North Sea.

The collection of WBAT data along the Dutch coast will complement the wealth of data that has been collected over the years by different projects in Belgium and in the Netherlands:

- VisZiON project (2019): AZFP¹ echosounders (Kok et al. 2021)
- APELAFICO² (2021-2024): within this project, WBATs were used to gain insight on 1) the deterrence effect (Hubert et al. 2024), 2) the impact of pile driving on pelagic fish and 3) the presence of fishes in operational OWFs in comparison to similar habitats (Slabbekoorn 2024).
- Pelfish project³ (2024): project aimed at providing fisheries and ecosystem knowledge to study the possibility to develop or restore small-scale 'niche' seasonal fisheries in the Belgian Part of the North Sea. WBATs were used to monitor fish biomass at various sites at high temporal resolution.
- Monitoring program at the Ecowende offshore wind farm (2025-): monitoring before/during/after the installation of the Ecowende offshore wind farm to investigate the impact on pelagic fish distribution

¹ <https://aslenv.com/azfp.html>

² <https://www.nwo.nl/en/projects/nwa123618004>

³ <https://www.vliz.be/nl/imis?module=dataset&dasid=8449&printversion=1&dropIMISitle=1>

and biomass. The monitoring will also bring knowledge on the effect of Tree reefs on fish distribution and abundance.

These projects have specific objectives (e.g. monitoring, impact assessment) but yielded data spanning various seasons at several sites in the Belgian and Dutch part of the North Sea in different context (shipwrecks, offshore wind farms, impact to noise). This would suit a meta-analysis combining data sets to investigate patterns over years and areas which could reveal temporal trends and heterogeneity between sites.

The value of stationary WBAT deployments increases substantially when integrated with complementary environmental and ecological data streams. While the WBAT system provides high-resolution temporal information on pelagic fish distributions, interpreting these patterns in a broader ecological context requires coupling with data on primary productivity, zooplankton biomass, hydrography, and predator behaviour. For instance, integrating chlorophyll-a concentrations or satellite-derived productivity estimates can help infer bottom-up drivers of fish aggregations. Zooplankton data can indicate intermediate trophic conditions, bridging the gap between phytoplankton dynamics and fish feeding behaviour. Additionally, coupling WBAT observations with physical oceanographic parameters—such salinity gradients, turbidity, and current velocity—can help clarify how water column structure influences fish vertical distribution and aggregation behaviour. Coastal fronts, for example, can act as a physical barrier influencing fish accessibility to certain water masses. Similarly, integrating turbidity and underwater noise data could reveal how human activities such as dredging or vessel traffic impact fish school cohesion or vertical displacement.

On the predator side, overlaying WBAT-derived prey fields with tracking data from seabirds and marine mammals offers direct insights into how mobile predators respond to prey availability. For example, GPS and dive data from foraging birds such as sea gulls, terns, or seals can be used to test hypotheses about prey encounter rates, foraging efficiency, and habitat selection in relation to observed fish distributions. Combining Passive Acoustic Monitoring (PAM) with WBATs allows one to link the presence of marine mammals (dominated by the presence of Harbor porpoises in the Dutch coast) to potential preys. Such an analysis was conducted within the APELAFICO project where the fish abundance and presence of harbour porpoises were compared using a pair design (Figure 5-1(a)). Through preliminary results of this study, a slight but consistent trend was found with more fish present when harbour porpoise were present (Figure 5-1 (b)). Ultimately, the strength of WBAT data lies not only in its ability to describe fish presence with high temporal resolution, but also in its potential to act as a central node in a multi-sensor monitoring framework that captures the interplay of biological and physical processes in marine systems.

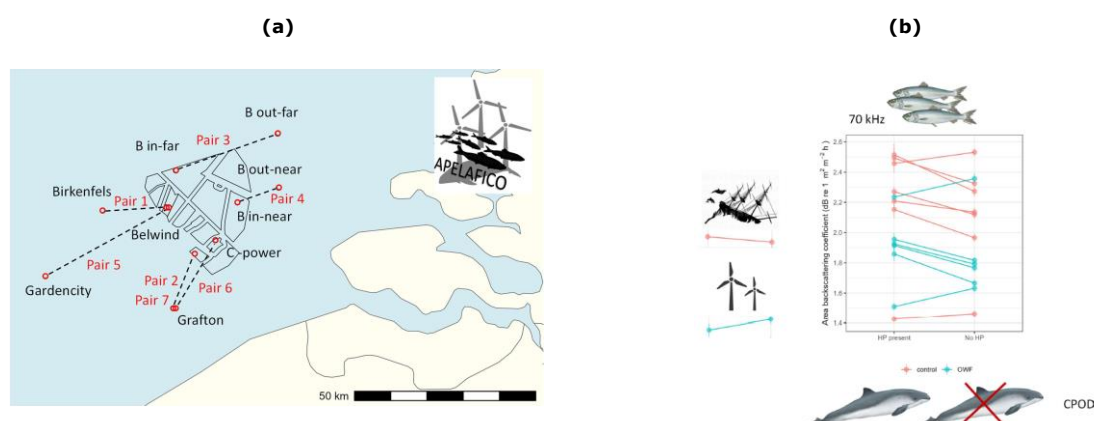


Figure 5-1: (a): Map of the Dutch and Belgian Offshore Windfarms around the Dutch-Belgian border with the 10 deployment locations that were paired in 7 sampling pairs. Note that Belwind OWF was used twice in different periods, and that CPower OWF was used three times in different periods with deployments in two distinct parts of the OWF. Extracted from (Slabbekoorn 2024). (b): Pelagic fish abundance related to the presence of harbour porpoise in 13 sites of offshore windfarm and shipwreck control sites.

6 Conclusions

The WBAT deployment at Borssele successfully yielded five months of continuous acoustic data, capturing a wide range of temporal and vertical patterns in fish distributions. The observed variability—including shifts from low to high densities, tidal cycles, and vertical movements within the water column—points to ecologically meaningful dynamics likely driven by environmental conditions. Rather than sparse or static results, the dataset is rich in interpretable features, demonstrating the value of WBAT-based monitoring. WBAT data, with its fine-scale resolution, provides the empirical evidence needed to directly link seabird foraging behaviour to prey availability, testing these weak associations in real time. The scale-dependent behaviour of seabirds implies that no single monitoring scale is sufficient. This pilot trial showed that, the WBAT data offers a complementary, sub-seasonal, fine-resolution window into prey fields, essential for interpreting seabird distributions and assessing ecosystem health, especially near human-impacted areas like wind farms. This trial can therefore be considered a successful proof of concept. Integration of these findings with independent ecosystem indicators will allow for more comprehensive ecological interpretations.

Key insights

- Stationary echosounders are powerful tools for capturing high-resolution temporal dynamics in pelagic fish distribution, particularly when aligned with seabird foraging ecology. When integrated with spatial simulations and strategically deployed across ecological gradients, they can provide meaningful ecosystem indicators.
- They are best used as part of a hybrid monitoring strategy, complementing periodic vessel-based surveys to ensure spatial coverage, species-level resolution, and ecosystem context. They cannot fully replace vessel-based acoustic surveys. Vessel surveys remain essential for broad spatial coverage, species identification via trawls, and ecosystem context through zooplankton and bird observations.
- Based on results from this and related studies, an optimal monitoring network might include 6–10 WBATs, positioned across diverse habitats such as estuaries, tidal fronts, offshore sandbanks, and wind farm zones. Such a network would capture ecologically important spatial variability and enhance representativeness for key trophic interactions.
- Moreover, the value of WBATs increases significantly when integrated with complementary data streams—such as primary productivity, zooplankton biomass, hydrographic conditions, seabird and marine mammal tracking, turbidity, underwater noise, and stratification. This integration enables the identification of mechanistic links between prey availability, predator behaviour, and environmental drivers.
- WBAT data, with its vertical and diel resolution, offers the empirical evidence needed to directly link seabird foraging behaviour at the patch level with prey availability, strengthening our understanding of these often weak associations in real time.
- Although stationary echosounders cannot fully replace vessel-based acoustic surveys, especially for broad-scale coverage and species identification, they offer substantial advantages for long-term monitoring. A hybrid approach—leveraging both platforms—presents the most effective strategy for ecosystem-based management and seabird conservation along the Dutch coast and broader southern North Sea.

7 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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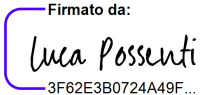
Justification

Report C052/25

Project Number: 4316100315

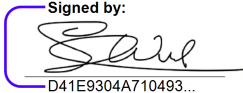
The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

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