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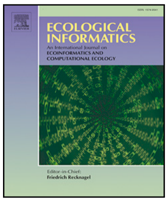

What AIS misses and Acoustics reveal: Monitoring seafloor disturbance and recovery from bottom trawling in the southern Baltic Sea over five years

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ABSTRACT

This study evaluates bottom trawling intensity and its ecological effects in the Fehmarn Belt (southern Baltic Sea) between 2020 and 2024. The region is dominated by small-scale fishing vessels (<12 m length) and therefore conventional Vessel Monitoring System (VMS) data are unavailable. We compare changes in seafloor integrity caused by bottom trawling with fishing activity inferred from Automatic Identification System (AIS) tracking. Trawling intensity was quantified using a previously developed trawling index (TI) based on furrow volume derived from multibeam echosounder (MBES) data. A pronounced alteration in seafloor integrity was observed between 2021 and 2022, with furrow volumes decreasing from 5067 m^3 to 1108 m^3 over an area of 3.4 km^2. This trend was not recorded by AIS-derived fishing activity, which showed only slight changes in vessel track counts. Spatial and temporal fluctuations in abundance, biomass and community structure were revealed through repeated macrofauna sampling. The fluctuations are likely linked to shifting trawling pressure related to the ban of a fishery targeting cod in the Western Baltic. These biological responses did not follow a linear trend but suggest a dynamic equilibrium may be reached over time. Although MBES data cannot replace AIS for tracking fishing effort, it can supplement and improve the AIS information, providing insights into physical impacts and benthic responses in regions of interest. Integrating MBES-derived indicators identifies the spatial extent of the seabed affected by bottom trawling, thereby strengthening ecological monitoring frameworks and supporting sustainable seabed management, including in marine spatial planning.

1. Introduction

The European Union (EU) aims to become climate-neutral by 2050 (“European Green Deal”, European Commission (2019)). To achieve this goal, an increased number of offshore wind turbines is needed. As other uses in the wind farm areas are prohibited, this creates a conflict of use with other interest groups. In addition, newly designated marine protected areas (MPA), established to comply with EU nature conservation requirements, further increase conflicts of use in the marine sector, as many users are excluded or restricted from and in these areas for nature conservation reasons. To minimize conflicts and ensure a high level of acceptance, Maritime spatial planning (MSP) aims to balance the interests of different stakeholders in the marine sector e.g., fishing, offshore renewable energies, shipping, military, and nature conservation (Heyken et al., 2025). Especially trawling, which requires large areas, is particularly affected as it has been banned from offshore wind farm areas for safety reasons and has also been excluded from many MPAs. The impact on commercial fisheries must be taken into account in MSP, and designated fishing areas have to be identified. To minimize the impact, identifying current fishing areas is of particular importance.

Besides MSP, identifying fishing effort in high spatial resolution also has other advantages. High-resolution fishing data makes it easier to assess whether sensitive or protected habitats are being affected, and the area affected by fishing can be calculated more accurately. The impact of fishing (especially bottom trawling) on the ecosystem can also be better assessed. Various indices can be calculated, such as fishing footprint, spatial overlap index, spatial effort density index, seafloor impact index, benthic pressure index and MPS index. These data support an ecosystem-based management approach, although exact fishing data are sparse. While fisheries operating vessels larger than 12 m in length are obliged to document their fishing effort using a satellite-based vessel monitoring system (VMS) that is interpreted at

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a km-scale resolution, fisheries with smaller vessels are only obliged to report with an even broader resolution. This makes it difficult to integrate their fishing grounds into MSP.

Bottom trawling is identified as the most significant anthropogenic pressure applied on seafloor integrity (Jennings et al., 2001; Grip and Blomqvist, 2020; Micallef et al., 2018), potentially causing physical disturbances (Oberle et al., 2016), the alteration of marine habitats (Hiddink et al., 2020) and reduction of biomass production and species richness in benthic communities (Mazor et al., 2021). Although advanced systems such as VMS, electronic logbooks, and port inspections provide reliable information on bottom trawling activity (for larger vessels), due to the low spatial resolution, there is no chance to evaluate the impact of bottom trawling on a finer scale, which is important for smaller benthic communities or structures like mussel beds or reef structures. Therefore, there are still very few methods that can verify the ecological impacts of bottom trawling. Approaches capable of assessing effects on seabed habitats and benthic communities, including biomass loss and habitat degradation, remain limited and continue to require further development.

The term ‘‘trawling intensity’’ describes the extent and how often mobile bottom-contacting gears were swept across the seafloor. The most common approach to quantify bottom trawling intensity is the swept area ratio (SAR), which is calculated based on VMS data (Gerritsen et al., 2013). The SAR quantifies the extent and frequency of the seafloor swept by trawling relative to the total area over one year and is integrated as an indicator in modeling approaches to predict the bottom trawling impact on marine ecosystems (Rijnsdorp et al., 2017; Eigaard et al., 2017; Rijnsdorp et al., 2020). However, due to the low spatial resolution of SAR and limited VMS availability in regions dominated by small fishing vessels the standardized methods likely result in underestimation of true fishing activity (Marsaglia et al., 2025). Recently, satellite-based monitoring enabled the use of Synthetic Aperture Radar to track the activity of small fishing vessels (<20 m) and to cross-reference these observations with data reported by automatic identification systems (AIS) (Li et al., 2024; Marsaglia et al., 2025; Paolo et al., 2024). This comparison reveals that approximately 72%–76% of global industrial fishing activities remain hidden from public view (Paolo et al., 2024).

A further constraint for effective models (Piet et al., 2009) and management strategies is the limited understanding of regional-scale seafloor and habitat sensitivity in response to bottom trawling. This includes the relationship between sediment remobilization and the transport of resuspended organic matter in the water column following trawling (Porz et al., 2024; O’Neill and Ivanović, 2016), the differentiation of anthropogenic sediment disturbances from natural bioturbation processes based on the analysis of bottom trawl-impacted substrates (Rooze et al., 2024; Forster et al., 2024), and the role of trawling in nutrient cycling and energy transfer within marine ecosystems (Jennings et al., 2001; Lipka et al., 2018; Pitcher et al., 2022; Gogina et al., 2024). Hydroacoustic mapping techniques can bridge the gap between satellite remote-derived parameters and direct physical observation of seafloor alteration and can assess bottom trawling in regions with limited AIS and VMS data availability.

High-resolution multibeam echosounder (MBES) data provide direct evidence of bottom trawling by detecting morphological and sedimentological changes, enabling a detailed quantification of trawling intensity (Schönke et al., 2022; Díaz-Mendoza et al., 2025; Durán et al., 2023). The spatial distribution of these morphological changes correlates with fishing intensity, and allows for assessing the cumulative physical impact of bottom trawling on the seafloor by computing the volume of trawl-induced furrows (Schönke et al., 2022; Durán et al., 2023).

This study focuses specifically on visualizing fishing with mobile bottom-contacting gears (hereafter referred to as ‘‘trawling’’) in the Fehmarn Belt region of the southwestern Baltic Sea. This is the first multi-year time series to apply high-resolution MBES and quantify trawling intensity in the Baltic Sea, spanning five consecutive years from June 2019 to July 2024 with a consistent methodology. Critically, this is the first direct empirical comparison between MBES-derived trawling indices and publicly available AIS data for small-scale fisheries (<12 m), in a region where VMS data is not representative. The Fehmarn Belt region is characterized by fine-grained sediments and is primarily influenced by trawling with bottom-contacting otter board nets from small vessels. Multiple datasets were integrated and evaluated to assess trawling intensity. The datasets included MBES data, AIS records, SAR estimates, and biological sampling. The study aims to address the following main objectives:

1. To quantify how well fishing effort inferred from publicly available AIS data correlates with the spatial and temporal patterns of trawl tracks detected through hydroacoustic mapping.
2. To characterize the spatial patterns of trawling activity and the corresponding recovery rates of seafloor morphology, as revealed by repeated high-resolution MBES surveys.
3. To document how variability in acoustically derived trawling intensities relates to changes in macrofaunal community structure, diversity, and functional indices
4. To demonstrate how the MBES-derived Trawling Index, when aligned to standardized grid systems (e.g. EEA/HELCOM), can complement AIS-based monitoring and inform marine spatial planning and ecosystem-based fisheries management under current Baltic Sea policy frameworks.

2. Research area

The research area is situated within the German Exclusive Economic Zone (EEZ) in the Fehmarn Belt (southern Baltic Sea) The Fehmarn Belt separates the German island of Fehmarn from the Danish island of Lolland and reaches depths up to 35 m. It is a pathway for approximately 70% of the water exchange between the North Sea and the Baltic Sea. The tidal currents within the Fehmarn Belt are negligible and current velocities are controlled by wind conditions. The horizontal current velocity in the Fehmarn Belt typically ranges from 0.14 m/s (at a depth of 10 m) to 0.23 m/s at a depth of 24 m (BSH, GeoSeaPortal, last accessed 14 March 2025). Peak current velocities around 0.4 m/s are recorded. A data gap exists from late 2020 to mid-2023 (BSH, GeoSeaPortal, last accessed 14 March 2025, Appendix).

The research area is located within the marine protected area (MPA) ‘Fehmarn Belt’ that is part of the European Natura 2000 network under the EU’s habitat directive. Closure of fishing with mobile bottom-contacting gears came into force in mid-December 2024. The research area encompasses 4.7 square kilometers, with water depths ranging between 22 and 25 m (Fig. 1). The site is adjacent to an abrasion platform located to the southeast, which extends westward from Fehmarn and is characterized by reworked glacial till (lag deposits). Away from the abrasion platform, sediment in the MPA is composed of silty sand (Schönke et al., 2022). Due to the prevailing westerly winds, the majority of the material remobilized from Fehmarn is transported in an easterly direction.

3. Instrumentation and methods

3.1. Multibeam Echosounder (MBES) survey

MBES represents the primary tool to investigate underwater morphology from shallow coastal zones to the deep sea. MBES provides the advantage of determining the water depth across a swath perpendicular to the sailing direction by beamforming an acoustic signal in a fan-shaped geometry. Upon reception, the reflected and scattered acoustic signal is separated into multiple beams, each with a well-defined angle of incidence that can be accurately assigned to a specific location on the seafloor. These locations are referred to as beam footprints,

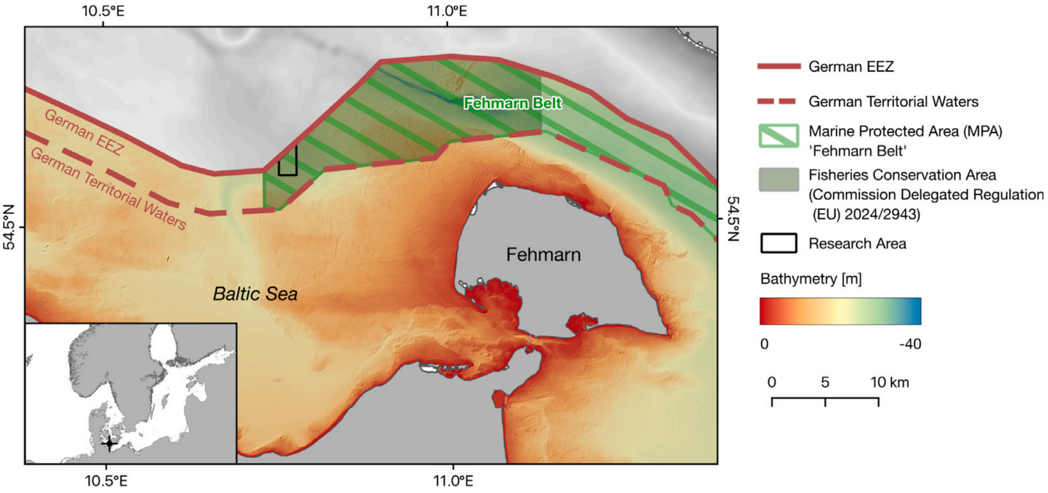

Fig. 1. The research area is situated in the southwestern Baltic Sea (Europe), within the 'Fehmarn Belt' Marine Protected Area (MPA). A Fishery Conservation Area came into force at mid December 2024, prohibiting the use of mobile bottom contacting gears.

and the event of transmitting a full swath of beams is known as a ping. To image the trawl trace features presented in this study, the hull-mounted, mid-water range MBES system R2Sonic 2024 (R2SONIC, Inc., Austin, TX, USA) was operated at a survey speed of 4.5–5 knots. Depending on the selected survey mode, the R2Sonic system recognizes 1024 equidistant beams per ping in ultra-high-density (UHD) or 256 in multi-frequency (MF) mode. Given a pulse length of 15–50 μs at a frequency of 400 kHz and assuming an average sound velocity of 1500 m/s, the system provides a vertical resolution of ≈1.13–3.75 cm. The horizontal resolution is determined by along-track and across-track spatial sampling rates, which are summarized in Table 1. Across-track resolution mainly depends on the swath opening angle, while along-track resolution is controlled by the vessel's speed and the average ping rate. At typical survey settings, the horizontal sampling rate primarily determines the ability to resolve fine-scale seafloor structures.

As an initial experimental campaign to determine the suitability of multi-frequency backscatter data for trawling intensity assessment, the EMB238 cruise (taking place in 2020) focused on MF mode, resulting in a significant reduction in horizontal resolution. The decreased resolution did not allow for resolving trawl traces in sufficient detail for consistent processing and comparability with bathymetric data from other years is limited. Although the 2020 dataset was collected in MF mode with coarser horizontal sampling than the UHD surveys of 2021–2024, we include it as a qualitative context for two reasons. First, it provides the most comprehensive acoustic and biological data available for a contrasting year of high fishing activity (pre-fish stock collapse and trawling closure), documenting seafloor and community conditions that would otherwise be undocumented. Secondly, although the precision of volume calculations is reduced, as discussed in Section 3.2, the spatial structure of the trawl traces is still preserved, including the main trawling corridor. This provides a crucial baseline for assessing furrow recovery, as it shows that the pattern of trawl traces seen in 2021 was not present in 2020. Until 2024, no full (i.e., gap-free) coverage of the research area was possible due to limited ship time and the fact that the outer beams were found unsuitable for accurate detection of the trawl traces.

3.2. Macrobenthic sampling

Benthic macrofauna samples were collected in the research area from one to five stations per sampling campaign, with three replicates per station, using a van Veen grab (75 kg, sieve lid) with a sampling area of 0.1 m^2. Station locations were initially, in 2020, selected based on a preliminary analysis of acoustic survey data to encompass areas with varying densities of trawl traces. Due to logistical constraints, biological sampling campaigns did not always temporally align with hydroacoustic surveys across all years. Notably, in 2021 data was only collected from a single station in July (cruise EMB271; additional samples at the same single location were also collected in January, March and November 2021). In 2022, biological data were gathered at the end of March during cruise AL570. This temporal mismatch requires caution as it may somewhat limit the direct comparisons between biological and acoustic datasets for certain years. Some samples (excluded from quantitative analysis but considered for assessing biodiversity and fauna penetration depth) were also taken using a multi-corer (MUC) with a sampling area of 0.0078 m^2. Occasionally, to qualitatively capture fast-moving, rare, or large species, a so-called "Kieler Kinderwagen" dredge was also used (inner opening width: 92 cm, mesh size: 5 mm), towed at a speed of up to 1 knot over the ground for approximately 1 min to provide a more comprehensive biodiversity estimate. Samples were sieved onboard using a 1.0 mm sieve, after which the material was fixed in a 4% seawater-formaldehyde solution buffered with marble chippings. In the laboratory, samples were sorted, and organisms were identified to the lowest possible taxonomic level, with taxonomy following the World Register of Marine Species (Worms, 2025). Organisms were counted and weighed to determine abundance and biomass per square meter. Ash-free dry weight (AFDW) was calculated from fresh weight using species-specific conversion factors (Gogina et al., 2022).

From a separate sample surface sediment (upper 2 cm) was collected to determine grain size distribution (using Mastersizer 3000) and total sediment organic content values (by loss on ignition). Near-bottom water salinity, temperature, and dissolved oxygen concentrations, factors often driving the distribution of benthic macrofauna, were recorded using CTD.

3.3. Trawl track segmentation

The general procedure to detect trawl traces in MBES data follows the method described by Schönke et al. (2022). To segment the trawl traces, a regression fit is applied to each ping to compute a reference depth profile. Subtracting the reference depth profile from the raw footprint values removes large-scale morphological features, effectively acting as a high-pass filter. Footprints above or below ±50 cm of the zero-mean surface and the outermost 50 beams were marked to be excluded. Residual depth footprints are then allocated into tiles,

Table 1
Sonar setting used during the surveys. Along and across track spacing were computed for a water depth of 25 m, a survey speed of 5 knots, and a sound velocity of 1500 m/s. EMB238 was recorded in MF mode where only every third ping was transmitted at a frequency of 400 kHz.

Cruises	EMB238	EMB267	EMB288	EMB320	EMB345
Survey date	28.05.2020	10.06.2021	03.03.2022	29.06.2023	18.07.2024
Width of swath [°]	140	140	145	150	120
Frequency [kHz]	400	400	400	400	400
Sampling mode	MF	UHD	UHD	UHD	UHD
Number of beams	256	1024	1024	1024	1024
Ping rate [1/s]	3.00	8.99	7.94	6.87	12.91
Along track spacing [m]	0.86	0.29	0.32	0.37	0.20
Across track spacing [m]	0.54	0.13	0.15	0.18	0.08

gridded, and mean-subtracted to normalize the surface to zero means. Based on the mean surface standard deviation (std) across all survey years (1.5 cm), values falling below a user-defined threshold of 5 cm (>3 × std) were marked as features related to the trawling activity.

The corresponding workflow of the 2022 study was adapted to improve comparability across survey years and for open-source reproducibility, with a key update being the migration to Python. The documented GitHub repository published on Zenodo provides full processing details (Schönke, 2025). As a high-pass filter, a second-order Savitzky-Golay filter was used to compute the reference depth profile per ping (2nd order, window length is 20% number of footprints per swath), replacing the previous MATLAB smoothing function. After filtering, footprints per tile were not explicitly horizontally aligned and gridded with 0.5 m horizontal resolution using SciPy's grid data function (method = 'linear'). For consistency between all surveys, tile locations were aligned within the 10 × 10 m EEA Reference grid (EPSG: 3035). Tiles statistic is stored in the GeoPackage format using the EEA Reference grid ID as a spatial reference. For the statistical analysis presented in this work, only tiles with at least 90% footprint area coverage were considered.

3.4. Trawling Index (TI), based on MBES data

The Trawling Index (TI), introduced by Schönke et al. (2022), is a hydroacoustically derived metric that quantifies the physical disturbance caused by bottom trawling on the seafloor, serving as a direct proxy for physical impact. For comparison of concepts, trawling intensity typically refers to the effort of trawling activity within a given area and is often estimated using vessel tracking data such as VMS or AIS. To compute the Trawling Index (TI), segmented features within each 10 × 10 m tile were summed and multiplied by the pixel area to calculate furrow volume. The TI quantifies furrow volume relative to the observation area, expressed in [m^3/m^2], a unit also validated by Durán et al. (2023) using an independent workflow. As an absolute value, the TI provides an intuitive measure of trawling intensity (a value of 0.5 $m^3/100\ m^2$ corresponds to an average erosion depth of 5 mm) and enables the identification of fine-scale trawling patterns across the study area and further allows an objective comparison between survey years. Trawling index classes were defined empirically based on the distribution of observed TI values: >0–0.2 $m^3/100\ m^2$ as low, >0.2–0.4 $m^3/100\ m^2$ as medium, and >0.4 $m^3/100\ m^2$ as high. To facilitate a statistically consistent comparison between acoustically derived Trawling Intensity (TI) and AIS-based shipping density data, the high-resolution TI values (10 × 10 m tiles) were upscaled (580 × 580 m (Fig. A.7f–j)) to match the HELCOM grid cell resolution (A.7, a–e). This upscaling was performed by averaging the TI values of all tiles within the targeted grid cell size. This enables a direct cross-comparison between TI values and shipping density (Fig. A.7k–o) as a proxy for seafloor disturbance caused by bottom trawling and also enables a comparison across other existing databases.

3.5. AIS data from Danish Maritime Authority

AIS data were downloaded from the Danish Maritime Authority (https://www.dma.dk/safety-at-sea/navigational-information/ais-data, last accessed 8 May 2025) as ASCII files. Full processing details are provided in the documented workflow published on Zenodo (Feldens, 2025). The files were filtered by time stamp to include only the years 2019–2024 (data download ends 31 July 2024). Subsequently, all vessels not reporting a navigational status of "Engaged in Fishing" were discarded from the dataset. Names and lengths were extracted from the remaining vessels. To enable comparison with TI values derived from annual hydroacoustic surveys, AIS data were filtered to include periods beginning one year prior to the first survey and continuing through the intervals between successive surveys. AIS data points were converted into vessel track lines and subsequently counted within each grid cell based on downloaded HELCOM data, resulting in maps of shipping density. The research vessels CLUPEA and SOLEA of the Thünen Institute of Baltic Sea Fisheries are responsible for a large percentage of fishing efforts reported by AIS systems in the research area after 2020 (13% of reported signals in 2019–2020, compared to 38% in 2020–2021). However, no actual trawling took place in the MPA area by these vessels and the vessel's AIS data were omitted from the dataset for clarity. In contrast to the specification provided by metadata information, the data is provided with a cell size of 580 × 580 m in EPSG:3857 - WGS84.

3.6. Biological monitoring data

Biological data were harmonized across years and cruises by standardizing abundance and biomass to square meter values and aggregating by taxonomic groups. Diversity responses were assessed using species richness, Shannon–Wiener diversity (H′), Pielou's evenness (J′) and Margalef's richness index (d) calculated per station and linked with trawling intensity expressed by furrow volume. The Shannon–Wiener Diversity Index is a commonly used biodiversity metric that accounts for both species richness and evenness of abundance distribution (how equally individuals are distributed among species). J′ ranges from 0 (uneven) to 1 (perfect evenness). The Margalef index (d) is a species richness metric that accounts for the number of species (S) relative to the logarithm of the number of individuals (N), with higher values generally indicating greater biodiversity, usually considered ecologically positive. This index was suggested as most sensitive to trawling pressure by some previous studies (Van Loon et al., 2018). Based on species abundance and biomass data, two traits-based indices, community bioturbation and bioirrigation potentials (BPc and BIPc), were computed following methods described in Solan et al. (2004) and Renz et al. (2018). Both indices were developed to assess the potential effects of macrozoobenthos on various ecosystem processes in cohesive sediments. We also explored a non-metric multidimensional scaling (NMDS) plot built on the Bray–Curtis similarity of square-root transformed abundance to analyze changes in community structure over time.

Table 2

Cumulative comparison between TI and AIS data in the research area across years.

Method	Cumulative parameter	2020	2021	2022	2023	2024
TI	Area coverage [km^2]	3.1	3.4	3.4	3.3	4.70
	Furrow volume [m^3]	1055.81	5067.13	1108.37	907.69	586.02
AIS	Unique vessels	11	7	3	5	5
	Track count per cell	330	52	33	105	39

4. Results

4.1. Spatial distribution and intensity of trawling activity based on MBES

High-resolution MBES data offers detailed insights into the spatial distribution and temporal development of bottom trawling patterns over a five-year period (Fig. 2a–e). Both similarities and changes in furrow volumes and spatial distribution can be observed throughout the years. The spatial distribution of trawl traces reveals consistent patterns across survey years, forming an eastward-curving arc around a wreck located in the northwestern part of the research area (Fig. 2a–e). This arc is bounded to the south by outcropping glacial till forming an abrasion platform, and to the northeast by boulder fields. The arc is particularly pronounced in 2020, 2021, and 2024 (Fig. 2a–b,e), whereas in other years, it is less distinct due to the reduced presence of trawling traces (Fig. 2c–d). In particular, in 2020 and 2021, the difference in tracked furrow volumes in the direct vicinity of the wreck (close to the noise level) and the rapid onset of furrows towards east are distinctive features. Smaller pockets of decreased trawling intensity can be observed within the arc-shaped trawling pattern, particularly pronounced in the south (Fig. 2b). These pockets, surrounded by tiles with high trawling intensity, likely result from natural obstacles, such as larger boulders observed in the MBES data, that act as barriers to fishing activity. A further feature is the persistent occurrence of higher-intensity trawling activity in the north throughout most years. The exception is 2020, where trawling impact in the north appears less distinct, which is most likely attributable to an artifact caused by different MBES settings during the initial campaign.

While the spatial distribution pattern remains similar throughout the years, individual trawl traces quickly degenerate over the annual cycle (also reported in Packmor et al. (2025)). An example of the residual bathymetry is shown in Fig. 3. Particularly pronounced traces can only be recognized as faint features that are difficult to distinguish from the natural roughness of the seafloor in the following year. The traces disappear completely after two years.

The comparison of trawling intensity from 2020 to 2024, based on the Trawling Index (TI), is illustrated in high resolution (10 × 10 m) in Fig. 2a–e. TI values range from 0 to over 0.5 m^3/100 m^2, with a peak of 1.6 m^3/100 m^2 recorded in 2021 (Fig. 2b; EEA Reference grid ID: 10mE437121N349579). A year-by-year summary of cumulative furrow volume is presented in Table 2. Across the five-year study period, 2021 exhibited the highest cumulative furrow volume, with 5067 m^3 detected within 3.4 km^2. This is nearly ten times higher than the lowest intensity recorded in 2024, where only 586 m^3 were detected based on an even higher survey coverage of 4.7 km^2 (Fig. 4e). Compared to 2020, 2022, and 2023 — years with cumulative volumes of 1056 m^3, 1108 m^3, and 907 m^3, respectively — the 2021 value is approximately five times higher than the average for the other years, highlighting a significant spike in trawling activity that year.

The distribution of the upscaled TI (580 × 580 m tiles) matching HELCOM grid size retains the general spatial trend of trawling pressure, including increased intensity in the center part and lower values in the southern part of the study area. However, the loss of spatial resolution results in a reduction of the detail in fine-scale trawling features. For example, the distinctive shape of the eastward arc becomes blurred, and small areas with no trawling impact are underrepresented or lost entirely due to averaging across larger grid cells.

Fig. 4a–e presents a year-by-year categorization of trawling intensity, illustrating both the cumulative furrow volume and corresponding seafloor area for each intensity class (defined in 3.4), across the five observation periods. Excluding the 2020 dataset, the smallest proportion of untrawled seafloor surface area was recorded in 2021, with only 14% of the 10 × 10 m tiles remaining unaffected by trawling. In contrast, untrawled areas accounted for 34% to 65% of the surface area between 2022 and 2024 (Fig. 4b). The proportion of the seafloor classified as low trawling intensity was relatively stable across all years, ranging from 27% to 38% (Fig. 4c). However, the contribution of low-intensity areas to the total cumulative furrow volume varied significantly: between 2022 and 2024, the low-intensity area accounted for 75% to 87% of the total furrow volume, whereas in 2021, the low-intensity area contributed only 28% (Fig. 4c). In contrast, medium and high-intensity trawling areas exhibited the reverse pattern (Fig. 4d–e). In 2021, 19% of the surface area fell into medium and higher-intensity categories, compared to just 0.6% to 1.9% in the following years. Furrow volumes associated with medium and high-intensity classes were up to 300 times higher in 2021 than in any other year, highlighting a period of concentrated and intensive trawling activity.

4.2. AIS data

The AIS data, provided by the Danish Maritime Authority, include vessel positions marked with the status “fishing” and cover five subsequent periods, each ranging from mid-year to mid-year of the following year (Fig. 2k–o). To enable direct comparison with HELCOM shipping density data, both the TI (Fig. 2f–j) and AIS-based shipping density (Fig. 2k–o) were processed using a standardized grid resolution of 580 × 580 m. This time framing was selected to align with the MBES survey schedule and account for the persistence of visible trawl traces on the seafloor over a roughly one-year timescale (Fig. 3). Cumulative track counts across all grid cells and vessel numbers are summarized in Table 2, while spatial patterns of vessel movement are visualized in Fig. 2k–o.

Over the five-year observation period, the cumulative number of fishing vessel tracks showed a clear decline. The high number of recorded tracks in 2019–2020 marks the peak in fishing activity during the observation period, followed by a marked decline in 2020–2021, after which the activity level remained relatively low but fluctuated moderately in the subsequent years. During the first period (2019–2020; Table 2), 11 unique vessels were identified as engaged in fishing, contributing to a total of 330 tracks. In the following periods, both the number of vessels and their associated track counts decreased: 7 vessels (52 tracks) in 2020–2021, 3 vessels (33 tracks) in 2021–2022, 5 vessels (103 tracks) in 2022–2023, and again 5 vessels (39 tracks) in 2023–2024 (Table 2). This pattern reflects a general reduction in recorded fishing activity based on AIS signals classified with “fishing” status.

Regarding spatial distribution, AIS data show notable similarities to MBES-derived patterns, particularly the prominent eastward-curving trawling arc around the wreck site during the first observation period (2019–2020; Fig. 2k). Across all observation years, AIS track density is generally higher in the northern part of the study area and lower in the southern part. While the entire research area showed reported fishing activity during 2019–2020, the subsequent periods (2020–2024) reveal spatial gaps in AIS track coverage, with several grid cells showing no recorded vessel activity.

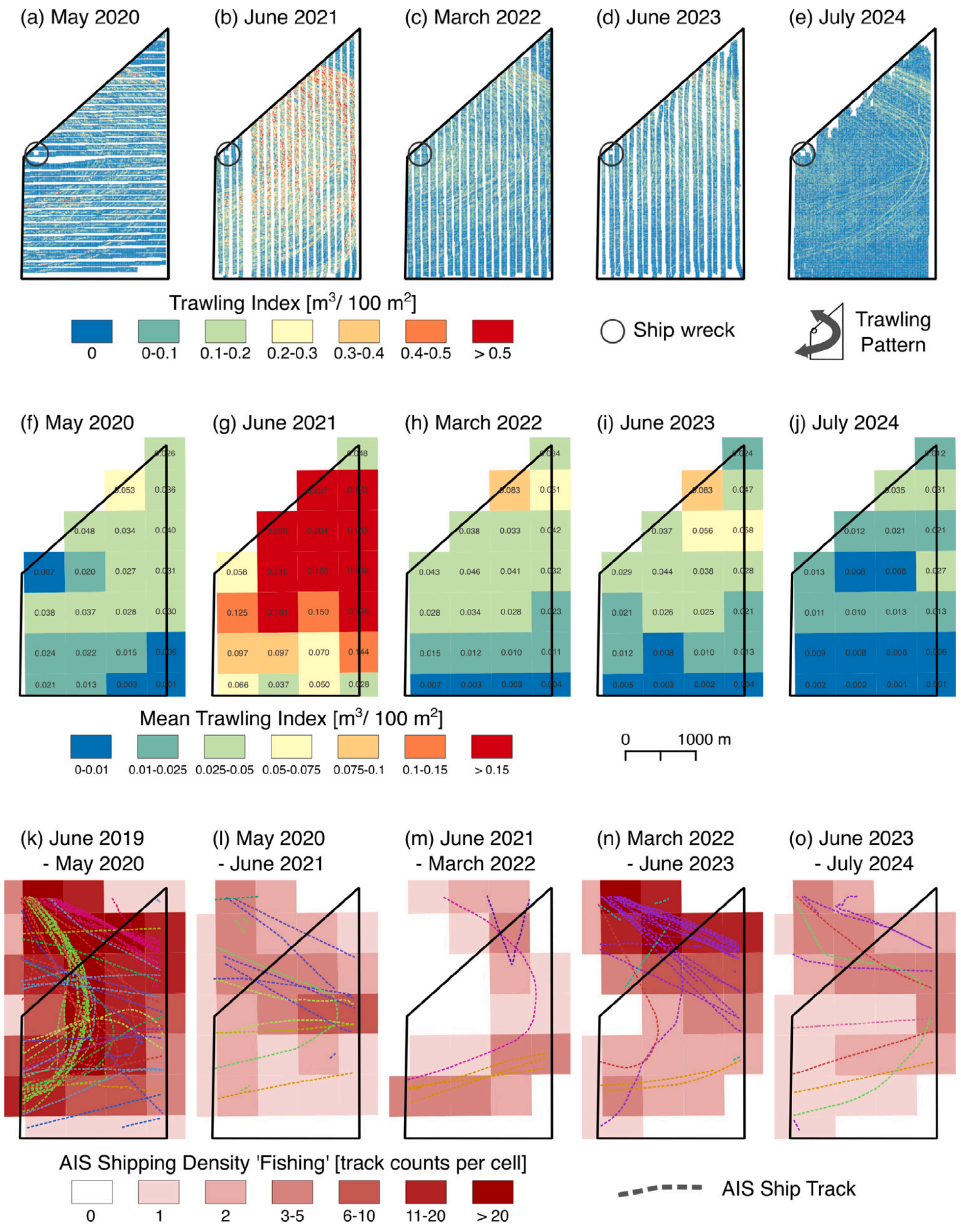

Fig. 2. Trawling in the research area is concentrated along an eastward-curving path as reflected in the following datasets: (a–e) Trawling Intensity (TI) derived from furrow volume per 10 × 10 m bathymetric tile, illustrating the impact of otter boards on seafloor morphology over a five-year period. (f–j) TI resampled to the HELCOM grid to enable direct comparison with the AIS data. (k–o) AIS ship tracks with status "Engaged in Fishing" over the five-year period and color-coded by vessel. The research vessels RV CLUPEA and RV SOLEA, which are known not to have trawled, are excluded. The time periods reflect the intervals between successive hydroacoustic surveys, with the first AIS dataset starting one year prior to the first survey. For the geographical location of the research area, see Fig. 1.

4.3. Macrobenthic response

Benthic macrofauna community composition showed substantial variability across sampled stations and over time (Figs. 4f, 5). A marked decline in abundance was observed between 2020 and 2023, both in average values (Table 3) and particularly at the most frequently visited station, f18 (station location marked in legend Fig. 5), located in the center of the study area. Biomass at that station also dropped in 2021 to only a quarter of its 2020 value, then doubled in 2022, but afterward decreased to a minimum in 2023. In 2024, a potential recovery of diversity was suggested by the highest values of the Margalef diversity index observed over the five-year period at all three visited stations, likely attributed to both reduced trawling pressure and favorable hydrographic conditions preceding the sampling. Abundance in 2024 also indicated recovery at two of the three stations: at f18 it nearly matched 2020 levels, while at the northern station f2 (close to the wreck) it was three times higher than in 2020 and ten times higher than in 2023. However, station f8 (located between f18 and f2), where the highest furrow volume and most recent trawling activity were indicated in 2024 acoustic data, showed the lowest abundance. Here, a 25% reduction compared to 2020 at the same station was observed, which is four times lower than at station f2 close to the wreck. Consequently, station f8 also exhibited the lowest Shannon–Wiener diversity. This resulted in the lowest evenness value averaged across the area for

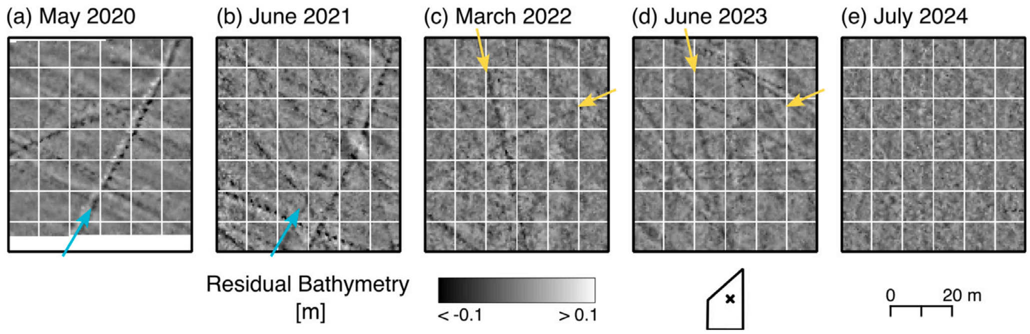

Fig. 3. The residual bathymetry shows the changing appearance of surface morphology over 5 years of hydroacoustic surveying. Trawl tracks remain visible for only about a year.

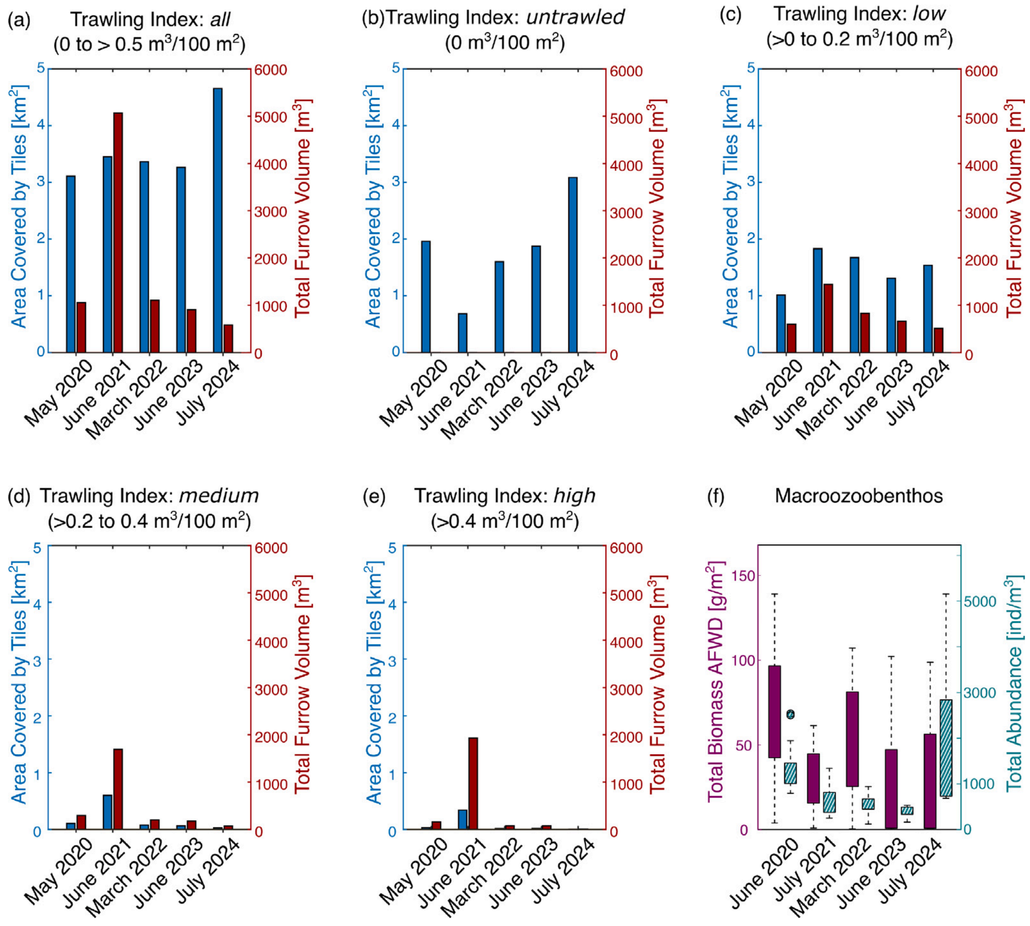

Fig. 4. Furrow volume relative to the area covered by 10 × 10 m tiles within the research area across five survey years. Results are presented for all tiles combined (a) and separately for four Trawling Index classes (b–e), ranging from untrawled to high. The results of the macrozoobenthic sampling include total biomass (AFWD) and total abundance (e).

that year. Biomass exhibited strong spatial and temporal fluctuations, being generally highest (particularly at f18) in 2020 and on average lowest in 2021 and 2023. Biomass at the two stations presumed to be untrawled for some time (f18 and f2) showed signs of potential recovery (doubling and 60% increase, respectively) from 2023 to 2024; in contrast, biomass at f8 (with relatively fresh trawl tracks in 2024) reached the lowest value in the entire dataset.

Functional indices of macrobenthic communities — reflecting their potential for bioturbation (BPc) and bioirrigation (BIPc) — reached their highest values at most stations in 2020, a year characterized in our analysis by rather moderate trawling intensity expressed in cumulative furrow volumes (see Fig. 3 and Section 4.1). At station f18, for example, BPc and BIPc values peaked at 760 and 2717, respectively, indicating high ecosystem functioning potential. In contrast, the lowest area-wide averages for both indices were observed in 2023, coinciding with persistent but spatially limited trawling activity and reduced seafloor disturbance. The lowest individual BPc value across the entire dataset (135) was recorded at the station near wreck in 2022, followed by very low values at station f2 in 2023 (133) and at freshly trawled station f8 in 2024 (145). Bioirrigation potential (BIPc) followed an overall similar spatial and temporal trend, reinforcing the interpretation that

Table 3

Averaged macrozoobenthos metrics (±SD) calculated across the stations sampled over the course of the study.

Year	2020	2021	2022	2023	2024
Sampling months	Jun	Jan/Mar/Jul/Nov	Mar	Jun	Jul
Number of grab samples	(n = 15)	(n = 12)	(n = 12)	(n = 6)	(n = 9)
Number of species observed	**87**	**50**	**99**	**70**	**95**
Shannon-Wiener diversity (H')	2.36 (±0.12)	2.34 (±0.26)	2.65 (±0.10)	2.46 (±0.22)	1.84 (±0.50)
Pielou's evenness (J')	0.75 (±0.06)	0.80 (±0.05)	0.83 (±0.02)	0.80 (±0.08)	0.54 (±0.17)
Margalef's richness (d)	3.18 (±0.62)	2.82 (±0.72)	3.72 (±0.18)	3.48 (±0.04)	4.20 (±0.76)
Abundance (ind/m^3)	1367 (±386)	655 (±357)	607 (±139)	371 (±99)	1817 (±1194)
Biomass (g FW/m^2)	999 (±438)	409 (±175)	878 (±426)	472 (±143)	525 (±290)
Biotubation potential (BPc/m^2)	577 (±202)	203 (±112)	292 (±153)	149 (±123)	229 (±139)
Bioirrigation potential (BIPc/m^2)	1935 (±885)	755 (±546)	1202 (±725)	590 (±618)	859 (±563)

benthic functional capacity is sensitive to local and cumulative trawling pressures.

While bivalves consistently dominated total biomass, polychaetes largely dominated the abundance structure across all years. However, in 2024, barnacles (Cirripedia) became the dominant group in terms of abundance (Fig. 5). The NMDS analysis of community composition highlighted differences across years. Although no consistent trends indicated a significant effect of trawling decline or ecological recovery, there was a tendency for samples with higher trawling pressure, as indicated by AIS and acoustic data (2021, 2023), to cluster together.

5. Discussion

5.1. Trawling induced seafloor disturbance comparison with AIS data

This study presents the evolution of trawling intensity within a 4.7 km^2 research area in the Baltic Sea over a five-year period (2020–2024), utilizing two complementary approaches: A MBES-derived trawling index (TI) and AIS-based vessel traffic metric. Both datasets cover about mid-year to mid-year intervals.

A comparison between trawling activity (based on TI) and AIS activity reveals pronounced differences, questioning the usability of AIS data to map the fishing effort for MSP and impact assessments. Between 2021 and 2023, the TI decreased by a factor of five (from 5067 to 908), while the AIS vessel track counts nearly doubled (from 52 to 105), showing poor correlation during high-disturbance periods. This aligns with Paolo et al. (2024) and Marsaglia et al. (2025) reporting AIS underestimation even for <15 m vessels, and Buhl-Mortensen et al. (2016) finding low VMS-trawl trace correlation. Marsaglia et al. (2025) demonstrated that in parts of the Mediterranean Sea, areas initially classified as low fishing activity based on AIS data were actually subject to significantly higher levels of fishing when re-assessed using satellite-based synthetic aperture radar data. Despite the growing use of AIS data since 2016 to monitor trawling activity, Oberle et al. (2016), De Souza et al. (2016), Kroodsma et al. (2018), Paolo et al. (2024) and Marsaglia et al. (2025), significant limitations remain in capturing the true footprint of bottom trawling. AIS reliability depends on consistent transmission and accurate vessel-reported metadata (gear type, trawling status), which is often incomplete (Rijnsdorp et al., 2017). Moreover, benthic stress depends not only on vessel activity but also on gear type, trawling frequency, and habitat sensitivity (De Souza et al., 2016; Mazor et al., 2021; Pitcher et al., 2022). These uncertainties highlight the need for more sensitive approaches that can capture the physical cumulative impacts of repeated trawling (Rijnsdorp et al., 2020). The 2021 TI peak (Fig. 2b) would be missed by AIS (Fig. 2l), risking incomplete pressure-response assessment when evaluating trawling impacts on benthic ecosystems (Sciberras et al., 2018). MBES provides high-resolution ground-truth to validate AIS models for MSP, with furrow persistence limiting the temporal resolution.

Long-term seabed mapping efforts have underscored that the integrity of benthic habitats in EU waters is widely affected by bottom trawling (Eigaard et al., 2017), reinforcing the call for direct assessments of physical disturbance to be carried out using seafloor-focused technologies such as MBES, to gain an initial understanding of the current true status. Although acoustic surveys cannot replace AIS and VMS as a global monitoring system to assess spatial–temporal fishing vessel activity, TI integration refines trawling pressure maps and addresses key ecological knowledge gaps, such as the relationship between benthic community structure, habitat condition, and localized trawling patterns (Mazor et al., 2021; Pitcher et al., 2022; Packmor et al., 2025). It should be noted that publicly available AIS data is not used as an official fisheries monitoring system, which relies exclusively on VMS and logbook data.

5.2. Change of seafloor over time

Understanding the chronological effects of trawling at both small and large spatial scales is essential for accurately assessing its long-term impact on benthic ecosystems. By presenting a multi-year time series, we contribute to the growing need for a deeper understanding of the relationships between benthic community structure, trawling footprints, and the increasing use of AIS-derived indicators such as hours of fishing per area or swept area ratio (Eigaard et al., 2017). It specifically explores seafloor recovery rates and benthic responses, critical as many organisms are sensitive to disturbances to varying degrees (Mazor et al., 2021). Bottom trawling in our MPA was prohibited from early 2025, post our final dataset, but the reduced cod quotas and subsequent closures — the main demersal target in western Baltic — significantly lowered fishing activity pre-2025 (ICES, 2024).

Regarding seafloor integrity, trawl tracks have been reported to persist for at least five years in fine-grained (grain sizes smaller than fine sand) deposits of Kiel Bay, Baltic Sea, based on repeated side-scan sonar (Krost et al., 1990) and MBES surveys (Jakobsson et al., 2024). For the southern Baltic Sea, Jakobsson et al. (2024) found that trawl traces in consolidated glacial clay exhibit a persistence time of up to eight years. In contrast, DeAlteris et al. (1999) found a recovery time after trawling of less than 60 days for muddy sediments offshore Rhode Island due to natural remobilization of the seafloor. In the Baltic Sea, a similar variability in trawl track preservation potential can be expected in fine-grained deposits, depending on hydrodynamic forcing due to currents. With the onset of fine-grained deposits in the German Baltic Sea mostly below 20 m (Tauber, 2012), the main cause of sediment remobilization is exceptionally strong storms (that may remobilize sediment down to 50 m depth) or inflows of marine bottom water (Bunke et al., 2019). In the timespan from 2019 to 2024, the strongest inflow event occurred in December 2023 due to the winter storm "Zoltan" (Purkiani et al., 2024) which triggered a moderate inflow event with current velocities of more than 0.5 m/s at the Darss Sill, and (due to a reduced cross sections) higher current velocities at the Fehmarn Belt (BSH, GeoSeaPortal, last accessed 14 March 2025, Appendix). Other events in the Fehmarn Belt area in the time period were less pronounced, with two minor inflow events occurring in 2022 from October to December (Naumann et al., 2024). In 2021 (Naumann

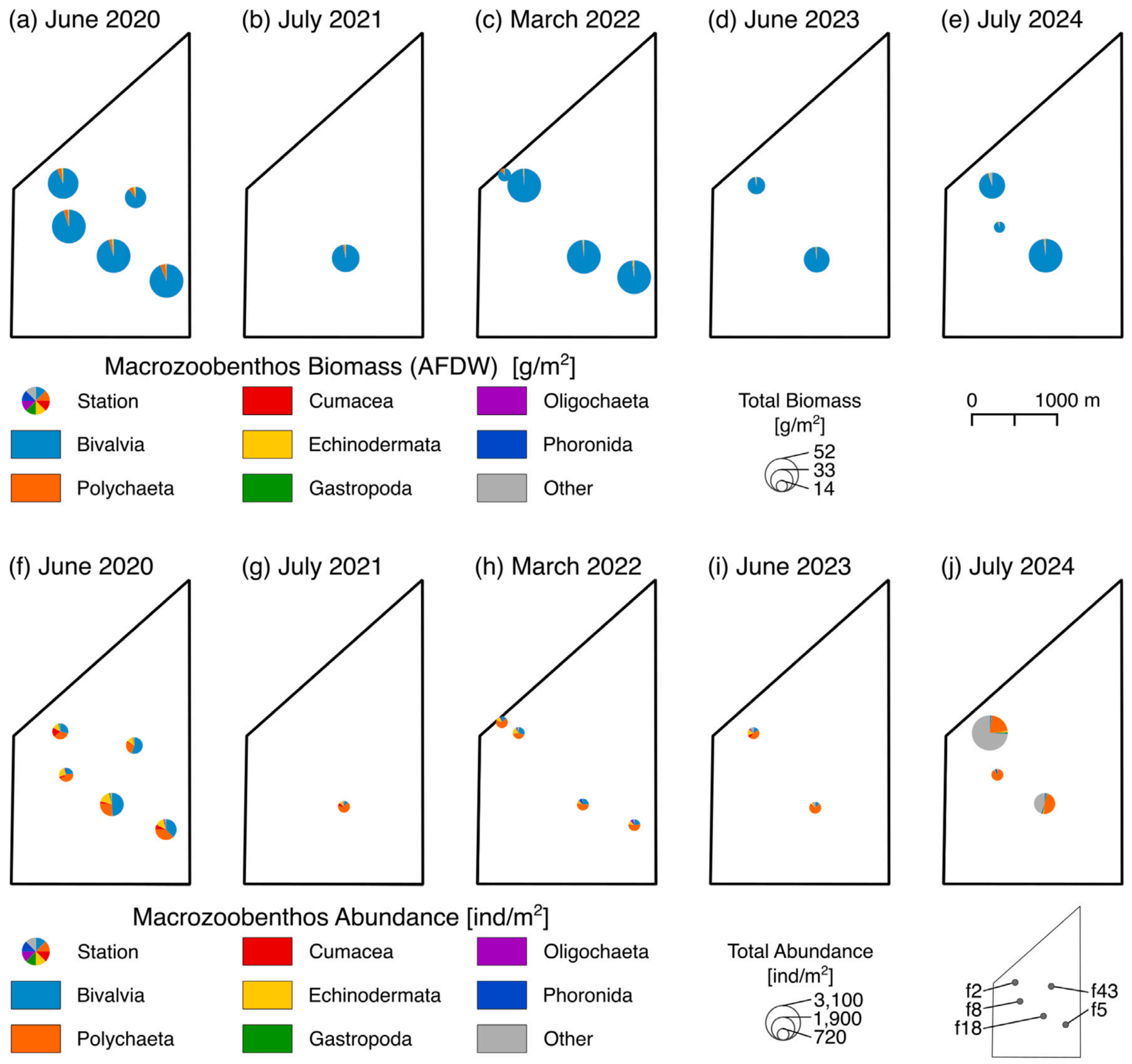

Fig. 5. Macrozoobenthos sampling stations and community composition resolved by group from 2020 to 2024. Note the different number of stations visited across years. The only station visited every year is station f18 at the center of the area. (a–e) Macrozoobenthos biomass (AFWD) dominated by Bivalvia at all stations and in all years. (f–j) Macrozoobenthos abundance, mainly composed of Bivalvia, Polychaeta (bristle worms) and Echinodermata. However, in 2024, Cirripedia (barnacles, here grouped as "Other") increased and were most abundant. For location see Fig. 1.

et al., 2023), no inflow events were reported, while minor inflow pulses were measured in the spring and autumn of 2020 (Naumann et al., 2021). However, a clear degeneration of trawl tracks in the Fehmarn Belt takes place mostly within one year, and with a maximum of two years, and thresholds for seafloor remobilization therefore have to be exceeded each year (Fig. 3). Threshold depth-averaged current speeds for the remobilization of sediments with a median grain size of 4Φ are around 0.4 m/s (Soulsby and Whitehouse, 1997). This value is underestimated due to the ignorance of coherence from the clay (approx. 3%) and organic content (approx. 3%–4%) of the samples, and overestimates the required values due to an assumption of a flat seabed, ignoring the form drag produced especially by trawl mounds that increase bed shear stress and causes the predominant erosion of trawl mounds observed by Schönke et al. (2022). For 2020, 2023 and 2024, available measurements of horizontal bottom current velocities at the Fehmarn Belt BSH station exceed 60 cm/s, relating to depth average current speeds exceeding 40 cm/s with standard values for von Karman constant and seafloor roughness lengths for coarse silt and fine sand (Soulsby and Whitehouse, 1997). Preferred remobilization of trawled seafloor is further supported by the results of Bruns et al. (2023), who report reduced shear strength of trawled sediments, which facilitates remobilization. It may be assumed that the Fehmarn Belt is an example of rapid trawl trace degeneration for the Baltic Sea. Hydrodynamic forcing in the Fehmarn Belt is high, as 70% of the water discharge between the North Sea and the Baltic Sea has to flow through this narrow section.

5.3. Change of benthic communities over time

Regarding macrozoobenthos communities, repeated sampling revealed pronounced changes over time in their structure, abundance, and biomass in the study area. Since the first survey in 2020, the development of communities at similarly trawled stations has followed a generally similar trajectory, though marked by strong seasonal and interannual variability. Between 2020 and 2023, station f18 (Fig. 5), in particular, showed a significant decline in abundance and biomass, with a drop in individual counts exceeding 50% compared to 2020 (Table 3). This change cannot be definitively attributed to a single cause like bottom trawling. Possible influencing factors include decreasing bottom trawling activity (potentially leading to increased benthivorous fish abundances), oxygen deficiency events, fine-scale variation in trawling footprints, natural habitat patchiness, ongoing successional processes, or other environmental changes. Sampling-related artifacts also cannot be entirely ruled out. Our results demonstrate that the condition of the benthic community at the time of sampling is closely linked to the time elapsed since the last trawling event. Samples with higher trawling pressure, indicated by both AIS and acoustic data, cluster closer together. Our findings reveal that trawling intensity (Table 2) and benthic community response (Table 3), tracked over five years, do not follow a simple linear relationship. Instead, both abundance and diversity appear to fluctuate cyclically until reaching a kind of dynamic equilibrium (e.g., Table 3, highest numbers were recorded in 2020 and in 2024). This suggests that benthic sampling at a single time point may offer only a limited snapshot of ecosystem health and can lead to misleading interpretations if not contextualized within a longer recovery timeline. Such insights may help explain divergent findings in the literature regarding trawling impacts. Models that derive trawling pressure from AIS data often indicate negative effects on benthic species, and call for reduced or more selective trawling practices to support ocean health (Hiddink et al., 2006; Pitcher et al., 2022; Mazor et al., 2021; Rijnsdorp et al., 2020).

However, field studies have shown that estimating seafloor disturbance and ecological response is challenging (Hinz et al., 2009; Rooze et al., 2024; Bradshaw et al., 2021, 2024; Forster et al., 2024; Sciberras et al., 2018) due to the complex interplay of spatial and temporal trawling variability (Packmor et al., 2025; Li et al., 2024), natural versus anthropogenic sediment mixing (Forster et al., 2024; Rooze et al., 2024), and the diversity and evolution of trawling gear types (Bearzi et al., 2024). Furthermore, Rooze et al. (2024) observed that in areas actively reworked by macrofauna, trawling does not necessarily leave a clear geochemical footprint. These studies demonstrated that even for biogeochemical parameters with relatively direct links to trawling-induced sediment disturbance, it is difficult to obtain statistically robust linear correlations with trawling intensity. This reflects the fact that multiple processes act simultaneously and on different time scales, so that simple monotonic relationships are rarely detectable even when a causal link exists. The present study points out that the situation is even more complex because benthic communities follow their own internal cycles of succession, food supply, and demand, which run in parallel to seafloor regeneration. As a result, the biological state at a given sampling time represents the superposition of trawling history, internal community dynamics, and hydrographic and environmental variability, rather than a direct snapshot of trawling impact alone. Additionally, collecting and evaluating macrozoobenthos samples is time-consuming, even for very small focus areas (small and heterogeneous datasets in time and space). This limits the statistical power to detect relationships, especially if responses are non-linear, delayed, or threshold dependent. Different functional groups and habitats on the seabed are also likely to show distinct sensitivities and recovery trajectories, which are not yet sufficiently understood to be captured by a single global regression model. Under these conditions, a formal regression or correlation analysis would risk suggesting spurious precision without actually improving ecological understanding.

The Margalef diversity appears to be the most sensitive index of benthic fauna response to bottom trawling, organic enrichment and sedimentation (van Loon et al., 2018), showing consistent decline across trawling gradients (van Denderen et al., 2024). Our results confirm this: Margalef's richness was the only macrozoobenthos parameter showing consistent significant negative correlation with increasing TI. TI uniquely explained 14% of its variance, approaching major environmental predictors like salinity (22%) and organic content (15%). This demonstrates that trawling meaningfully affects certain community dimensions, particularly Margalef's richness, while its role in explaining biomass, productivity, and compositional evenness remains small relative to environmental gradients. Biological changes can be confidently attributed to trawling only where its unique contribution is substantial, other responses remain dominated by natural variability, at least in our comparatively large but still limited dataset. These findings highlight the importance of interpreting point-in-time observations within the context of temporal recovery dynamics. A critical parameter for assessing trawling impact is the recovery time required for the disturbed seafloor to return to pre-impact state (Jakobsson et al., 2024).

5.4. *Evaluating the TI and limitations*

The TI quantifies the physical disturbance caused by bottom trawling on the seafloor, within a standardized reference area of 10 × 10 meters (Fig. 2a–e). The TI metric offers a fast and objective method for detecting bottom trawling disturbances based on MBES data, eliminating the need for manual segmentation and enabling consistent year-to-year and spatial comparisons. This is particularly valuable given the ongoing challenges in harmonizing diverse data sources to quantify fishing effort, especially in small-scale fisheries and semi-enclosed seas like the Baltic Sea (McCluskey and Lewison, 2008; Rufino et al., 2023). Bottom trawling can pose a major threat to seafloor habitats — especially muddy areas — and has proven difficult to correlate reliably with reported fishing activity (Díaz-Mendoza et al., 2025; Rijnsdorp et al., 2020; Rooze et al., 2024). While side-scan sonar (SSS) was traditionally used for furrow detection (Gournia et al., 2019; Bruns et al., 2020), MBES are now increasingly utilized in both local (Schönke et al., 2022; Durán et al., 2023; Bradshaw et al., 2021) and regional-scale assessments (Díaz-Mendoza et al., 2025; Jakobsson et al., 2024). Despite this advancement, there is still no standardized protocol for deriving fishing effort from acoustic data, and correlating hydroacoustic observations with AIS-derived trawling intensity remains difficult (Díaz-Mendoza et al., 2025; Durán et al., 2023). The TI metric addresses several of these limitations for the Baltic Sea basins. It is scalable, efficient (Fig. 2f–j) and does not require manual annotation (Bruns et al., 2023; Jakobsson et al., 2024), allowing integration into modeling approaches (Rooze et al., 2024) and comparison with AIS-based activity (Fig. 2k–o). It is robust to data gaps between profiles and built-in filters reduce the need for data cleaning, making it a promising tool for enhancing traditional AIS-based assessments and providing much-needed ground-truth for areas where AIS data are sparse or incomplete. A tile size equivalent to the EEA Reference grid cells facilitates direct comparison with existing spatial datasets, such as the HELCOM database, by ensuring consistent spatial resolution and alignment across data sources. However, TI detects only those areas significantly disturbed by otter boards, with less distinct trawl traces incised less than 5 cm falling below detection thresholds. Moreover, TI values can be influenced by MBES resolution and water depth—factors that must be carefully controlled across basins of different water depths to ensure comparability. Additionally, trawl tracks in sandy sediments often vanish within days, limiting detectability and application of the TI in predominantly sandy environments such as the North Sea (Bruns et al., 2020).

5.5. *Implications for ecosystem-based management, comparison with existing MSP approaches*

High-resolution MBES-derived Trawling Index (TI) data — defined over standardized 10 × 10 m tiles (Fig. 2a–e) — provide fine-scale spatial patterns of bottom trawling not detectable by conventional AIS/VMS monitoring (Eigaard et al., 2017). High-resolution spatial fisheries data are essential for ecosystem-based fisheries management, as they provide information on where fisheries actually interact with various ecosystem components (Eigaard et al., 2016). Fishing pressure is distributed heterogeneously, concentrated in certain hotspots while other areas remain less used (Piet and Quirijns, 2009). Understanding these spatial differences enables the assessment of fisheries impacts on species, habitats, and food webs (Hiddink et al., 2023; Rufino et al., 2025). For example, bottom-contact fishing gears negatively impact sensitive benthic components (Pitcher et al., 2017), making

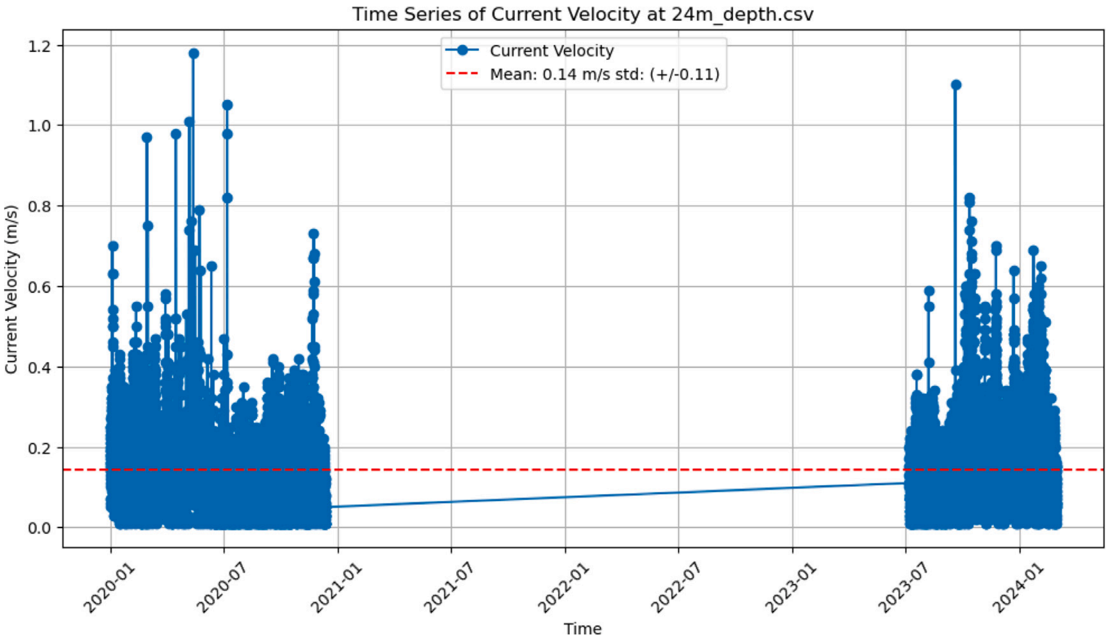

Fig. A.6. Horizontal current velocity measured by the Großtonne Fehmarn Belt at 24 m water depth.

high-resolution data critical for protecting sensitive areas such as including spawning and nursery grounds or structurally complex habitats with fragile benthic communities (Rufino et al., 2025). Further, bycatch of juvenile fish, seabirds, or marine mammals tends to occur in spatial clusters, and TI data can be used to identify these hotspots and interactions to implement effective management measures. At the same time, modern ecosystem models require spatially accurate information on fishing locations and times to accurately represent food webs, habitat use, and interactions between species (Piet et al., 2007). Finally, high-resolution spatial data increases transparency and facilitates regulatory oversight and efforts to curb illegal fishing. Overall, they form the basis for fisheries management that keeps not only individual stocks but the entire ecosystem healthy in the long term. Further, climate change and environmental changes are causing fish stocks to shift geographically, and fisheries are following these movements. Only high-resolution data can capture these dynamics and enable effective management that can respond to such changes (Riley et al., 2024; Rufino et al., 2025).

Such high-resolution spatial data are already requested in the EU-MSFD and used by HELCOM/ICES to assess mobile bottom-contact gear impacts. In the context of the Marine Strategy Framework Directive (MSFD), TI maps can provide data for a high-resolution indicator of physical disturbance to the seafloor, which is directly linked to Descriptor 6 (seafloor integrity). These maps can be used to validate current pressure layers and determine whether modeled trawling footprints accurately represent small-scale fishing activities conducted by vessels not covered by VMS. In marine spatial planning, identifying zones of low-, medium-, and high-intensity trawling on a common grid enables planners to estimate the impact on fisheries, e.g., designing MPAs or offshore windpark areas (Hiddink et al., 2023). It also allows them to prioritize heavily trawled corridors for impact mitigation or gear transition and evaluate whether newly implemented closures (e.g., fishery conservation areas or marine protected areas) are effectively reducing seafloor disturbance over time.

6. Conclusion

This study demonstrates that acoustic-based TI metrics provide a high-resolution and spatially consistent method for quantifying seabed disturbance caused by bottom trawling. Combined with AIS-derived fishing activity data, the TI reveals both spatial similarities and discrepancies. Both methods consistently reveal an eastward-curving trawling pattern in the research area, where vessels avoid shipwrecks and coarse substrates. However, only the acoustic TI captures a pronounced alteration in seafloor disturbance — with furrow volumes decreasing from 5067 m^3 in 2021 to 1108 m^3 in 2022 — which AIS-tracked fishing activity does not reflect. This underscores the limitations of AIS-based monitoring to assess fishing pressure, particularly in areas with smaller fishing vessels lacking VMS coverage. To reduce dependency on manual thresholding regarding TI precision, future improvements could include AI-driven 3D feature extraction.

The Fehmarn Belt, with silty sand sediments and rapid trawl mark degradation due to high water exchange, enables year-to-year comparisons of seafloor disturbance and recovery. This dynamic environment enables year-to-year comparisons of seafloor disturbance and recovery. Despite its site-specific conditions, the findings demonstrate that MBES-derived TI shows strong potential for broader application in muddy sediment environments, offering valuable insights into benthic resilience and trawling impacts.

Overall, the TI method enhances understanding of how benthic communities respond to trawling, revealing non-linear relationships between trawling intensity, AIS-derived activity, and benthic structure, suggesting that simple linear pressure–response models may be insufficient. A key challenge remains the lack of long-term, high-resolution geochemical and biological datasets to capture ecosystem responses fully. Advanced systems such as VMS, electronic logbooks, and port inspections provide reliable information on trawling activity (for larger vessels). However, due to their low spatial resolution, it is not possible to evaluate the impact of trawling on a finer scale which is important for smaller benthic communities and structures such as mussels beds or reef structures (Rufino et al., 2025). Therefore, there are still very few methods that can verify the ecological impacts of trawling (Riley et al., 2024). Approaches capable of assessing effects on seabed habitats and benthic communities, including biomass loss and habitat degradation, remain limited and continue to require further development. The use of standardized grid cells aligned with EU specifications also supports integration with other spatial datasets, such as the HELCOM database, promoting consistency across monitoring frameworks. Integrating physical seabed impact data with biological observations is essential for improving fisheries management and environmental assessments.

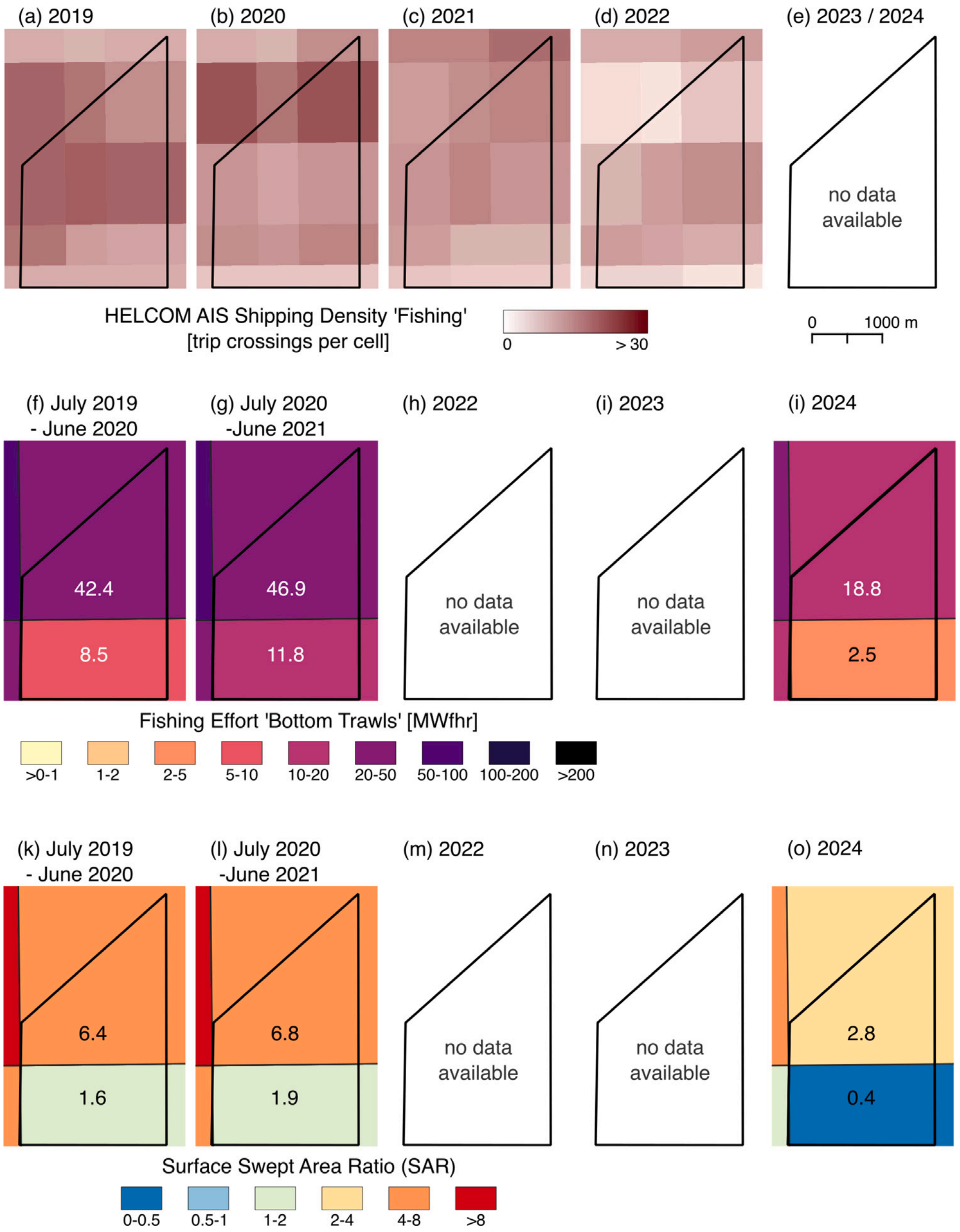

Fig. A.7. Fishery intensity datasets publicly available from HELCOM (a–g, k–l) and forwarded from Thünen-Institute (i,o). HELCOM AIS shipping density maps for ship type "Fishing" are shown in a-e. (f–j) Fishing Effort based on VMS data filtered for gear group "Bottom trawls". (k–o) Surface SAR based on VMS data.

CRediT authorship contribution statement

Mischa Schönke: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Inken Schulze:** Writing – review & editing, Validation, Investigation. **Mayya Gogina:** Writing – original draft, Investigation, Formal analysis. **Christian von Dorrien:** Writing – review & editing. **Daniel Oesterwind:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Peter Feldens:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Ethics in publishing statement

All authors agree that:

This research presents an accurate account of the work performed, all data presented are accurate and methodologies detailed enough to permit others to replicate the work.

This manuscript represents entirely original works and or if work and/or words of others have been used, that this has been appropriately cited or quoted and permission has been obtained where necessary.

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The manuscript is not currently being considered for publication in another journal.

All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

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That generative AI and AI-assisted technologies have not been utilized in the writing process or if used, disclosed in the manuscript the use of AI and AI-assisted technologies and a statement will appear in the published work.

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Declaration of competing interest

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

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Appendix

See Figs. A.6 and A.7.

Data availability

All results derived from multibeam echosounder (MBES) data used in this study are openly available through the IOW data repository. These include tile-based statistics (GeoPackage format) for assessing bottom trawling intensity in the Fehmarn Belt Marine Protected Area (MPA) (Schönke et al., 2025b), residual bathymetric maps of trawl-induced seafloor disturbance (Schönke et al., 2025a), and the hydroacoustic datasets collected during cruises EMB345 (18 July 2024), EMB320 (29 June 2023), EMB267 (10 June 2021), and EMB238 (28 May 2020) (Schönke et al., 2025f,e,d,c). The EMB288 dataset (3 March 2022) cannot be made publicly available because it was acquired during a NATO exercise but can be provided upon reasonable request to the corresponding author. AIS data used in this study were obtained from the Danish Maritime Authority (Danish Maritime Authority, 2025). The Python-based toolkit for MBES data analysis, as well as the Python scripts used to process AIS data from the Danish Maritime Authority, are publicly available in the associated code repositories (Schönke, 2025; Feldens, 2025).Macrozoobenthos data are available from the corresponding author upon reasonable request.

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