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Spatiotemporal variations in trawling intensity in the German Baltic Sea Basins based on bathymetric data

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Abstract

Bottom trawling is the largest source of anthropogenic seafloor disturbance globally, yet spatiotemporal variations are poorly constrained in most regions due to non-reporting or low-resolution fishing effort data. To overcome this gap in knowledge, we use a U-Net convolutional neural network to segment trawl marks across approximately 1,069 km² of seafloor in the German sector of the Western Baltic Sea. The model was trained and applied to open-source bathymetric data collected between 2016 and 2025 with a resolution of 1 m. Trawling intensities vary substantially in space and over time, as evidenced by time-lapse bathymetric data for the Fehmarn Belt area. Here, repeated surveys of a Marine Protected Area (MPA) in 2024 and 2025 confirm seafloor regeneration timescales of approximately one year. Within the MPA, trawl mark densities and AIS-derived fishing effort both increased from 2024 to 2025, indicating continued trawling activity despite a bottom trawling ban that entered into force in 2025. Circular untrawled zones in Mecklenburg Bay, often with diameters of more than 500 m, coincide with seafloor pockmarks indicating localized fluid seepage. We attribute these untrawled zones to fishermen avoiding the pockmark depressions which pose a risk to bottom-contact gear. Trawl marks are morphologically healed in areas with intense commercial ship traffic. This study demonstrates the potential of open-source bathymetric data to monitor anthropogenic seafloor disturbances.

Highlights

- Segmentation of trawl marks from morphological data of 1 m resolution for 1069 km² in the German Baltic Sea
- Trawling density maps allow to determine pristine Holocene Seafloor less disturbed by human impact
- Commercial shipping can accelerate morphological seafloor recovery from trawling

Keywords

Baltic Sea · Bottom Trawling · Multibeam Echo Sounder · Trawl Marks · Deep Learning

Introduction

Bottom trawling represents the largest anthropogenic source of physical disturbance to the seafloor. It affects ~15 million km² of global seafloor annually (Bradshaw et al., 2012). At a 1 km² resolution, 70% of the European shelf regions experience trawling impacts (Amoroso et al., 2018), with numerous effects across seafloor morphology, sediment dynamics, geochemical fluxes and benthic ecosystems. For shelf regions, Pusceddu et al. (2014) suggested that trawling leads to a decrease in organic matter content (up to 52%), slower organic carbon turnover, and reduced meiofauna abundance, biodiversity, and nematode species richness. Direct morphological impacts include formation of trawl mark furrows and mounds (Depestele et al., 2016). Trawling-induced resuspension can generate sediment transport rates up to six times greater than natural processes on continental shelves (Palanques et al., 2014; Oberle et al., 2016), locally altering sediment composition and geotechnical properties of the seabed (Mengual et al., 2016).

Beyond sediment mobilization, bottom trawling can modify the geochemical environment through changes in organic carbon content and denitrification rates. Global modelling suggests that trawling remineralises 0.16–0.4 Gt C yr⁻¹, while an estimated 0.3–0.4 Pg CO₂ yr⁻¹ is potentially transferred to the atmosphere on decadal scale (Atwood et al., 2024; Zhang et al., 2024). Trawling also reduces denitrification, increasing nitrogen retention in coastal systems and potentially amplifying eutrophication and deoxygenation (Van De Velde et al., 2018). Depending on the gear, these physical and chemical perturbations can have biological and biogeochemical effects (Morys et al., 2021; Rooze et al., 2023), including direct mortality and habitat degradation of long-lived benthic fauna. For some gears, direct mortality includes *Arctica islandica* (Powilleit et al., 2025), a key species in the Western Baltic Sea (Lampadariou et al., 2005; Clark and Rowden, 2009; Schulz et al., 2025).

The intensity of bottom trawling on continental shelves has only been quantified in a few regions, leaving substantial gaps in our understanding of its global footprint (Amoroso et al., 2018). Monitoring of fishing effort commonly relies on Automatic Identification System (AIS) data. However, not all fishing vessels are required to carry AIS transponders, and AIS spatial resolution is insufficient to resolve fine-scale trawling patterns (Schönke et al., 2026). Morphological evidence of bottom trawling preserved in seafloor bathymetry offers a complementary approach, recording trawling activity regardless of vessel reporting status and at sub-meter resolution. Such information is crucial for assessing the cumulative impact for marine management purposes (Eigaard et al., 2016). Recovery of seafloor morphology, seabed functions and benthic ecosystems is often slow, while trawl marks can remain visible and stable for several years. Recovery of benthic biota after trawling disturbance was found to require 1.9 to 6.4 years to reach 50–95% of pre-impact biomass levels, depending on gear type, fishing intensity, environmental context, and sediment characteristics (Hiddink et al., 2017). Physical remnants of trawl marks in the Baltic Sea have been reported to be stable for one to more than five years (Werner et al., 1990) and exceptionally more than a decade for Mecklenburg Bay (Bunke et al., 2019). The persistence of trawling-induced morphology is particularly relevant in the Baltic Sea, where fishing pressure has recently decreased, particularly following a breakdown of cod populations (Möllmann et al., 2021). The reduced disturbance level provides an opportunity to establish baseline maps of trawling impacts and monitor seafloor regeneration dynamics. Bathymetric data

routinely collected and publicly released by national hydrographic authorities provide an underexplored resource to fill this monitoring gap, particularly when combined with automated deep learning-based trawl mark detection.

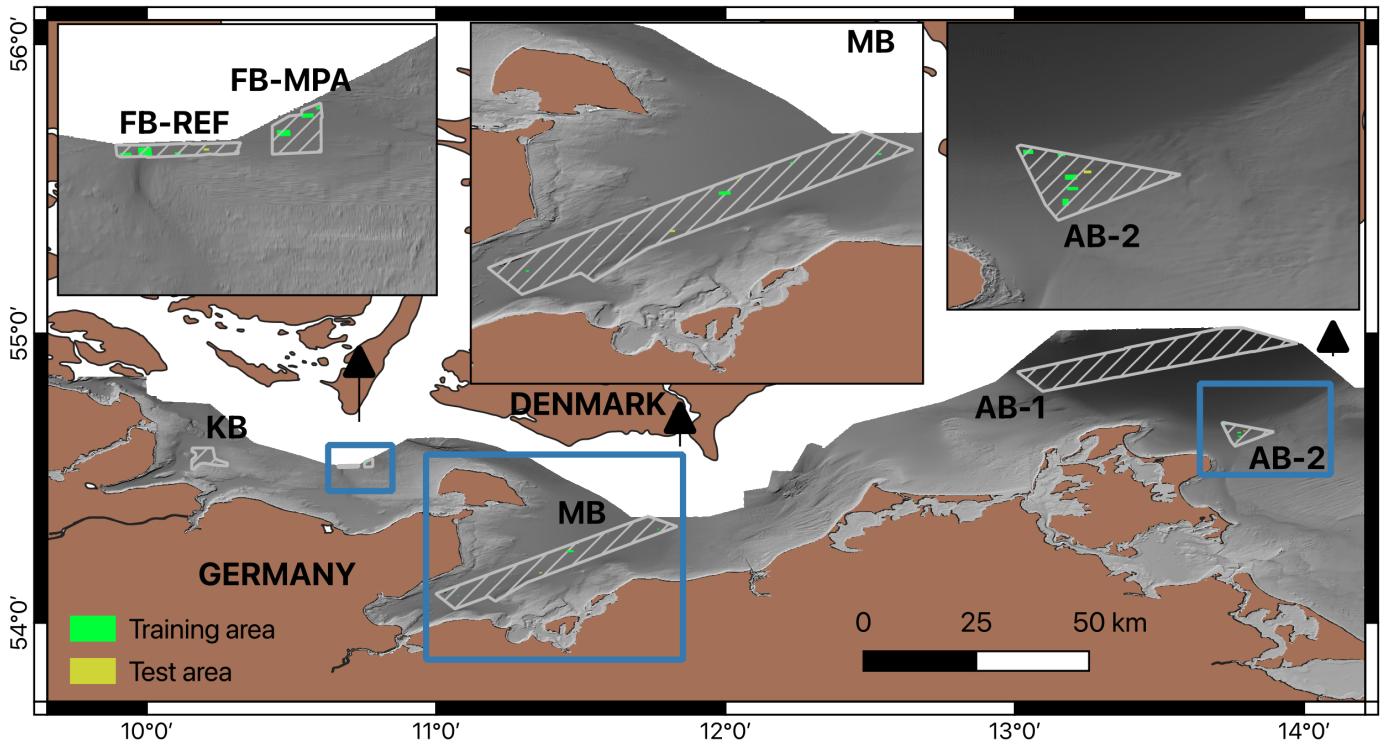


Figure 1. Overview of the research area in the German Baltic Sea, location of training and test areas in the Fehmarn Belt (FB), Kiel Bay (KB), Arkona Basin (AB) and in the Mecklenburg Bay (MB). Grey boxes outline the areas for which bathymetric data is available.

The shape of trawl marks ranges from continuous linear scars to discontinuous rows of pit-like depressions, which are often accompanied by lateral mounds of excavated material (Friedlander et al., 1999; Bruns et al., 2020; Schönke et al., 2022). The different morphologies are caused by differences in fishing gear, sediment type and hydrodynamic conditions during and after trawling. It has therefore proven challenging to systematically map trawl marks using geomorphologic toolboxes such as Geomorphon (Jasiewicz and Stepinski, 2013) or the benthic terrain modeler (Walbridge et al., 2018). Acoustic remote sensing technologies, particularly multibeam echo sounders (MBES) and side-scan sonar, have proven effective for detecting trawl marks across extensive seafloor areas (Krost et al., 1990; Gournia et al., 2019; Bruns et al., 2020; Schönke et al., 2022). However, manual interpretation of acoustic data and especially the segmentation of thousands of individual trawl marks within a single basin is not feasible. Convolutional neural networks (CNNs), particularly U-Net architectures designed for semantic segmentation, can automatically detect morphological features across a wide range of scales and morphologies. Deep learning approaches are increasingly applied in the marine domain for automated interpretation of acoustic data. Examples include the classification of large-scale seafloor morphology and reef structures, detection of small-scale seabed features such as geological surveys (Nguyen et al., 2024), pockmarks and boulders (Feldens et al., 2019; Lundine et al., 2023), and mapping of anthropogenic

infrastructure (Wei et al., 2025). Using deep learning approaches, repeated acoustic surveys can be efficiently analyzed to track changes in trawl mark density, morphology, and rates of seabed recovery.

In this study, we use a U-Net convolutional neural network to automatically segment trawl marks in multibeam echo sounder (MBES) datasets from Mecklenburg Bay, Kiel Bay, Arkona Basin and Fehmarn Belt in the Western Baltic Sea (Fig. 1) within cohesive, fine grained sediments that can preserve the morphological imprint of trawl marks over long time periods. The bathymetric grids were routinely collected and publicly released by national hydrographic authorities, making the automated approach inherently scalable to other regions where such data are available.

Regional Setting

Seafloor composition

Mecklenburg Bay (MB) MB (Fig. 1) is a shallow basin in the southwestern Baltic Sea with maximum water depths of 20 to 25 m that was shaped by late-Quaternary glacial and post-glacial processes (Kostecki and Radziejewska, 2021). In the central bay, fine-grained (mud and silt) sediments, deposited since the Littorina transgression, are situated above varved clays and sandy sediments that relate to the Baltic Ice Lake, Yoldia Sea and Ancylus Lake phases (Lemke, 1998). Glacial till partially crops out at the seafloor, even at depths of 20 m b.s.l., hosting sites of archaeological relevance (Geersen et al., 2024). Few published reports of fluid flow in Mecklenburg Bay exist. Díaz-Mendoza et al. (2023) describe circular features in the inner Mecklenburg Bay (Lübeck Bay) and west of Fehmarn Island related to release of free gas. Sedimentation rate in the Mecklenburg Bay is around 1 mm/year (Niedermeyer and Lange, 1989).

Arkona Basin (AB-1 and AB-2) The Arkona Basin (Fig. 1) is separated from Mecklenburg Bay by the Darss Sill. It is the deepest basin in German waters, with water depths reaching 45 to 50 m (Moros et al., 2002). The Arkona Basin is seasonally stratified and under hypoxic conditions. The basin floor is characterized by a thick sequence of organic-rich Holocene muds overlying limnic clays (Lemke, 1998). These fine-grained sediments combined with low sedimentation rates (Mitchell et al., 2021) of 21.7 cm/1000 years (Trimonis et al., 2008) cause high preservation potential for anthropogenic seabed features. High concentrations of organic matter also drive intense microbial methanogenesis, resulting in free gas within the sediment and pockmarks, particularly in the central basin (Mogollón et al., 2012; Thießen et al., 2006). AB-1 is located in the central Arkona Basin, while AB-2 is located at its southern boundary.

Fehmarn Belt (FB-REF and FB-MPA) The Fehmarn Belt (Fig. 1) connects the Kiel Bay and the Mecklenburg Bay, facilitating the major inflow of saline North Sea water into the main Baltic Sea (Feldens et al., 2015). This high-energy environment is dominated by strong bottom currents that actively reshape the seafloor, resulting in extensive areas of sediment transport and erosion. The seabed is largely composed of coarse sand, gravel, and lag deposits. Bedforms such as sand ribbons and subaqueous dune fields occur (Feldens and Schwarzer, 2012; Feldens et al., 2015). The study sites in Fehmarn Belt are located at its eastern entrance, where muddy deposits still prevail on the seafloor. Following Schönke et al. (2022), they are separated into the areas FB-MPA, a designated Marine Protected Area (MPA), and FB-REF, an area outside of the MPA.

Kiel Bay (KB) Kiel Bay (Fig. 1) is morphologically complex and defined by a system of incised glacial meltwater channels cutting into glacial till. While the shallow

areas are covered by coarse-grained lag deposits resulting from the erosion of underlying glacial till, the deeper basins and channels are depositional centers for fine-grained Holocene muds. Localized fluid flow features such as pockmarks are documented in the vicinity of Kiel Bay (Whiticar, 2002).

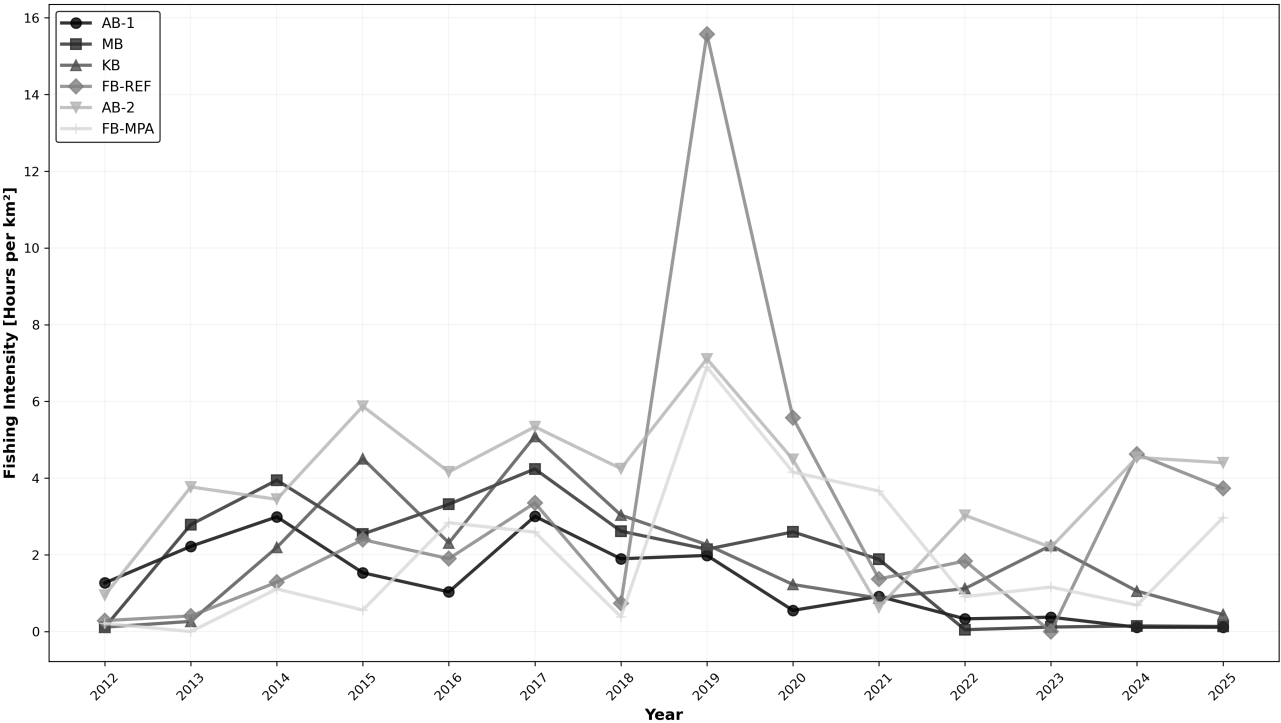


Figure 2. Fishing intensity normalized by the size of the investigated areas show highest relative intensity in the FB-REF area, notable especially in 2019. Data based on GlobalFishingWatch (2025).

Trawling intensities in the different regions

Data compiled by Global Fishing Watch (GlobalFishingWatch, 2025) show the apparent fishing intensity at all study sites (Fig. 2). The data are based on AIS information, and the methodology is described in Kroodsma et al. (2018). Although these are estimated values (computed using machine learning models to analyse publicly available data on ship movement, speed, and track patterns) and taking into account the fact that not all fishing vessels are required to use AIS systems (Schönke et al., 2026), the data show a long-term reduction in fishing intensity in most basins while maintaining a high degree of variability in fishing effort. A spike in fishing intensity occurred in the FB-REF area in 2019. The rate of decline increased especially for AB-1 and MB after 2019–2020. In contrast to the long-term trend the FB-REF and AB-2 areas have seen an increase in apparent fishing effort since 2023 and the FB-MPA area since 2024.

Methods

Generation of training data and model training

Bathymetric data from selected areas provided by the Federal Maritime and Hydrographic Agency were used to train an U-Net model (training areas are indicated

in Fig. 1). Training data were only acquired in the fine-grained basins of the Baltic Sea, as earlier studies have shown that trawl marks quickly deteriorate in sand environments (Bruns et al., 2023). To generate a model that could be used in different Baltic Sea basin settings in the future, training data in the Kiel Bay, the Mecklenburg Bay, the Fehmarn Belt and the Arkona Basin were utilized. All data were interpolated during export from QGIS to a resolution of 0.25 m from the original resolution of 1 m per pixel to harmonize the training data with higher-resolution MBES datasets acquired by the IOW at 0.25 m resolution, and to represent the typical imaged trawl mark width of approximately 1.5 m with sufficient pixel coverage (six pixels in the label masks). Label masks were digitized as line features using Global Mapper with a line width of six pixels (corresponding to 1.5 m), as this was found to be the common imaged width of trawl marks at a grid resolution of 0.25 m. Although it would have been more accurate to delineate the trawl marks as polygons, this was not attempted due to the significant time required to digitize elongated and thin features at a high resolution in a GIS system. Our approach represents a simplification of actual trawl mark geometry on the seafloor.

Slope rather than depth was used as model input. Slope maps normalize regional depth gradients and maintain consistent image contrast across tiles regardless of local bathymetry. This follows earlier work on boulder detection in MBES data, where slope outperformed raw bathymetry as model input (Hinz et al., 2024). The slope grids of the training areas were exported as GeoTIF. The single-channel images were expanded to three channels by duplicating the values of the first channel to match the three-channel input expected by the encoder. The GeoTifs were cut into 256x256 pixel tiles with an overlap of 30% to reduce edge effects. Tile size was derived from initial model exploration with 128, 256 and 512 pixel sizes. This resulted in 2331 images. Each image was then randomly augmented 5 times, including rotation up to 45 degrees, horizontal and vertical flips, random brightness and contrast changes, elastic transformation as well as random cropping and padding. 10% of images were used for validation. We trained the U-Net model using the *Segmentation Models PyTorch* library with a ResNet-34 encoder pre-trained on ImageNet. The model accepts 3-channel RGB input and was trained for binary segmentation (trawl marks and background). Training was conducted with automatic mixed precision to reduce memory consumption. Training images were normalized to ImageNet average values prior to training. Optimization was performed using the *AdamW* optimizer with a base learning rate of 0.0001 and a weight decay of 0.001. The learning rate was then dynamically adjusted based on the validation Dice score. The loss function combined binary cross-entropy loss with Dice loss, the latter penalizing poor spatial overlap between predicted and true trawl mark locations. The Dice component of the loss function also addresses class imbalance by optimising spatial overlap rather than pixel-level accuracy. No additional class-weighting strategy was applied. The optimal classification threshold of 0.4 that maximized the F1 score was determined on the validation data set. Training was performed on a single NVIDIA GPU (RTX 3080, 10 GB VRAM) and ran overnight.

Model application

Bathymetric grids covering a total of 1,069 km², mostly provided by the BSH were analysed across multiple investigation areas in the southwestern Baltic Sea. The data were recorded between 2016 and 2025 (Table 1). BSH data is available at a 1 m resolution. The dataset comprised 419 km² of bathymetric data in MB, 554 km² in area AB-1, 51 km² in area AB-2, 36 km² in area KB, and 8 km² in area FB (data in FB were recorded by IOW during cruises EMB345 (Bruhns et al., 2025) and EMB369 (Piontek et al., 2025)). All datasets were exported at a spatial resolution of 0.25 m, with upsampling applied where necessary to achieve uniform resolution across all survey

areas. The unified dataset was subsequently divided into non-overlapping 256 x 256 pixel tiles. Binary segmentation masks were generated to classify pixels as either trawl marks or background. Segmentation results in raster format were converted to vector format using the Geospatial Data Abstraction Library (GDAL) using *gdal polygonize*. Only white pixels (corresponding to the trawl label identified by the model) were kept and isolated using *gdal ogr2ogr*. All polygons in an area of interest (e.g., Fehmarn Belt, Kiel Bay) were merged using *gdal ogrmerge*.

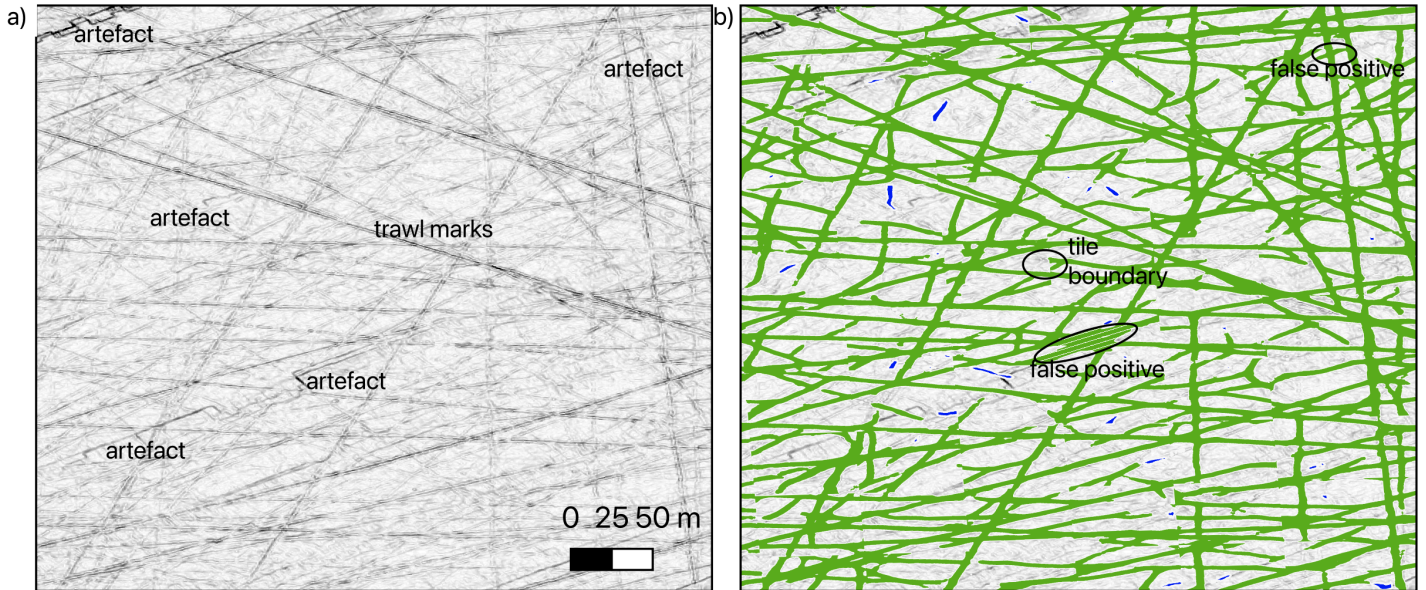


Figure 3. Example of trawl marks and the effect of filtering. Left: Slope values are displayed from 0 to 5 degrees. Right: Detected trawl marks are displayed in green. Blue polygons extend for less than 100 m² and were discarded to reduce noise.

To reduce computational complexity and minimize noise artifacts inherent to bathymetric datasets of varying quality, trawl mark polygons smaller than 100 m² were excluded from the analysis prior to further processing using QGIS. This filtering approach effectively eliminated noise while preserving the primary spatial patterns of trawling activity (see Fig. 3). The reduction in polygon count achieved through this filtering step significantly decreased processing time for subsequent spatial intersection operations. Trawl mark density was quantified within a regular 25 m x 25 m grid fitted to the extent of detected trawl mark polygons. Density values are normalized on a scale of 0 to 1, where 0 indicates no trawl marks present and 1 represents complete cell coverage by trawl marks.

Model validation

The model was applied to five test areas that were not included in the training data; these areas were each annotated manually. We followed the same processing pipeline for model application as for the training data and evaluated the predictions against the manual ground truth at pixel level. Model performance was assessed with Precision, Recall and F1 scores. However, as it is not feasible for a human interpreter to produce a pixel-perfect annotation of the thin, elongated trawl marks, we also compute a spatially tolerant variant of each metric following Mnih and Hinton (2010). Under this definition, a predicted pixel is counted as a true positive if it falls within d pixels of any ground-truth pixel, and vice versa. We set $d = 4$ pixels, corresponding to a spatial tolerance of 1 m at the survey resolution of 0.25 m/pixel. This also equals the native

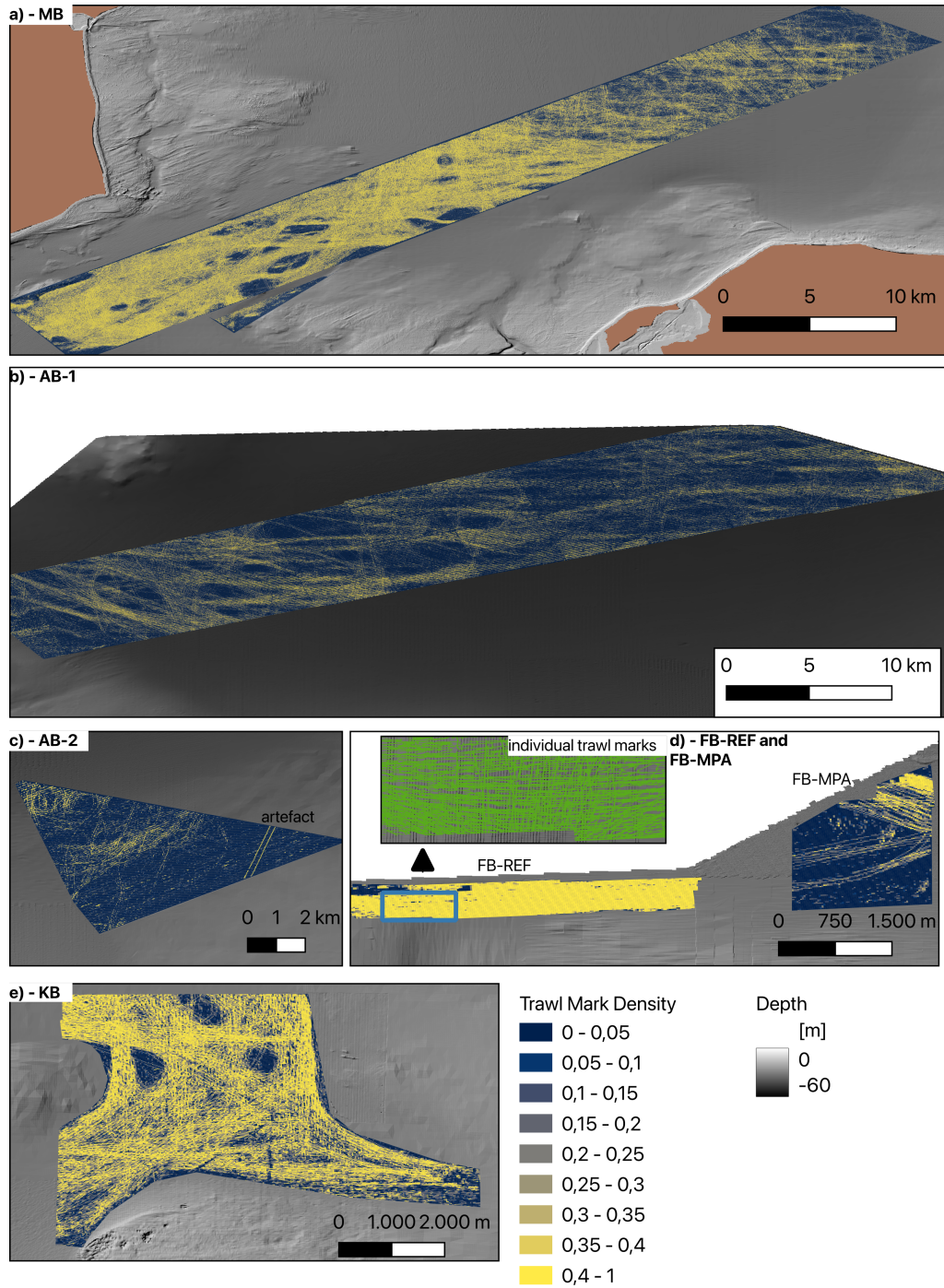


Figure 4. Trawl mark density maps detail trawling impact on the seafloor based on regional slope maps within Mecklenburg Bay (a), northern Arkona Basin (b), southern Arkona Basin (c), Fehmarn Belt (d) and Kiel Bay (e).

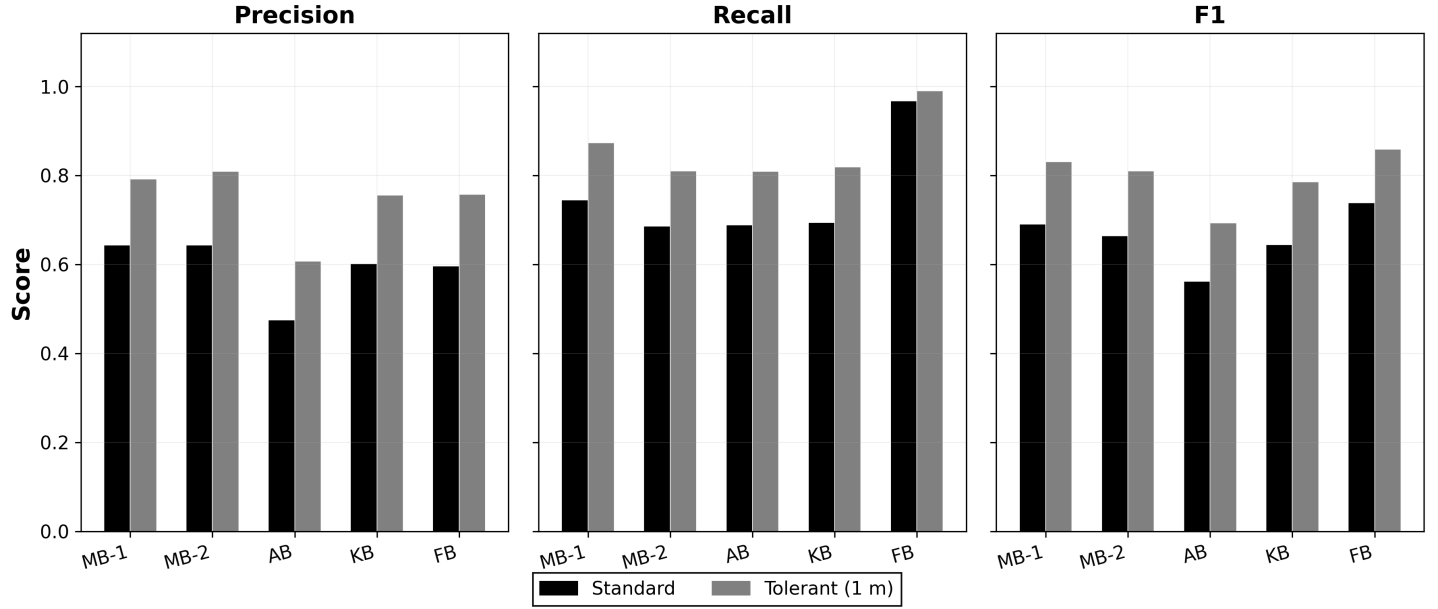


Figure 5. Precision, recall and F1 score of the five test areas used for model validation, located in Mecklenburg Bay (MB-1, MB-2), Arkona Basin (AB), Kiel Bay (KB), and Fehmarn Belt (FB). Tolerant values allow for a 1 m difference between prediction and ground-truth.

pixel size of the source bathymetric data (with 1 m resolution).

The aggregated F1 score

$$F1 = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

is 0.66 (precision 0.61, recall 0.73), with the F1 score of individual sites ranging from 0.56 to 0.74. Precision is defined as $TP/(TP + FP)$ and Recall as $TP/(TP + FN)$, with TP being true positives, FP false positives and FN false negative detections. The results for the individual areas (Fig. 4) are displayed in Fig. 5. All trawl mark ground truth labels in this study were interpreted by a single interpreter to reduce inter-interpreter noise. The aggregated tolerant metrics are $F1 = 0.80$, precision = 0.77 and recall = 0.84, with the tolerant F1 score of individual sites ranging from 0.69 to 0.86. The results for the individual test areas are shown in Fig. 5.

Results

Mecklenburg Bay

The model identified trawl marks across the central bay based on bathymetric data (Fig. 4a) recorded in 2016 and 2017, that, however, do not overlap. The density of trawl marks decreases from a maximum of around 0.92 (with a 95th percentile of 0.55) in the southwestern to zero in the northeastern part of the bay. The mean density is 0.26 (standard deviation 0.18) (see Fig. 6), with less than 20% of the 25 x 25 m grid cells in Mecklenburg Bay showing no morphologic evidence for trawling. This includes cells containing glacial outcrops within the investigation site. Superimposed on this regional trend, the distribution of trawl marks is locally heterogeneous and characterized by zones ranging from circular to elongated with a reduced presence or absence of trawl marks. With no navigation buoys visible on the nautical charts, these zones fall into two

categories, both of which are shown in Fig. 7: (1) areas with rough morphology (2) areas showing either no apparent change to the seafloor morphology or circular features interpreted as pockmarks (Díaz-Mendoza et al., 2023). A seismic line crossing the untrawled spot (Fig. 7C) confirms the presence of free gas in the shallow subsurface. In the northern part of the seismic line, the reflection character of the shallow sediments changes abruptly at the transition from the altered to the un-altered seafloor, while in the southern part of the seismic line the transition is more gradual. Finally, reduced trawl mark density is also observed along a SW-NE trending linear ridge located in the southwestern part of the dataset. The ridge extends for around 9 km, is approx. 50–200 m wide, and elevates 20–30 cm above the adjacent seafloor. It narrows from southwest to northeast and, despite its morphologic appearance, does not coincide with a change in seafloor sediment composition.

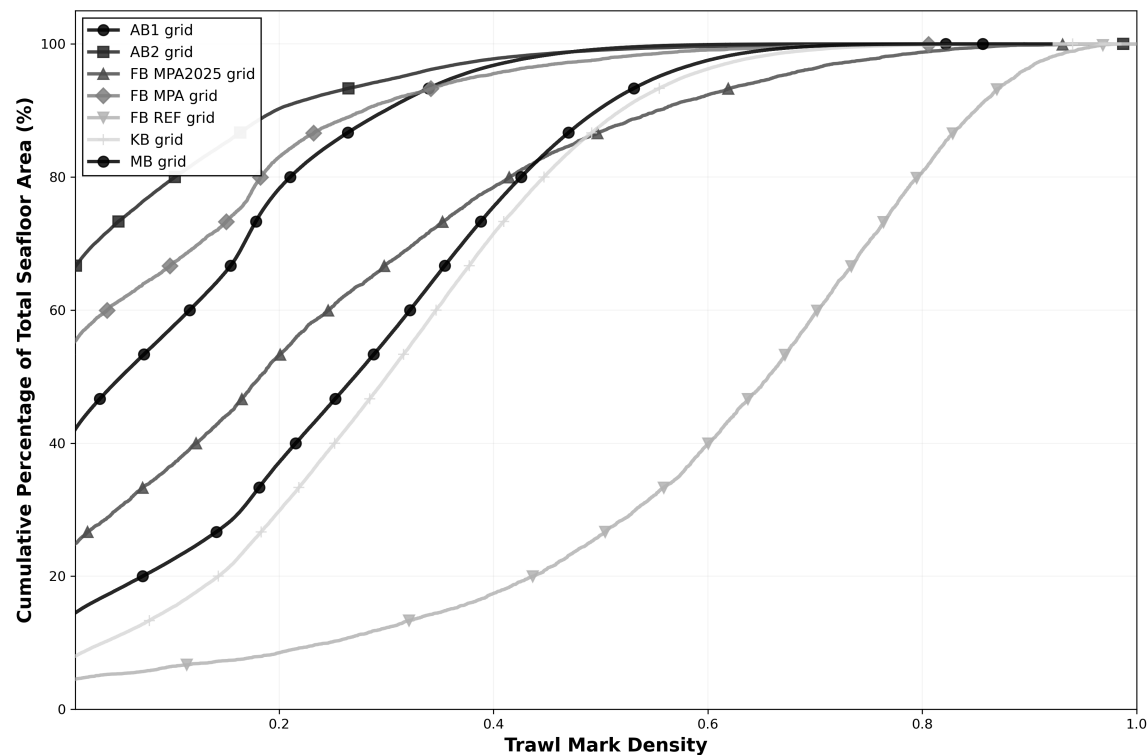


Figure 6. Cumulative plots showing the percentage of seafloor affected by trawl marks in the different areas.

Site	Area km ²	Year	TM Density	Std Dev
AB-1	554	2022-2023	0.11	0.13
AB-2	51	2016	0.06	0.11
MB	419	2016-2017	0.26	0.18
FB-REF	3.7	2024	0.60	0.23
FB-MPA 2024	4.0	2024	0.09	0.14
FB-MPA 2025	4.0	2025	0.22	0.21
KB	36	2020	0.30	0.17

Table 1. Survey years for the individual datasets. TM Density refers to the Mean Trawl Mark Density. TM Density values reflect the accumulated trawling imprint integrated over the local preservation duration of trawl marks; absolute values are therefore directly comparable only within a site, or across sites with similar preservation durations.

Arkona Basin

In the northern part of the Arkona Basin (see Fig. 4 inset AB-1; data recorded in 2022 and 2023), the overall density of trawl marks is comparable to the north-eastern part of Mecklenburg Bay, which has a similar environmental setting, (see Fig. 4A). The trawl marks are, however, more heterogeneously distributed in space, with lanes of high trawl mark density trending in different directions alternating with areas of low density. Circular to elliptical areas of low trawling induced morphology are especially evident in the south-western part of the basin, but are less sharp than those in Mecklenburg Bay and Kiel Bay. Overall, trawling-related morphologic features are absent in almost 40% of the 25x25 m grid cells, resulting in a mean trawl mark density of 0.11 (standard deviation 0.13). Maximum trawl mark density values reach 0.89, with the 95th percentile at a trawling density of 0.36 (Fig. 6).

Grid AB-2 in the southern part of the Arkona Basin (Fig. 4C), which was surveyed in 2016, shows the lowest trawling densities of all sites, with almost two-thirds of the grid cells showing no morphologic impact of trawling. This results in a mean trawl mark density of 0.06 (standard deviation 0.11), and the 95th percentile at 0.31. Trawling activity is concentrated in the north-western tip and the central part of the study area. The SW-NE lines in the eastern part of AB-2 are model artefacts.

Fehmarn Belt

Bathymetric data in the Fehmarn Belt were recorded in 2024 (Fig. 4D). The highest trawl mark density in the Fehmarn Belt is observed in the southern part (area FB-REF), where values exceeding 0.8 are widespread. The 95th percentile is 0.83, the mean trawling density is 0.60 (standard deviation 0.23). In contrast, the north-eastern Fehmarn Belt area, which is located within a marine protected area (FB-MPA), shows a higher percentage of seafloor that is unaffected by trawling. In 2024, one third of the seafloor showed no traces of trawl mark morphology. However, patches of high trawl mark density in the northern part of the FB-MPA area and individual strongly trawled linear features in its southern part, result in a mean trawl mark density of 0.09 (standard deviation 0.14), with the 95th percentile located at 0.38. For the FB-MPA area, a repeated survey recorded in 2025 shows an increase in trawl mark density (Fig. 8). Correspondingly, the mean trawl mark density rises to 0.22 (standard deviation 0.21), and the 95th percentile rises to 0.66 (Tab. 1).

Kiel Bay

The trawl mark density in the Kiel Bay (data recorded in 2020; Fig. 4E) is slightly higher compared to the Mecklenburg Bay in 2016/2017. The mean trawl mark density is 0.3 (standard deviation 0.17), and less than 10% of the grid cells show no morphological trawling impact. The 95th percentile is at a trawling density of 0.58. Similar to Mecklenburg Bay, circular to elliptical spots with no trawling induced morphology exist.

Discussion

Model performance

Deep Learning techniques have recently been applied to bathymetric data (Garone et al., 2023; Nian et al., 2023), which has a high discriminative power for habitat mapping (Che Hasan et al., 2014). Also in this study, despite variable data quality across multi-year acquisitions and a resolution of 1 m, the U-Net model demonstrated robust but not perfect trawl mark detection across the homogeneous sediments of the

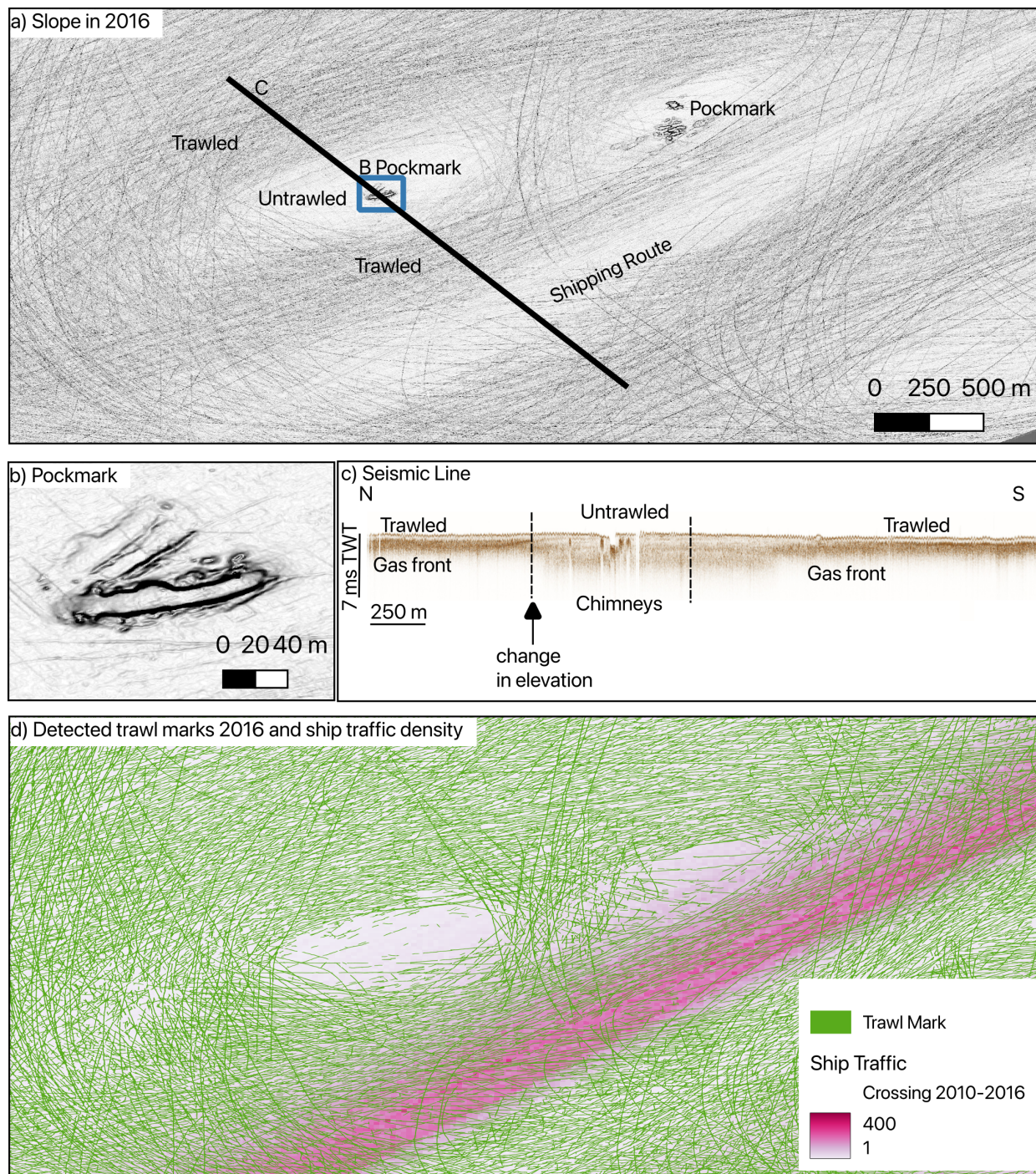


Figure 7. (A) Slope map from 2016 showing the locations of two pockmarks in Mecklenburg Bay, as well as a linear feature with a reduced occurrence of trawl marks corresponding to shipping routes. (B) A detailed view of the western pockmark showing its central depression in the slope data. (C) A sediment echosounder profile crossing the pockmark showing free gas fronts to the north and south and chimney features below the pockmark. (D) The individual trawl marks detected in the bathymetric data are plotted on top of AIS data points for vessels with a draught greater than 4.0 meters and a speed greater than 2.0 knots, as reported in 25 x 25 meter grid cells between 2010 and 2016. Source of AIS data is the Danish Maritime Authority, last accessed 17. December 2024. Data processing following Geersen et al. (2026).

south-west German Baltic fine-grained basins (compared to previous studies using 0.25 m for trawl mark detection, Schönke et al. (2022)).

Visually, the model rarely produced false positives when artefacts were present in the training data (Fig. 3). The FB-MPA 2025 datasets recorded after model training was finalized had improper sound velocity profile corrections. This generated artefacts visible as long track noise due to overlapping profile lines that the model occasionally misinterpreted as north-south oriented trawl marks. These are best visible and marked in the south-eastern part of Fig. 8. Ship induced seafloor features (labelled as artefact in Fig. 4c) and grid boundaries (Fig. 4b) in the Arkona Basin produced false positive detections due to changing image contrast to the background. In both cases, the model had not been sufficiently trained to ignore these artefacts. False detection of this type could be reduced by expanding the training dataset to better represent these artefact types. Similarly, faint trawl marks are partly not continuing between 256x256 image tiles (Fig. 3).

The five selected test areas showed modest performance with F1 scores ranging between 0.56 and 0.74 (Fig. 5). However, we argue that the detection of linear features such as trawl marks (essentially 1D features on a 2D map) suffers from lateral offsets between prediction and ground-truth. This is due to the difficulty for the human interpreter to annotate trawl marks with pixel accuracy, and the constant width of the line features used in the GIS system to simplify trawl mark geometries. We therefore also report performance metrics allowing for a 4 pixel (corresponding to 1 m) deviation between prediction and ground-truth, following the procedure introduced for tracking roads in high resolution aerial images by deep learning (Mnih and Hinton, 2010). With this, the aggregated F1 score increased to 0.80 (varying between 0.69 and 0.86 between the areas), which we argue is a more realistic assessment of current model performance. The lowest performance was observed in the Arkona Basin. Here, the increased water depth (and thus increased multibeam echo sounder footprint size) and generally lower data quality made the distinction of trawl marks more difficult also for the human interpreter. In addition, no training sites are present in the larger AB-1 area, with training focussing on the AB-2 area towards south-east. The lower recall values compared to the other regions suggest that trawling density in the Arkona Basin is underestimated compared to other regions. In contrast, merging of the prediction masks (and thus recall of 0.97 and a precision of 0.60) for the very closely spaced trawl marks in the FB-REF area suggests that the impact of trawling is overestimated in this region compared to others.

Our method requires minimal data pre-processing and operates directly on 1 m resolution BSH data. The only preprocessing steps required are upscaling to a resolution of 0.25 m and calculating slope maps. In contrast, filtering out polygons smaller than 100 m² as a post-processing step reduces noise while preserving the spatial patterns of trawling activity. This boundary value increases the subjectivity of the approach, but it can likely be avoided with improved training datasets and model architecture. The combined approach enables straightforward monitoring of trawling intensity. However, quality control by human experts remains essential for result interpretation and the results do not allow for a direct quantitative characterisation of trawl mark parameters such as furrow volume, as recently described (Durán et al., 2023; Schönke et al., 2026). Trawl mark density integrates fishing activity over the local preservation duration of trawl marks, which varies between sites e.g., depending on sediment composition, hydrodynamic energy, and sedimentation rate. Cross-site comparisons of absolute density values therefore reflect differences in both fishing intensity and trawl mark preservation duration.

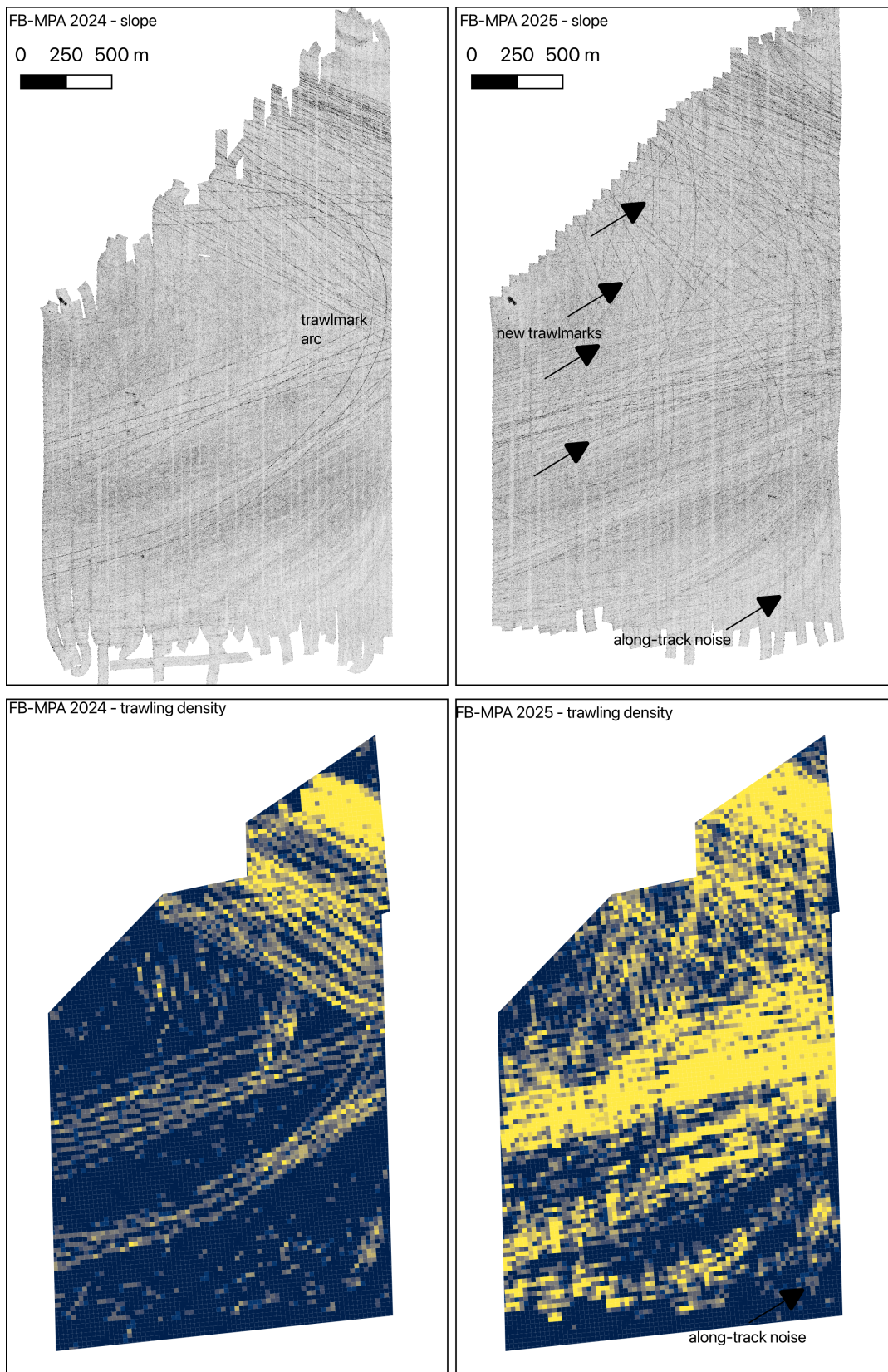


Figure 8. Difference in trawling intensity in the Fehmarn Belt MPA area between 2024 and 2025. Top: Slope of the FB-MPA area (0-5 degree). Bottom: Trawling density. Refer to Fig. 4 for legend.

Reduced trawling activity in regions of seafloor fluid seepage

Trawl mark density is high where muddy Holocene sediments build the shallow subsurface strata. In Mecklenburg Bay, circular to elliptical areas with little to no trawling induced morphology exist (Fig. 7). Several patches of reduced trawl mark density coincide with regions where outcropping glacial till creates a rough seafloor morphology that poses a risk to the trawling gear, or with the presence of navigational buoys in sea charts (indicated in Fig. 9). However, there are several patches located within the central basin, where the seafloor is made up of muddy Holocene sediments. These should not cause any damage to trawling equipment, and the area is free of navigational hazards. Here, the local absence of trawling induced morphology is particularly surprising, due to a known long preservation of trawl marks in this area (Bunke et al., 2019) and high fishing pressure at the time of data recording in 2016 and 2017. A close examination of the underlying bathymetry indicates that these patches coincide with circular to elongated depressions, which are interpreted as pockmarks indicative for active fluid flow and seafloor seepage (Díaz-Mendoza et al., 2023).

From sediment echosounder data (Fig. 7) there is evidence for the presence of free gas in the shallow subsurface beneath the pockmark and possibly active methane release at the seafloor. The related morphology, i.e. the depression (pockmark) created by the escaping fluid, may present an obstacle to bottom-contact fishing gear which is avoided by fishermen. An alternative explanation, that gas release resuspends sediments that cover existing trawl marks is not supported by the data, as individual trawl marks circle the depressions, suggesting active avoidance of these areas by fishermen. Circular features with reduced trawl mark density are observed in Kiel Bay and in the northern part of the Arkona Basin (Fig. 4B and E). However, a relation to fluid features has not yet been established here and would require further collection of sediment echosounder data.

In areas of particularly intense trawling, time-marker profiles such as those of mercury and caesium-137 are completely erased, making it impossible to precisely date the sediment and obscuring the temporal record of contaminant deposition (Bunke et al., 2019). Furthermore, trawling induced resuspension depletes reactive organic carbon and alters early diagenesis on decadal timescales (Paradis et al., 2021; Rooze et al., 2023), with consequences for long-term carbon storage in marine sediments (Zhang et al., 2024). We therefore hypothesize that untrawled pockmarks within otherwise heavily trawled basins may preserve rare, quasi-natural Holocene sediment sequences and biogeochemical archives, and may therefore provide a window into a Holocene-like seafloor as currently discussed within the Planetary Boundaries framework (Richardson et al., 2023).

Another noteworthy observation that requires further investigation is the apparent relation between intense trawling and the presence of free gas just below the surface at the northern end of the seismic line. This is accompanied by an elevation increase of around 10 cm across this boundary, as illustrated in Fig. 7. This may represent a long-term morphological response to intense trawling as already observed by Durán et al. (2023). Such morphological changes are resulting from ongoing sediment resuspension and inter-basin sediment transport and have for the Baltic Sea been modelled by Porz et al. (2023).

Trawl Mark Density in Relation to Global Fishing Watch AIS Data

The majority of the basins of the Baltic Sea have been affected by trawling (Anderson, 2010; Amoroso et al., 2018), although fishing pressure has declined in recent years due to reduced fishing effort for economic reasons and predating the establishment of

bottom fishing exclusion zones in the German Baltic Sea. In principle, the impact of trawling tracked by morphology aligns with the intensity of trawling reported by GlobalFishingWatch, based on AIS data. The spatial match between GlobalFishingWatch data and preserved trawl marks is exemplarily shown for the Mecklenburg Bay. Here, the southwest to northeast decline in trawling induced morphology mirrors the spatial pattern of fishing pressure observed in GlobalFishingWatch data, with reduced fishing pressure towards North-East (Fig. 9). Maximum trawl mark densities exceeded 0.92 in the southwestern region, which corresponds to areas of highest fishing activity (Bunke et al., 2019). Discrepancies were obvious when comparing both methods in a quantitative manner over larger scales. In the north-eastern third of the MB region, the density of trawl marks was reduced by a factor of 1.8 compared to the south-western two-thirds, whereas the fishing pressure based on AIS data for the years 2012–2017 is smaller by a factor of 2.2 for the same regions (Fig. 9). The higher number of trawl marks in the north-east, relative to fishing hours, cannot be explained by changes in seabed sediment composition or water depth. However, it is not possible to determine whether the discrepancy is related to uncertainty in model accuracy, incomplete AIS datasets, or because trawl marks are preserved for longer timescales in the north-eastern part of the bay. We note that Global Fishing Watch’s AIS data reports hotspots of bottom trawling within individual cells (see Fig. 9 for examples). However, these are not supported by corresponding trawl marks in the bathymetric data.

On a regional scale, the Arkona Basin exhibits a similar pattern compared to the Bay of Mecklenburg. Lower mean trawl mark densities correspond to lower overall fishing intensity (Fig. 4). Locally, there are, however, persistent lanes of high trawl mark density that alternate with low-impact areas. This suggests that fisheries concentrate on the same routes over time, for reasons that lie beyond the resolution or spatial coverage of our data.

In contrast to the possibly patchy AIS data, especially in more remote areas like the northeastern Bay of Mecklenburg, the seafloor systematically records all trawling activity for the preservation duration of trawl marks with high spatial resolution. In this way it acts as a non-selective memory of trawling. This concept of seafloor memory constitutes a potential different monitoring paradigm. Instead of tracking individual events, this integrates their cumulative morphological signature particularly relevant for retrospective assessment and monitoring in areas with limited real-time trawling coverage. In addition to the regional trends discussed above, the presented data further show that the impact of trawling inside individual areas can differ substantially over short distances that are not adequately captured by AIS data. These local changes might either be controlled by a local absence of trawling or a rapid healing (at least from a morphological perspective) of a previously trawled seafloor. Further time series are required to determine seafloor healing timescales after bottom trawling in different regions. The preservation duration of trawl marks depends on sediment type, hydrodynamic conditions, and sedimentation rate.

The Seafloor Healing effect of commercial shipping

In Mecklenburg Bay, a linear trending stripe of reduced trawl mark density was observed (Fig. 7A). The feature showed no correlation with seabed sediment types, water depths or seafloor roughness. This suggests that its genesis is controlled by sedimentary processes that post-date the trawling activity, rather than by a systematic avoidance of trawling along this feature for geologic reasons. When plotted together with AIS density maps of commercial shipping (for vessels with more than 4.0 m draught and traveling faster than 2 knots), it becomes evident that the stripes coincide with the main shipping route (Fig. 7d). In contrast to the areas where trawling is actively avoided, the reduced

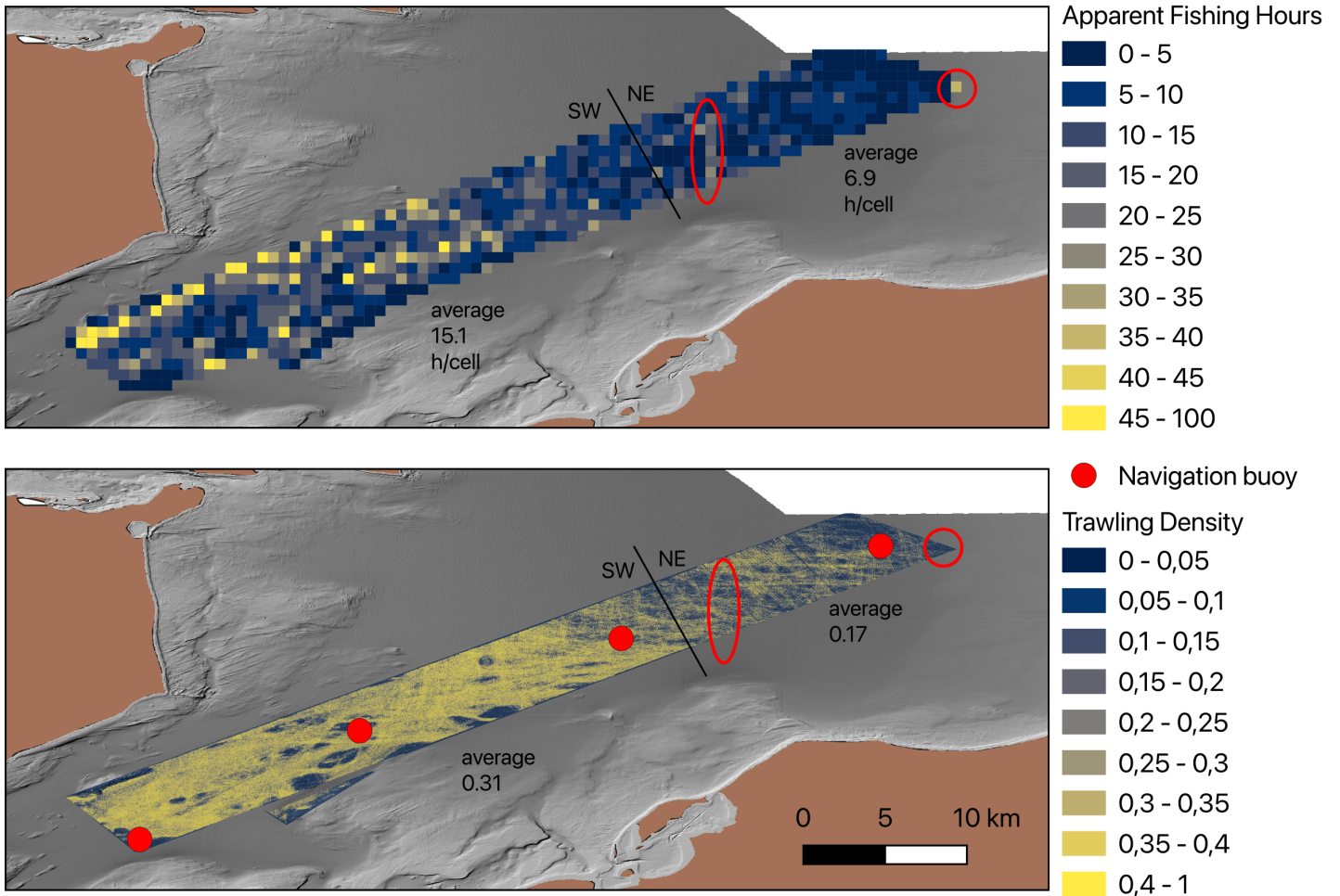


Figure 9. Top: GlobalFishingWatch data from 2012-2017 in Mecklenburg Bay, showing cumulative fishing hours per grid cell during this time interval. Bottom: Trawling Density in data from 2016 to 2017. The average fishing hours and average trawling density per grid cell are given for the south-western and north-eastern parts of Mecklenburg Bay, respectively. Red circles indicate clear discrepancies between AIS-derived fishing hours and morphology-derived trawling density.

density and fading of trawl marks in this area likely relates to the resuspension of seabed sediments caused by the wake of commercial ships, as recently discussed by Krämer et al. (2025) and Geersen et al. (2026). As sedimentation rates are generally low in the Mecklenburg Bay (Niedermeyer and Lange, 1989), commercial shipping locally acts as an agent from above that redistributes sediments, leading to a more rapid recovery of a trawled seafloor from a morphological perspective. It has to be noted, however, that ship-wake induced turbulence also causes suspension and redistribution of shallow sediments, thereby enhancing effects such as remineralization and denitrification (Geersen et al., 2026). These processes, however, only work in regions like the Western Baltic Sea, where the water depth is shallow enough for ship wake induced turbulence to reach the seafloor. In the Mecklenburg Bay, the effect of ship wake induced turbulence on trawl marks is observed down to 23.5 m water depth.

Time Series in the Fehmarn Belt MPA

The repeated survey of the Fehmarn Belt Marine Protected Area (MPA) in 2024 and 2025 demonstrates that bottom trawling is still actively shaping the seafloor in the Western Baltic Sea (Fig. 8). The mean density of trawl marks increased from 0.09 in 2024 to 0.22 in 2025 within the MPA (Tab. 1), although the MPA has been an exclusion zone for bottom trawling since January 2025. In the Fehmarn Belt, a furrow-volume-based trawling index derived from MBES (Schönke et al., 2026) revealed strong interannual changes in bottom-contact fishing that were not captured by AIS track counts, primarily because the fleet is dominated by vessels <12–15 m for which AIS and VMS coverage is incomplete. The discrepancy between trawl mark density and AIS-derived fishing hours in Mecklenburg Bay further underscores the limitations of AIS-based monitoring for small-vessels. Together, these findings highlight the added value of repeated hydroacoustic surveys for compliance monitoring in both remote high-intensity regions and small-vessel-dominated MPAs (Rufino et al., 2025).

However, the increase in trawling density, as well as the obvious presence of fresh trawl marks in slope maps (Fig. 8), may be due to fishing activities in the second half of 2024 that were still detectable in the 2025 survey. The observed time for trawl mark degeneration in the area is approximately one year (Schönke et al., 2026), meaning that the identified trawl marks give a rough impression about the accumulated trawling intensity of the last year. A timescale of one year is also apparent from 2024 to 2025: an eastward-bending trawl mark that was distinctly visible in 2024 was largely unobservable in 2025 (Fig. 8). This regeneration timescale of one year is rapid compared to the situation of the Mecklenburg Bay, likely due to strong bottom currents remobilising sediment and filling trawl furrows, with peak currents exceeding 0.4 m/s (BSH, GeoSeaPortal, last accessed 17 March 2025). However, the AIS-based data from 2025 suggest an increase in fishing activities in the FB-MPA area as well (Fig. 2) and supports the creation of trawl marks after closure of the MPA to bottom trawling. Therefore, this area should be monitored in future to assess the regeneration of natural seafloor conditions and absence of bottom trawling within the Marine Protected Area.

Conclusion

This study demonstrated that open-source bathymetric data, which is routinely collected by hydrographic authorities, can be used in combination with a U-Net deep learning workflow to map trawling intensity across large areas. Across five independent test areas the workflow achieved an F1 score of 0.66, increasing to 0.80 when a 1 m spatial tolerance is allowed to account for the difficulty of pixel-accurate annotation of trawl marks. Due to low computational requirements, the model can easily be improved

and adapted for operational use by authorities. It reliably identifies trawl marks on the seabed in a quick and cost-effective manner and derives bottom trawling intensity in high spatiotemporal resolution on cohesive seabeds. The results show a better spatial resolution of fishing intensity than the data currently available from the fishing industry’s reporting obligations. Even though the preservation of trawl marks depends on the type of sediment, the type of fishing gear and the local hydrodynamic conditions, the improved spatial resolution achieved here will be useful for marine spatial planning, mitigation of fishing impacts, and nature conservation. Based on the obtained results, spatial variations in fishing intensity can be outlined and the impact of fishing intensity on various ecosystem components can be investigated. The method can be applied in areas with cohesive seabed and is capable of detecting fishing activity in areas where unreported fishing takes place.

Data availability

Bathymetric data compiled by the Federal Maritime and Hydrographic Agency (BSH) can be retrieved from <https://marine-data.de/viewers/8b50affd-66ac-4f51-8633-1874b92ba5a1> (last accessed 5. June 2026). For these grids, the slope needs to be calculated and the grids upscaled and tiled according to the method description. AIS data of the Baltic Sea is provided by the Danish Maritime Authority (<http://aisdata.ais.dk>, last accessed 5 June 2026). GlobalFishingWatch data is available from <https://zenodo.org/records/14982712>, last accessed 5. June 2026. The training dataset and masks, test dataset and masks and fishing density maps can be accessed from <https://doi.org/10.5281/zenodo.19131526>, last accessed 5. June 2026. The used UNet implementation is <https://github.com/milesial/Pytorch-UNet>, last accessed 5. June 2026.

AI disclosure

During the preparation of this work, the authors used Claude to assist with the development and debugging of software code. DeepL was used to check the grammar and language. The authors reviewed and edited the output as needed and take full responsibility for the content of the published article.

Author contributions

The research was conceptualized by PF, IS and MS. Funding acquisition was carried out by PF and DO. Investigation and data acquisition were performed by PF, MS, IS, JG, SP and ES. Data curation was conducted by PF. Validation and interpretation of the results were undertaken by PF, JG, MS and IS. Visualization was prepared by PF. PF wrote the original draft of the manuscript. All authors (JG, MS, DO, ES, AN, SP, IS) reviewed and edited the manuscript. All authors contributed to the investigation and approved the final manuscript.

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