

Estimating bottom trawling pressure and inferring relative benthic status in Taiwan's EEZ when benthic data are limited

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Abstract

Bottom trawling is one of the most widespread human disturbances to the seabed. Although trawl fisheries are intense in the waters surrounding Taiwan, their benthic impacts have yet to be quantified. To address this gap under data-limited conditions, this study combined two vessel tracking data sources from 2013 to 2023 to estimate the spatial distribution of annual average swept area ratio (SAR) and to infer relative benthic status (RBS) from trawling pressure within Taiwan's Exclusive Economic Zone shallower than 1000 m. RBS was inferred using globally synthesized depletion and recovery parameters for benthic invertebrates, together with localized gear width and sedimentary habitat data. Mean annual SAR was 6.24 and the median was 1.34, indicating highly heterogeneous trawling intensity concentrated in sand and muddy-sand habitats. The mean RBS across the study area was 0.85, with a median of 0.99. Areas with relatively lower RBS were mainly distributed in nearshore waters dominated by domestic trawling and near the EEZ boundary where both Taiwanese and foreign vessels operated, suggesting higher cumulative trawling pressure in these areas. Given limited local benthic data, assumptions on taxon distribution across habitats and on impact parameters were required. Sensitivity analyses showed that mean RBS ranged from 0.73 to 0.90 under extreme habitat preference and trawling impact scenarios, indicating the range of variation in inferred status under these assumptions. This study is the first in East Asia to infer RBS by combining spatially explicit trawling pressure with ecological parameters, filling a gap in global trawl impact maps and providing critical baseline science for ecosystem-based fisheries management in Taiwan under data-limited conditions.

Keywords seabed habitats, trawl footprints, fishing impacts, benthic invertebrates, ecological risk assessment

Introduction

Recent decades have seen significant advances in understanding the spatial footprint and ecological impacts of bottom trawling at the global scale. Several studies have integrated fishery monitoring data worldwide, using key indicators such as swept area ratio (SAR) and relative benthic status (RBS) to assess seabed impacts of trawling (Collie et al. 2000, Kaiser et al. 2006, Mazon et al. 2017, Hiddink et al. 2017, Pitcher et al. 2017, Amoroso et al. 2018, Sciberras et al. 2018, Mazon et al. 2021, 2022, Hiddink et al. 2026). Despite these efforts, Asian waters remain systematically underrepresented in global assessments. This gap stems in part from the limited availability and transparency of vessel monitoring system (VMS) data in many Asian coastal nations, restricting visibility into spatial trawling intensity. Moreover, even with tracking data, the lack of region-specific gear parameters, such as trawl width, limits the accuracy of SAR estimation and raises uncertainty about applying global models

to local contexts (Rickwood et al. 2025). These limitations underscore a regional barrier to assessing bottom trawling impacts, highlighting the need for VMS alternatives and local gear data.

The affordability and wide coverage of AIS have made it a viable alternative in regions with limited VMS availability (Taconet et al. 2019, Drakopoulos et al. 2023, Orofino et al. 2023). However, AIS data face critical limitations, such as signal gaps, intentional shutdowns, spoofing, and falsified transmissions, that may introduce bias into estimates of bottom trawling activity. To evaluate these risks and the reliability of AIS, this study incorporates data from the voyage data recorder (VDR) system installed on Taiwanese trawlers. Unlike AIS, VDR provides continuous and tamper-resistant records, providing a valuable reference for assessing AIS-derived fishing effort. By comparing VDR and AIS data, we aim to identify discrepancies in estimated fishing intensity and highlight potential risks associated with AIS-based assessments of regional fishing activity.

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Taiwan is located on the continental shelf region of the East China Sea, where bottom trawl fisheries are widespread. Previous research has predominantly focused on the composition of commercial demersal fish resources and the spatiotemporal dynamics of fishing activities within Taiwan's Exclusive Economic Zone (EEZ) (Shao et al. 2012, Wang et al. 2013, Chen and Lee 2013, Gao et al. 2020, Lee et al. 2021, Chen et al. 2022, 2025). In contrast, benthic invertebrate communities potentially affected by bottom trawling have received far less attention. These research patterns reflect a knowledge bias in which management frameworks focused on economically targeted species, leaving nontarget groups underrepresented in impact monitoring and ecological assessment. In fact, benthic invertebrate communities play a critical role in maintaining the structural and functional integrity of seabed habitats, and support the stability of marine food webs through energy transfer and trophodynamic feedbacks (Jennings et al. 2001, Collie et al. 2017, van de Wolfshaar et al. 2020). Existing studies have characterized bottom trawling behavior and fishing effort (hours) distribution in waters around Taiwan (Chang 2016; Lee et al. 2021, 2025), providing a basis for characterizing trawling pressure at a regional scale. However, information on trawling hours alone is still insufficient to evaluate the potential ecological effects of such pressure on benthic communities, and therefore requires an analytical framework that can link fisheries pressure to benthic ecological response. In this context, RBS model provides an approach for quantifying how accumulated swept-area disturbance relates to the relative status of benthic invertebrate communities (Pitcher et al. 2017), and can be used to infer potential changes in benthic communities relative to an untrawled state.

Although some studies on benthic invertebrates are available for Taiwan, most have focused on coral reef or rocky reef communities (Dai 1993, Ribas-Deulofeu et al. 2016, Lin and Denis 2019), intertidal and estuarine mangrove environments (Hsieh 1995), or particular systems such as coastal areas influenced by infrastructure, shallow hydrothermal vents, and deep-sea environments (Cheng et al. 2004, Lin et al. 2014, Wang et al. 2022). However, for local data to directly support the application of RBS, benthic biological data from the main habitats where bottom trawling occurs, or at least survey designs that reflect community responses under trawling pressure, would ideally be required. Existing studies provide important background on the distribution and community characteristics of benthic biota in Taiwanese waters, but their sampling locations are generally outside the sedimentary habitats where bottom trawling mainly occurs, and their designs were not intended to evaluate benthic responses to trawling disturbance. They therefore cannot yet provide a direct local basis for parameterizing the relationship between trawling pressure and benthic responses in trawled sedimentary habitats. Under these conditions, this study aims to combine open-access AIS data, VDR tracks from Taiwanese trawlers, localized gear width and sediment data, and depletion and recovery parameters synthesized across regions, habitat types, and benthic invertebrate taxa in previous studies (Sciberras et al. 2018, Mazor et al. 2021, Pitcher et al. 2022). Specifically, we infer the spatial distribution of bottom trawling pressure and its implications for the relative status of benthic communities under data-limited conditions. Rather than directly assessing actual benthic condition, the study provides pressure-based maps of RBS for identifying areas of relatively higher benthic risk.

Methods

Study area and vessel tracking data

The EEZ shapefile used in this study was obtained from the Marine Regions EEZ dataset (version 12, Flanders Marine Institute 2023). Because bottom trawl fisheries in eastern Taiwan can extend to depths of about 1000 m, we restricted the analysis to waters shallower than 1000 m to ensure that the study area encompassed regions where bottom trawling is likely to occur. Depth contours were delineated using the GEBCO gridded bathymetric dataset (GEBCO Compilation Group 2023).

To represent trawling activity in the study area, we used tracking data from two sources. VDR systems, which are widely installed on Taiwanese vessels, record high-resolution positional data at 3-minute intervals and can be linked to landing records to identify the gear type used during each trip (Chang 2016, Lee et al. 2021, 2025). AIS data obtained from the Global Fishing Watch platform were used to detect trawling activity throughout the region (Global Fishing Watch 2025). Based on AIS flag state information, Chinese vessels were identified as the predominant nondomestic fleet conducting bottom trawling in the area (see Table S1). Accordingly, this study focused on Taiwanese (TWN) and Chinese (CHN) trawlers, using tracking data to estimate seabed disturbance intensity and RBS from 2013 to 2023. To enhance the reliability of swept-area estimates, annual fishing hours derived from AIS and VDR sources were compared as a basis for data selection and correction.

Swept area ratio

The SAR is defined as the proportion of each grid cell's area swept by trawlers annually, expressed in units of yr^{-1} . The estimation method followed Amoroso et al. (2018), considering gear width and trawling distance to assess the spatial distribution of SAR within the study area.

Gear width definition

The TWN fleet employs three demersal trawl gears, with otter trawl being the predominant method, followed by shrimp beam trawl and pair trawl (Lee et al. 2025). The average gear width for each gear type was defined to account for gear size variation by vessel size (see Table S2 and Zhou & Su 2002; Matsushita et al. 2005). For the CHN fleet, an average gear width of 60 m was assumed to approximate the specifications used by Taiwanese bottom trawlers, given their similar operational characteristics.

Swept area ratio estimates

Following the gridded trawl-footprint approach of Amoroso et al. (2018), SAR was calculated for each 1 km^2 spatial unit as the ratio of total swept area to unit area. In this framework, the uniform assumption treats trawling activity within each unit as approximately evenly distributed when converting SAR to the proportion of area swept. It is therefore an areal approximation for standardized estimation, not a direct description of actual trawling-path geometry.

Trawling events were identified based on speed thresholds defined by Lee et al. (2025), with a minimum continuous operation duration of 30 min required to confirm valid activity. These criteria enabled the reconstruction of trawling paths and

calculation of swept areas. For the CHN fleet, AIS data processed through machine learning algorithms developed by Global Fishing Watch (2025) were used to identify trawling activity and summarize total fishing hours per grid cell. Because specific trawling paths could not be derived from AIS data, we assumed an average speed of 3.5 knots for CHN trawlers, which falls within the typical operational range of 2 to 5 knots. This speed was used to convert fishing hours into trawling distances, which were then multiplied by gear width to estimate the swept area generated by the CHN fleet.

Trawling distances were calculated using the World Geodetic System 1984 ellipsoid model (EPSG:4326), while area calculations were performed using a Universal Transverse Mercator projection for the study area (UTM Zone 51 N, EPSG:32651). Final spatial mapping was presented in the UTM coordinate system.

Relative benthic status

RBS is derived from a dynamic equilibrium model described by a logistic population-growth equation, which incorporates the depletion rate and recovery rate of biomass in different benthic invertebrate taxa following trawling disturbance (Pitcher et al. 2017). The parameters vary according to gear types and sedimentary habitat types (e.g. mud, sand, or gravel), together with the estimated disturbance intensity represented by the SAR (Mazor et al. 2021, Pitcher et al. 2022). The index ranges between 0 and 1, where values closer to 0 indicate near-complete depletion of benthic biomass, and values closer to 1 represent conditions approaching an untrawled reference state. The following describes how parameters were adjusted and applied in the study area.

Sedimentary habitats

Sediment data were obtained from 1874 sampling points publicly available from the Department of Land Administration, Ministry of the Interior, Taiwan. In this study, the inverse distance weighting (IDW) method was used to interpolate the sediment data and generate a continuous distribution map. The IDW method is based on the assumption that observations closer in space are more similar in value, relying solely on spatial geometry without requiring a variogram model or formal modeling of spatial autocorrelation, which is particularly suitable for datasets with limited sampling coverage (Shepard 1968).

Subsequently, to convert the continuous sediment composition data (e.g. the proportions of sand, mud, and gravel) into categorical habitat types, the triangular classification scheme proposed by Folk (1954) was applied. According to this classification, Sedimentary habitat were divided into four types: gravel, defined as gravel content exceeding 30%; sand, where mud content is less than 20%; mud, where sand content is less than 20%; and mud-sand, representing mixed categories not falling into the above definitions.

This classification has also been adopted in other trawling impact studies (Pitcher et al. 2017, 2022) to facilitate comparisons of responses among different habitat types. The spatial distribution of seabed sedimentary habitats within the study area is shown in Fig. 1.

Parameter sources and adjustment

We adopted the depletion rates (d), recovery rates (R), and conservative lower bounds of recovery rates ($R_{\text{lower CI}}$) reported in Mazor et al. (2021) as the initial parameters for benthic invertebrate taxa in this study (Table S3). These parameters were not estimated directly for waters around Taiwan or for the gear combinations considered here, but were derived from globally synthesized trawl-impact studies based on regional benthic survey data spanning depths from 0 to 2000 m (table 1 in Mazor et al. 2021). Because the d and R responses of benthic taxa vary with sedimentary habitat conditions, we further adjusted the parameter values for each taxonomic group according to the sediment composition of each grid cell, following the method described in the supplementary materials of Mazor et al. (2021).

The eight benthic taxonomic groups included in this study were Anthozoa (e.g. sea anemones and corals), Ascidiacea (sea squirts), Asteroidea (sea stars), Bivalvia (bivalve mollusks), Gastropoda (sea snails and slugs, including coiled, conical, or shell-less forms), Malacostraca (crabs and shrimps), Ophiuroidea (brittle stars), and Polychaeta (segmented worms). Publicly available biodiversity databases, including Ocean Biodiversity Information System and iNaturalist, were used as a general check on whether these eight groups have been recorded within Taiwan's EEZ. Their inclusion was therefore considered reasonable for this study, while also reflecting the current availability of globally synthesized d and R parameters. Accordingly, they should be regarded as an operational subset of taxa under data-limited conditions rather than a complete representation of all benthic taxa in Taiwan's EEZ.

The depletion rate (d) serves as an indicator of the extent of benthic biomass loss resulting from a single bottom trawl disturbance, representing the proportion of biomass removed after each trawl pass. Given that otter trawl is the dominant gear type in the study area, and that the meta-analysis by Pitcher et al. (2022, Table S3) does not include depletion rates for pair trawl and Taiwan-specific shrimp beam trawl, we used otter trawl d values for sand (0.045), mud (0.115), and gravel (0.108) as the closest available proxy values. For each grid cell, a weighted average was calculated according to sediment composition to reflect the relative disturbance intensity under local sedimentary conditions, and this value was then used to adjust the initial d values for each taxonomic group. These adjusted d values should therefore be interpreted as approximations based on sediment differences and the predominance of otter trawl under data-limited conditions, rather than locally estimated depletion rates for all bottom trawl gears.

The recovery rate (R) quantifies the speed at which benthic biomass recovers to its undisturbed state after trawling. As sedimentary habitat types influence the recovery potential of benthic communities, this study applied an adjustment method proposed by Mazor et al. (2021) and Pitcher et al. (2022) to account for local habitat conditions. Specifically, we calculated a habitat-specific recovery adjustment coefficient ($R_{\text{scaling ratio}}$) for each grid cell based on the proportions of sand, mud, and gravel in the seabed sediments.

The empirical formula used to estimate this coefficient is as follows (1):

$$R_{\text{scaling ratio}} = \frac{F}{1 - 10^{[(a(\%Gravel + 1) + b(\%Sand + 1) + c(\%Mud + 1)) \times F]}} \div 0.437(1)$$

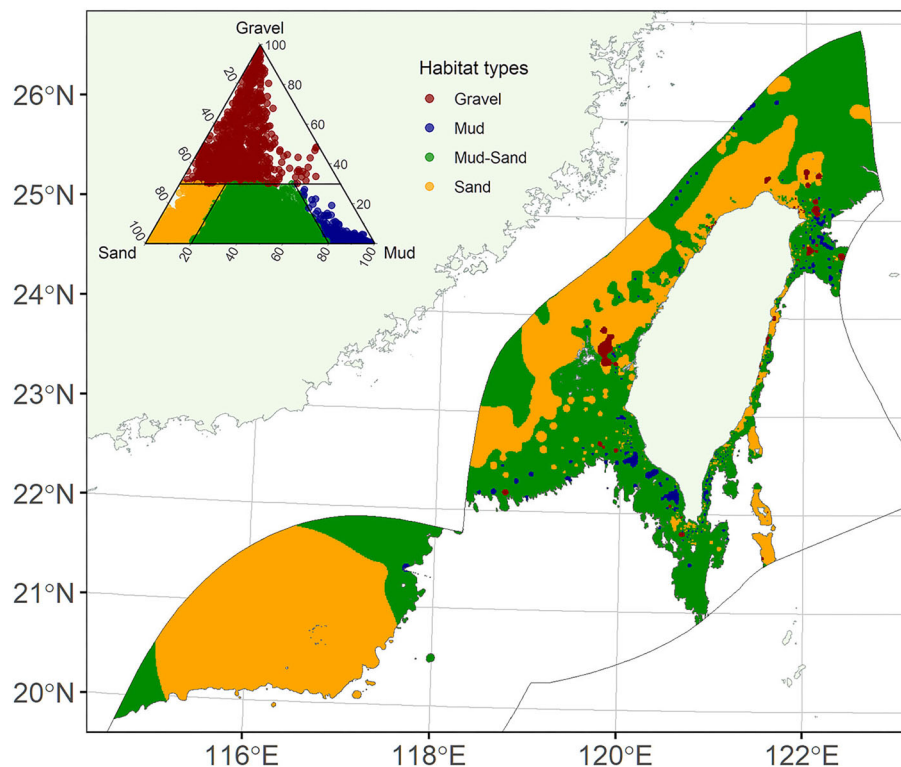


Figure 1 Sedimentary habitat map of study area (Taiwan's EEZ depth <1000 m) and ternary diagram showing grain-size fraction classification into habitat types.

where $F = 10^{-6}$, and the regression coefficients are $a = -0.0145$, $b = -0.0083$, and $c = -0.0061$. These values are derived from a regression model developed by Pitcher et al. (2022) to predict recovery rates based on sediment composition. The denominator 0.437 serves as a normalization baseline, corresponding to the average recovery rate under mean sediment conditions (28.8% gravel, 52.3% sand, and 18.8% mud) synthesized from trawl-impacted studies analyzed in Hiddink et al. (2020). In other words, $R_{\text{scaling ratio}}$ indicates the relative adjustment in recovery potential under different sediment compositions compared to this reference condition. The original R values for each benthic taxonomic group were then multiplied by the corresponding $R_{\text{scaling ratio}}$ of each grid cell to obtain recovery rates adjusted for local sedimentary habitat characteristics. According to Mazor et al. (2021), the values of $R_{\text{scaling ratio}}$ range approximately from 0.67 (gravel-dominated habitats) to 1.56 (mud-dominated habitats).

Status assessment

Due to the absence of survey data characterizing the composition of benthic assemblages across different habitats in the study area, we adopted a feasible and simplified assumption: the eight benthic taxa were uniformly distributed across all habitat types. This assumption provides a neutral and controllable framework for estimating taxon-specific RBS values across diverse sedimentary environments, based on standardized depletion and recovery rates.

For each taxon, we estimated benthic status using the RBS model (Pitcher et al. 2017), with standardized depletion (d) and re-

covery (R) rates adjusted for habitat type. The RBS is defined as

$$RBS = \begin{cases} 1 - \frac{SAR \times d}{R} & \text{if } SAR < \frac{R}{d} \\ 0 & \text{otherwise} \end{cases}$$

This conditional formulation ensures that RBS values remain bounded between 0 and 1, while also capturing the risk of benthos collapse under conditions of high trawling intensity. In addition, we computed the lower bound of the 95% confidence interval ($R_{\text{lower CI}}$) for each RBS estimate to reflect the associated parameter uncertainty. Within each spatial grid cell of a given substrate type, the RBS values of the eight taxa were averaged arithmetically to represent the overall benthic community status of that unit (All_taxa). The resulting values were aggregated to generate a spatial RBS map, indicating the relative state of benthic communities across habitat types in the study area.

Sensitivity analyses

Although the estimation procedure in Section Status assessment assumes a uniform distribution of taxa across habitat types, this simplification may involve two key limitations. First, it may mask the vulnerability of the benthic system, particularly if taxa show strong preferences for habitats with low recovery potential (e.g. gravel), which could lead to an overestimation of regional RBS. Second, the d and R values adopted from the global synthesis by Mazor et al. (2021) and inherently contain variability. These estimates may not fully capture the range of possible parameter values under the highest or lowest impacts of trawling. To evaluate how RBS estimates may vary when these assumptions and parameter settings are altered, we conducted a sensitivity analysis based

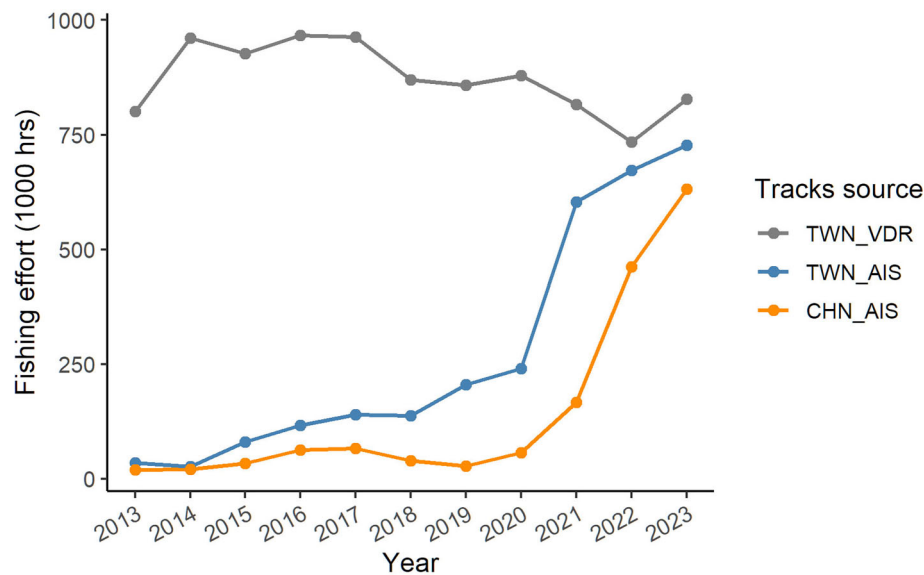


Figure 2 Annual trends in total fishing effort (in 1000 h) of TWN and CHN fleets based on different track data sources (VDR and AIS) during 2013–2023.

on six cases (see Table S4). Among them, the *Normal* case reflects the baseline method and assumptions used in Section Status assessment, serving as a reference for comparison with the five extreme cases described as follows:

1. Extreme habitat preference scenarios

To estimate the potential bias introduced by the uniform distribution assumption, we defined three habitat-specific cases (*pure_Sand*, *pure_Mud*, *pure_Gravel*), where the entire study area was hypothetically composed of only one substrate type. For each case, the RBS for each taxon was calculated using the *d* and *R* values corresponding to that specific habitat. This setup tests how extreme habitat affinity could influence the overall RBS estimation.

2. Extreme impact scenarios

To assess how sensitive RBS estimates are to variation in the input parameters, we defined two cases representing the bounds of parameter uncertainty. The *High_impact* case applies the maximum *d* and minimum *R* across all habitat types for each taxon, representing a pessimistic context. Conversely, the *Low_impact* case uses the minimum *d* and maximum *R*, representing an optimistic context. These extreme parameter values were drawn from the range observed in the habitat-specific cases described above.

This sensitivity analysis focused on changes in assumed habitat preference and trawling impact parameter settings, but did not explicitly incorporate habitat-specific dominance of particular sensitive taxa.

ing hours estimated from VDR data for the TWN fleet remained relatively stable between 750 000 and 1 000 000 hours per year. In contrast, AIS-based estimates for both TWN and CHN fleets only increased significantly after 2021, reflecting previous limitations in AIS signal reception and system coverage. Using TWN vessels as a reference, which have both VDR and AIS records, we inferred that early AIS data likely underestimated effort due to poor reception quality or low installation rates. Accordingly, VDR was adopted as the primary data source for TWN fleet analysis, given its higher positional resolution and gear-specific detail.

For the CHN fleet, AIS was the only available dataset. To reduce the potential bias from underreported effort in earlier years, we evaluated the interannual variation in the spatial distribution of SAR based on VDR-derived estimates for the TWN fleet. Figure 3 presents normalized cumulative SAR distributions across grid cells over multiple years. While the number of trawled cells varied slightly, the distribution curves remained highly consistent, indicating strong temporal stability in spatial effort ranking. For instance, in the SAR range of 1–10, the variation in cumulative cell proportions was only 7% to 19% across years. Additionally, annual SAR maps confirmed that the geographic locations of core trawling areas remained stable (see Fig. S1). Based on this, we inferred that the CHN fleet, which operated in the same region, likely exhibited spatial consistency. Therefore, the annual mean AIS-based effort from 2021 to 2023 was used as a proxy to estimate CHN fishing intensity prior to 2020, while AIS-derived values from 2021 onward were retained without adjustment. This approach offers a more stable baseline for historical inference and helps mitigate the influence of AIS data limitations on long-term trend estimates.

Results

Bottom trawling footprints

Representation of tracks data

To characterize annual trawling effort, we compared trends derived from different tracking sources. As shown in Fig. 2, total fish-

SAR distribution

Given the limited interannual variation in SAR from 2013 to 2023, we focus on the spatial distribution of annual mean SAR values and the corresponding statistics across different levels of trawling intensity. Overall (Fig. 4a), the maximum annual mean SAR reached 400.04. This extremely high value occurred in nearshore

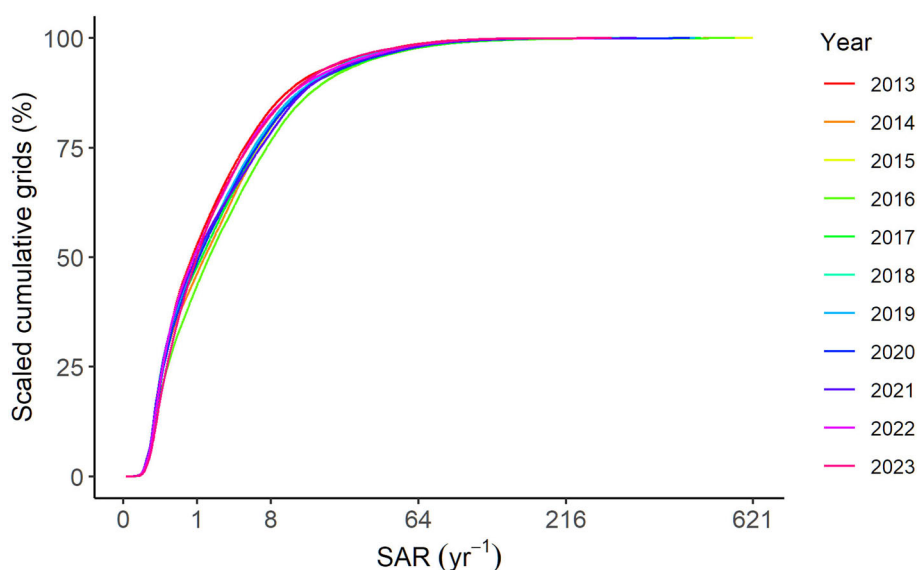


Figure 3 Annual SAR and the corresponding normalized cumulative proportion of grid cells (%) for the TWN fleet based on VDR track data.

fishing grids along the northwestern coast of Taiwan and was only estimated from VDR tracks of Taiwanese trawlers, likely reflecting highly concentrated local trawling activity. This result also indicates that, in nearshore hotspot grids, cumulative swept intensity can reach very high levels when estimated from high-resolution vessel track data.

Across all trawled grid cells, mean annual SAR was 6.24 and the median was 1.34, indicating a strongly right-skewed distribution concentrated in lower-intensity ranges. Medium to high-intensity trawling ($SAR > 1$) was mainly distributed in coastal waters, the Taiwan Bank, the Taiwan Strait, and the northeastern continental shelf, accounting for approximately 53.4% of the total trawled area. Among these, 18.0% experienced high impact ($SAR > 10$). A comparison of SAR spatial patterns between the TWN and CHN fleets (Fig. 4b and c) reveals notable differences in their core fishing grounds, with the TWN fleet operating predominantly in nearshore waters. However, areas of high-intensity trawling were concentrated near the EEZ boundary, indicating potential competition for shared fishing grounds between the fleets.

Inferred RBS across the EEZ

After adjusting for gear types and substrate composition, taxonomic groups showed variation in d and R parameters, and inferred pressure-related RBS within trawled grid cells (Fig. 5). The intergroup differences in parameters remained broadly consistent with the unadjusted values, indicating that sediment-based adjustment mainly affected the range of parameter values for each taxon rather than substantially altering their relative ranking. The median d ranged from 0.008 to 0.144, with Bivalvia showing the highest median depletion rate; the median R ranged from 0.146 to 4.708, with Polychaeta exhibiting the highest recovery rate. Focusing on RBS estimates for trawled cells (Fig. 5c), the median RBS for All_taxa was 0.92 (mean: 0.76), and the lower CI status was 0.82 (mean 0.63) reflecting statistical uncertainty in the input parameters. Across the eight individual taxonomic groups, RBS medians

ranged from 0.88 to 0.97, and their lower CI estimates ranged from 0.77 to 0.89.

The boxplots show substantial spatial variation in RBS across taxonomic groups. Although part of this variation reflects local differences in sediment composition, it was driven primarily by strong spatial heterogeneity in trawling intensity. This pattern is also evident from the spatial comparison between the All_taxa RBS map (Fig. 6) and SAR distribution (Fig. 4). Overall, 38.4% of the study area remained untrawled throughout the study period. An additional 38.1% of the study area had $RBS \geq 0.8$ within trawled cells, with a conservative estimate of 31.7%. In contrast, approximately 12.7% of the area had $RBS < 0.5$, increasing to 21.5% under the lower CI parameter estimates, indicating an inferred RBS below half of the theoretical untrawled reference state. Overall, the inferred All_taxa RBS for the entire EEZ, including untrawled areas, remained high under both the mean status parameters (median = 0.99, mean = 0.85) and for lower CI parameters (median = 0.98, mean = 0.77).

Relationship between SAR and RBS

The overall spatial patterns and trends in the relationship between SAR and RBS are illustrated in Fig. 7. Results show a general decline in RBS with increasing SAR. When $SAR \leq 1$, which accounts for 67.1% of the total EEZ area, the mean RBS remains above 0.94 (SD = 0.01), with relatively low variability among grid cells. As SAR increases, RBS values gradually decline and become more variable among grid cells, suggesting that increasing trawling pressure affects benthic recovery potential differently across space. Notably, when SAR exceeds approximately 64, RBS declines to near zero, indicating that recovery rates across all taxa are no longer sufficient to compensate for biomass loss caused by ongoing disturbance. Therefore, the relatively high inferred RBS across the entire EEZ (0.85; see Section Inferred RBS across the EEZ) mainly reflects the extensive area with low SAR or no trawling activity.

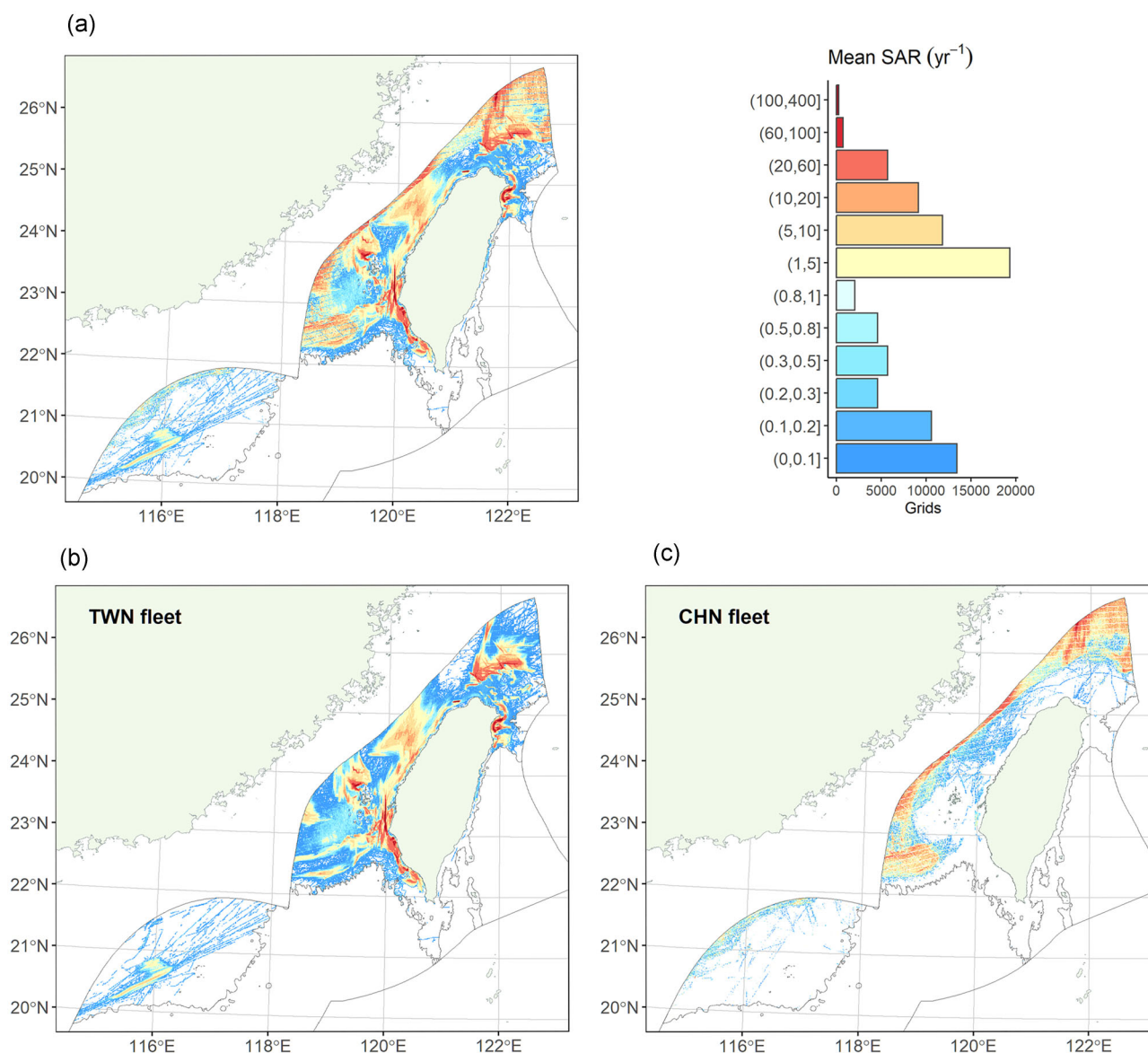


Figure 4 Annual mean SAR within the study area, with (a) showing the overall spatial distribution and corresponding histogram of grid cell counts across SAR intervals, and (b)–(c) showing the SAR contributions from the TWN fleet (based on VDR data) and the CHN fleet (based on AIS data), respectively.

Further insights from Table 1, which summarizes habitat-specific RBS under different SAR intervals, reveal that Mud-Sand habitats constitute the majority of trawled areas (54.65%) and have the lowest RBS among all habitat types (mean = 0.61; SD = 0.32). In contrast, Sand habitats, although representing the second largest disturbed habitat type (43.04%), have the highest RBS (mean = 0.86; SD = 0.27), suggesting that these differences more likely reflect variation in the d and R parameters used to describe habitat-specific sensitivity and recovery potential. However, it is worth noting that across all SAR levels, actual trawling activity is largely concentrated in sand and mud-sand habitats. Other habitats such as Gravel and Mud, although potentially more sensitive to trawling, account for only a very small fraction of impacted area and therefore provide limited opportunity to observe their response. The spatial heterogeneity in RBS across SAR levels and habitat types thus reflects not only differences in inferred benthic status, but also the concentrated spatial pattern of trawling activity within the study area.

RBS sensitivity analyses

The sensitivity analysis results (Fig. 8) show that, across the five extreme cases, median All_taxa RBS within the EEZ remained above 0.98, while mean values ranged from 0.73 to 0.90. Relative to the *Normal* case mean of 0.85, the estimates under these extreme scenarios varied, but the overall magnitude of change remained limited, indicating that these differences were primarily driven by different combinations of d and R parameters.

Under the extreme habitat preference scenarios, we examined extreme counterexamples to the assumption that taxa are uniformly distributed across habitat types. In the *pure_Gravel* case, all taxa were assumed to occur exclusively in gravel habitat, and mean RBS declined to 0.74, indicating that overall RBS would be substantially reduced when lower recovery habitats dominate. By contrast, in the *pure_Sand* case, mean RBS remained 0.87, as sand has relatively higher recovery and lower depletion per trawl pass.

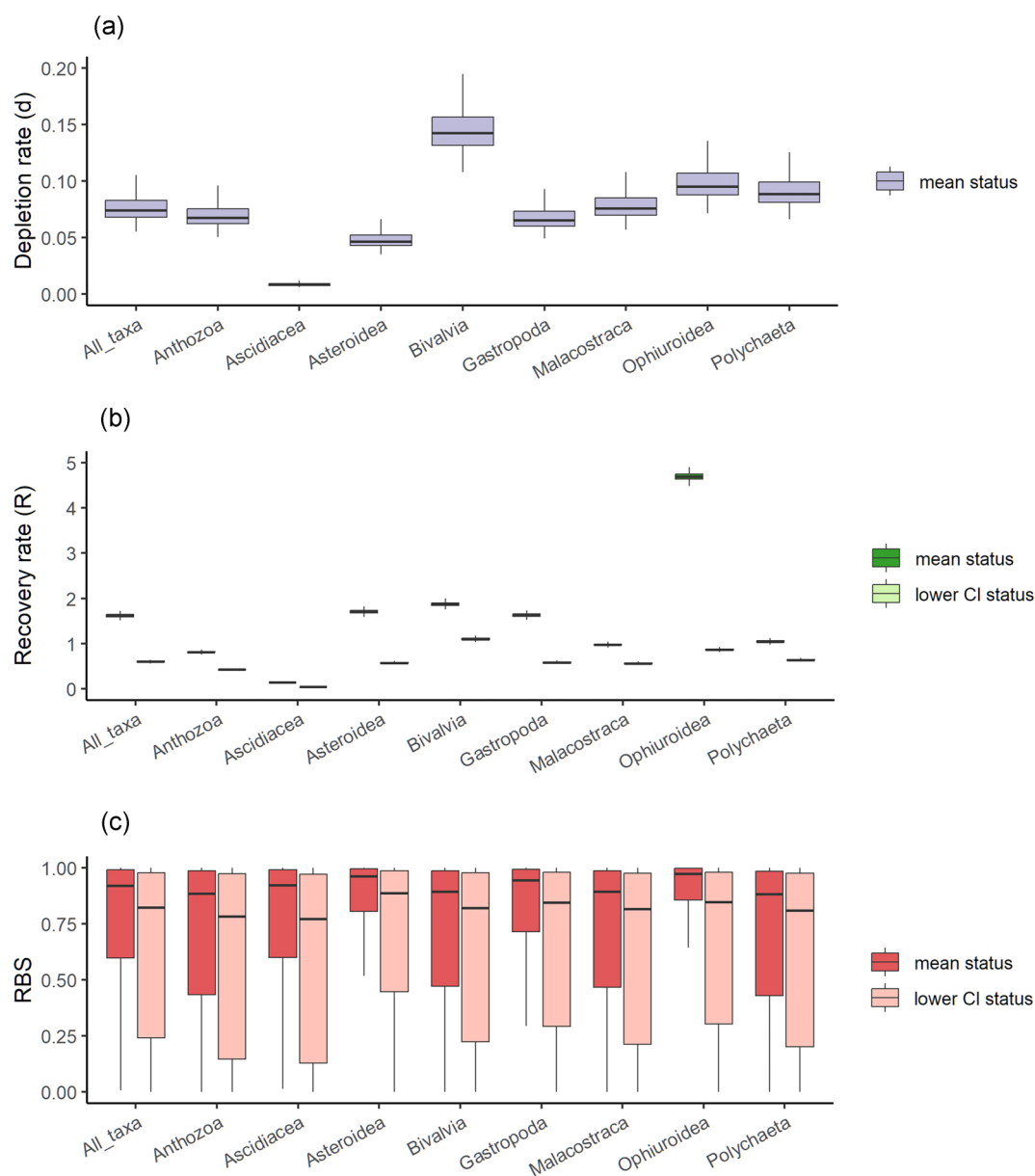


Figure 5 Box plots of (a) depletion, (b) recovery, and (c) RBS across benthic taxonomic groups, based on grid cells with SAR > 0. Values are estimated using mean status parameters and conservative settings (lower CI status) from Mazor et al. (2021).

These results indicate that extreme habitat preference can alter overall RBS estimates, and that the direction of change depends on the habitat type in which taxa are concentrated, showing that the uniform distribution assumption can influence inferred RBS.

Under the extreme impact scenarios, the *Low-impact* case yielded a mean RBS of 0.90, only slightly higher than the *Normal* case, indicating limited change in overall RBS under an optimistic parameter setting. In contrast, the *High-impact* case reduced mean RBS to 0.73 and produced greater spatial variation, with some grid cells approaching zero. This suggests that inferred RBS is more sensitive to spatial differences in trawling pressure under pessimistic parameter settings. Because all taxa were assigned the same fixed extreme combinations of d and R in this scenario, spatial variation in RBS primarily reflects heterogeneity in SAR, with higher pressure areas more likely to be inferred as having low RBS.

Discussion

Comparing AIS and nonpublic tracking system

Quantifying trawling activity is central to assessing benthic impacts. Although AIS was originally developed for navigational safety, it has become widely used for identifying fishing activities (Taconet et al. 2019, Drakopoulos et al. 2023, Orofino et al. 2023). However, its reliability declines in mixed-gear fisheries where movement patterns converge. In Taiwan's coastal waters, midwater and bottom trawlers often exhibit similar trajectories (Lee et al. 2025), complicating gear types classification. Without supporting evidence such as landing data, AIS-based estimates risk inflating SAR. Moreover, AIS interpretation faces two main limita-

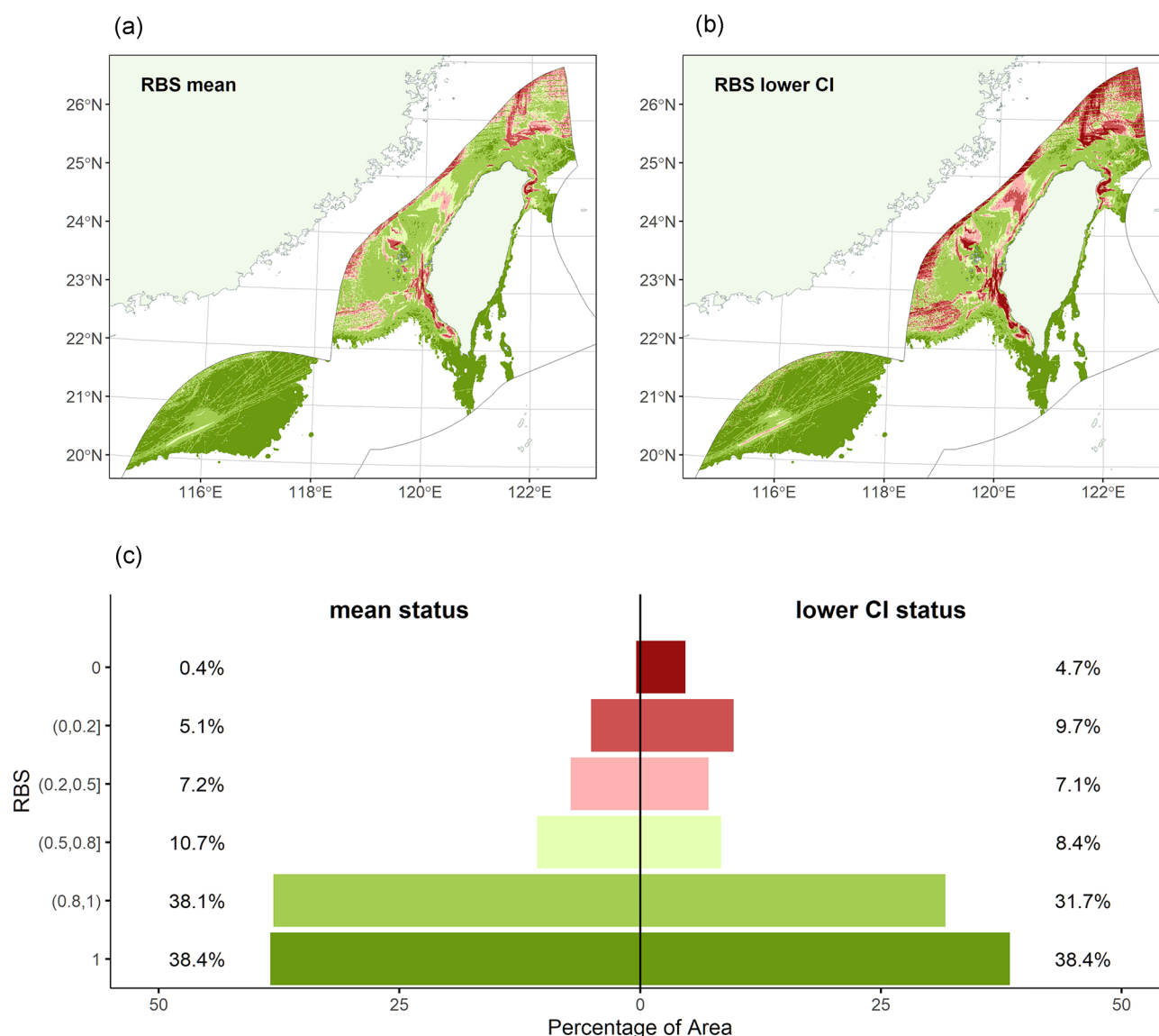


Figure 6 RBS estimates for All_taxa across the study area are presented as (a) mean status, (b) lower CI status (conservative estimate), and (c) percentage of areas within each RBS class under both estimates.

tions. First, data gaps are common in areas with prevalent illegal, unreported, and unregulated fishing, where vessels may deactivate AIS or use falsified MMSI codes that carry flag state information, thereby compromising traceability. Second, disparities in policy and technology adoption affect coverage. In many countries where small-scale fisheries dominate, AIS is not mandatory. This creates substantial blind spots that hinder accurate estimation of trawling intensity and spatial extent.

AIS reception in the study area has improved since 2021 (see Fig. 2), but data quality remains uneven between TWN and CHN fleets, indicating regional inconsistencies in implementation. Notably, over 70 flag states are represented among trawlers operating in Taiwan's EEZ (see Table S1), a pattern that does not reflect the actual composition of fishing fleets. Although these signals account for only a small fraction of total effort, they suggest potential errors in vessel identity or anomalies in transmission data. These findings highlight the limitations of relying solely on

AIS for SAR estimation and underscore the importance of integrating high-confidence sources such as VMS. Such multisource fusion is essential for constructing robust maps of fishing activity and reducing uncertainties caused by AIS-specific biases. Overall, while AIS holds significant promise for advancing fisheries transparency and enabling real-time monitoring, its full effectiveness depends on integration with complementary systems and the reliability of both transmission signals and vessel identity data. For future applications, particular attention should be given to data grooming, signal quality validation, and cross-verification across tracking sources to improve interpretability and analytical accuracy.

To evaluate the potential limitations of AIS data, this study used VDR records from TWN fleet as a reference for assessing data quality and reliability. The VDR system offers several implemental advantages and limitations, as follows. As a closed-recording device, it ensures data security but lacks satellite-based real-time trans-

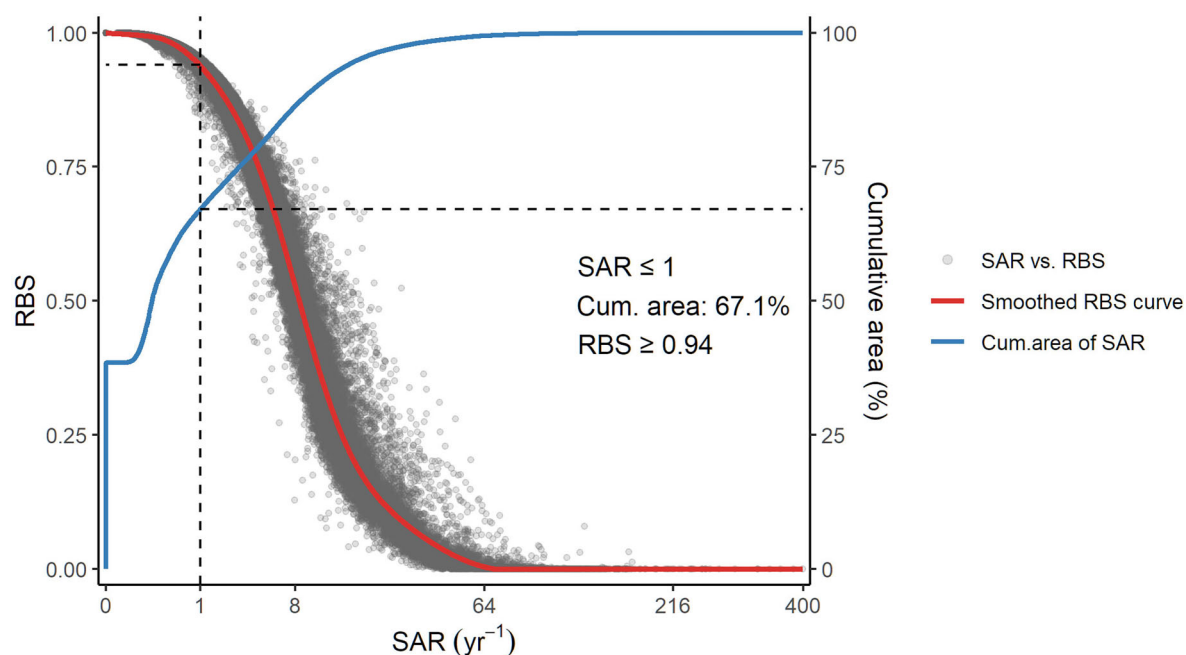


Figure 7 Relationship between trawling intensity (SAR) and benthic status (RBS) of All_taxa in the study area, illustrated by the cumulative area distribution of SAR and the smoothed RBS curve. The figure shows that RBS exhibits corresponding patterns of ecological status across spatial areas defined by different SAR values; for instance, 67.1% of the area has $SAR \leq 1$, where the mean RBS remains above 0.94.

Table 1. Mean and standard deviation (SD) of RBS across grid cells within each SAR interval, and area proportions of different sedimentary habitat types.

Habitat stats		SAR							Total
		(0, 1]	(1, 5]	(5, 10]	(10, 20]	(20, 60]	(60, 100]	(100, 400]	
Sand	Grids%	23.33	9.56	5.19	3.16	1.98	0.21	0.07	43.50
	RBS mean	0.98	0.86	0.62	0.35	0.11	0.01	0.00	0.86
	RBS SD	0.01	0.06	0.07	0.10	0.08	0.01	0.01	0.27
Mud-sand	Grids%	21.61	11.97	8.06	7.03	4.37	0.58	0.21	53.84
	RBS mean	0.98	0.83	0.56	0.28	0.09	0.01	0.00	0.61
	RBS SD	0.02	0.08	0.09	0.08	0.07	0.02	0.01	0.32
Mud	Grids%	0.73	0.27	0.18	0.18	0.13	0.02	0.01	1.52
	RBS mean	0.98	0.80	0.48	0.23	0.04	0.00	0.00	0.66
	RBS SD	0.02	0.08	0.10	0.10	0.04	0.00	0.01	0.36
Gravel	Grids%	0.89	0.19	0.04	0.02	0.01	–	–	1.15
	RBS mean	0.97	0.76	0.39	0.14	0.04	–	–	0.79
	RBS SD	0.03	0.12	0.12	0.07	0.01	–	–	0.22

Notes. Grids% represents the proportion of total trawled cells. A dash (–) indicates cells with no trawling data. SAR intervals follow a simplified grouping scheme as shown in Fig. 4, and habitat type classifications are based on substrate data shown in Fig. 1.

mission like that of VMS. While technically simplified, it is both cost-effective and affordable for fishermen. Originally established under a government fuel subsidy scheme (Chang 2016), VDR data submission is voluntary and tied to subsidy eligibility. Without legal enforcement, some small-scale coastal vessels may choose not to submit data, leading to uneven coverage. However, due to high fuel consumption, bottom trawlers are more motivated to apply for subsidies. Consequently, about 77% to 90% of vessels submit VDR data annually (Figure S2), making it a reliable basis for representing the spatial extent and intensity of TWN bottom trawling and for validating AIS-based estimates.

Interpreting SAR and RBS

The SAR and RBS estimates presented here help position Taiwan's EEZ within the global context of bottom trawling impacts. In the global continental shelf analysis of Amoroso et al. (2018), the mean SAR for this region was 6.24, second only to the Adriatic Sea, indicating that trawling intensity in Taiwan's EEZ ranks among the highest globally. Although the overall inferred RBS remained relatively high, with a mean of 0.85, comparable to estimates reported for most EEZs (Mazor et al. 2021, Pitcher et al. 2022). These results suggest that trawling impacts in Taiwan's EEZ reflect a strongly

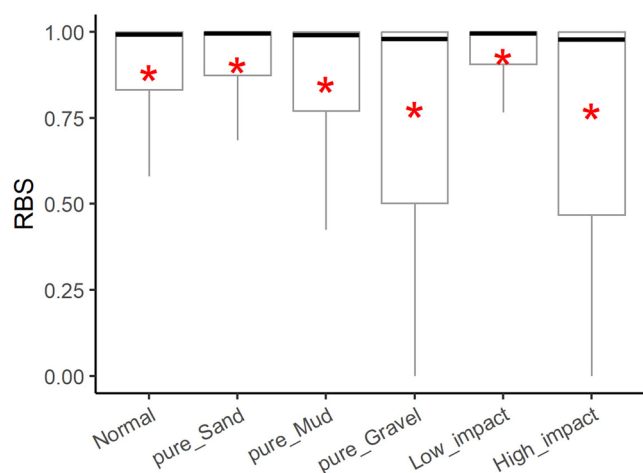


Figure 8 Boxplots of RBS from sensitivity analyses within study area under extreme habitat preference scenarios (*pure_Sand*, *pure_Mud*, *pure_Gravel*) and extreme impact scenarios (*Low_impact*, *High_impact*). The normal case representing the baseline using substrate-adjusted parameters. Boxes indicate the interquartile range, horizontal black lines represent the median, whiskers extend to 1.5 times the interquartile range, and asterisks (*) denote the mean RBS for each scenario.

heterogeneous spatial pattern, with a limited number of high intensity hotspots coexisting with extensive areas exposed to little or no trawling.

This spatial heterogeneity is also reflected in the extreme upper tail of SAR values. The maximum annual mean SAR reached 400.04 in a nearshore grid cell off northwestern Taiwan, based on VDR records from the TWN fleet. Given that this area is one of Taiwan's major shrimp fishing grounds, such an extreme value likely reflects highly repeated trawling within a localized fishing ground. High-resolution tracking data are particularly useful for resolving this kind of repeated towing in small coastal fishing areas and for capturing the accumulation of swept area pressure within individual grid cells. By contrast, about 38.4% of the study area was estimated to be untrawled. The coexistence of a few heavily trawled hotspots and extensive undisturbed areas therefore produces a highly uneven spatial distribution of SAR and, under the parameterization used here, helps maintain a relatively high mean RBS across the EEZ.

Notably, about 12.7% of the area had an RBS below 0.5, indicating an inferred benthic status below half of the theoretical untrawled reference state. These areas were concentrated in coastal waters with intensive activity by the TWN fleet and along EEZ boundary zones where TWN and CHN trawling grounds overlap. Here, $RBS < 0.5$ is used only for descriptive purposes and should not be interpreted as a fixed threshold of ecological health. Under the present data limitations, RBS is more appropriately treated as a relative, spatially explicit screening tool for identifying areas of potentially greater trawling impact, and areas with lower RBS should be viewed as priorities for future monitoring, management, and local ecological data collection.

The distribution of trawling effort was also closely associated with habitat conditions. Trawling was not distributed randomly, but was concentrated in particular sediment types, especially mud-sand and sand, which therefore experienced greater fishing pressure (Rijnsdorp et al. 2020). Our comparison of sediment class

with SAR and RBS (Table 1) showed the same pattern, with trawling concentrated in mud-sand and sandy habitats, while sandy areas tended to retain relatively high RBS. This may be consistent with greater disturbance tolerance in benthic assemblages associated with more dynamic environments (Kaiser et al. 2006, van Denderen et al. 2015, Hiddink et al. 2020, Pitcher et al. 2022), although the mechanism should be interpreted cautiously in the absence of local benthic community data. Waters around Taiwan are also subject to frequent natural disturbance, including typhoons and seasonal currents (Shiah et al. 2000, Jan et al. 2002, Shih et al. 2020), which may also help shape how benthic communities respond to additional disturbance from bottom trawling. Future work that examines variation in benthic functional traits across disturbance regimes would help strengthen the ecological interpretation of RBS in this region.

Uncertainty and sensitivity of RBS

A primary limitation of this study is the lack of local benthic data from trawled habitats in Taiwanese waters, including information on species composition, biomass, and key biological traits relevant to recovery assessment, such as longevity. To estimate RBS under these data-limited conditions, we relied on taxon-specific depletion and recovery parameters synthesized from large-scale comparative studies (Mazor et al. 2021, Pitcher et al. 2022). These baseline parameters were developed using standardized approaches across global studies employing grabs, dredges, beam trawls, and otter trawls, and included both epifauna and infauna. Species responses to trawling intensity were inferred from comparisons between disturbed and control areas (Mazor et al. 2017, Hiddink et al. 2017, Sciberras et al. 2018, Hiddink et al. 2020, Mazor et al. 2021). Although the environmental settings and species compositions represented in those studies do not necessarily match those of Taiwan's EEZ, the resulting parameter sets encompass benthic taxa that are common across many continental shelf ecosystems and therefore provide a reasonable basis for first-order regional RBS inference.

However, the relative differences among taxon-specific depletion and recovery rates should be interpreted cautiously as outcomes within an existing globally synthesized parameter framework, rather than as direct evidence of local ecological sensitivity in this study area. Apparent differences among taxa may also reflect the regional composition and study basis underlying these parameter estimates. For example, the relatively high depletion rate associated with *Bivalvia* may reflect the geographic distribution of the studies contributing to that estimate (Mazor et al. 2021). The parameter patterns presented here are therefore better understood as adjusted relative differences under data-limited conditions than as local validation of taxon-specific or even depth-specific vulnerability in Taiwan's EEZ.

The sensitivity analysis showed that RBS estimates were affected by the assumption of uniform taxon distribution across habitat types and by the choice of depletion and recovery parameters, but these factors did not overturn the main interpretation of the overall pattern of relative risk in this study. Although the regional mean varied across extreme scenarios, median RBS remained relatively high in all cases, indicating that the estimated status of most grid cells was comparatively stable. This suggests that the simplifying assumptions adopted here may influence the magnitude of RBS estimates, particularly under more vulnerable

habitat settings or more pessimistic parameterizations, but do not alter the broader pattern in which most low-pressure or untrawled areas retain relatively high inferred status. However, the effects of these assumptions were not equally pronounced across all trawled areas. Under the RBS framework, RBS approaches its lower bound as SAR increases. As a result, in the most intensely trawled grid cells, differences among assumptions may become relatively limited because estimated status is already close to its minimum. Greater sensitivity is more likely in adjacent high-pressure areas where trawling intensity is already substantial but RBS has not yet fully approached this lower bound. In this sense, the sensitivity analysis supports the use of RBS for regional-scale identification of relative risk, while also showing that RBS values and the extent of low-RBS areas around localized high-pressure zones may still vary with assumptions about habitat vulnerability and parameter choice. Under more pessimistic parameterizations, heavily trawled areas near the transition to low RBS were more likely to fall into this lower range, indicating that uncertainty has its greatest influence on local risk interpretation where SAR is high but RBS has not yet fully approached its lower bound.

Even so, the sensitivity analysis considered only extreme scenarios of taxon distribution across habitat types and did not account for the possibility that particular sensitive taxa may dominate specific habitats. The influence of community composition on local RBS estimates therefore remains only partly resolved. Future integration of trawl-based biomass observations, environmental covariates, and species distribution models would improve representation of taxon-specific spatial structure and strengthen the ecological relevance and local applicability of RBS estimates. Open-access biodiversity databases may provide useful supplementary information on species occurrence and potential distribution patterns, but at present they cannot substitute for the trawl-impact response data required for this type of assessment.

Broader implications and conclusion

While focused on bottom trawling, our results offer broader value for environmental and spatial planning contexts. Bottom trawling is known to disrupt sediment structure and affect carbon storage (Tiano et al. 2024, Zhang et al. 2024, Rooze et al. 2024, Bradshaw et al. 2024, Porz et al. 2024). Hung et al. (2024) have provided a baseline estimate of Taiwan's EEZ's blue carbon capacity. Building upon this, integrating trawling-induced sediment disturbance could enhance the precision of carbon budget assessments. Additionally, large-scale offshore wind farm development is underway in the Taiwan Strait and may exclude trawling operations from their original grounds, potentially displacing effort into areas with higher RBS and thereby increasing ecological risks associated with effort redistribution. Future wind farm planning should incorporate trawl impact maps to reduce ecological pressures and enhance cross-sectoral coordination.

Overall, this study combines AIS and VDR data to characterize the spatial distribution of bottom trawling pressure in Taiwan's EEZ and demonstrates how relative benthic impacts can be inferred from fishing effort under conditions of limited local benthic data. By combining quantified trawling pressure with globally synthesized parameters, the analysis provides a first regional assessment of the relative effects of bottom trawling on benthic invertebrate communities in Taiwan's EEZ. These results should therefore be interpreted as spatial inferences of relative benthic

impact based on trawling pressure, rather than direct measurements of actual benthic condition. Nevertheless, this approach remains useful for identifying potential impact hotspots, comparing relative risk across areas, and informing priorities for future monitoring and management in data-limited regions.

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Author contributions

Yi-Jou Lee (Formal Analysis [equal], Investigation [equal], Methodology [equal], Writing—original draft [equal]), and Ray Hilborn (Conceptualization [equal], Supervision [equal], Writing—review & editing [equal])

Supplementary material

Supplementary material is available at *ICES Journal of Marine Science* online.

Conflicts of interest

None declared.

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Data availability

The data underlying this article include publicly available datasets from Global Fishing Watch (globalfishingwatch.org), Marine Regions (marineregions.org), GEBCO (gebco.net), and the Department of Land Administration, Ministry of the Interior, Taiwan (ocean.moi.gov.tw). The Taiwanese vessel VDR data cannot be shared publicly due to data access restrictions and vessel confidentiality requirements.

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