Mexico Baja California Sur blue and brown shrimp – bottom trawl/cast net

Fishery Improvement Project (FIP)

Action 3. Evaluate the impact of fishery on the habitat and on the ecosystem.

One Year Progress Report

October 2025

Task 1. Gather the essential data for evaluating the impact on both the habitat and ecosystem.

As part of this specific FIP Action, a specialized researcher was contracted to assess the Habitat Impact of Artisanal Shrimp Trawling in Bahía Magdalena, Baja California Sur, Mexico. The consultant's technical report is attached as supporting documentation for this action.

The study concludes that the habitat characteristics and species longevity indicate a high level of resilience, demonstrating that the magnitude of the fishery's disturbance remains low and consistent. Overall, the results suggest minimal disruption to the benthic structure and its ecological function, supporting the view that the current level of fishing activity is compatible with the long-term sustainability of the habitat.

Final Report

Consultancy title: ``Assessment of the Habitat Impact of Artisanal Shrimp Trawling in Bahía Magdalena, Baja California Sur, Mexico´´.

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3. Introduction.

Trawling fisheries, both industrial and artisanal, represent a major component of global seafood production. Large-scale bottom trawling contributes roughly one-quarter of global marine fish catches, yet it is usually associated with habitat degradation, high bycatch, and long-term disruption of benthic ecosystems (Amoroso et al., 2018; Hiddink et al., 2017; Sala et al., 2021). Although trawl fisheries are often associated with negative environmental impacts, they can achieve improved sustainability when effectively managed (Hilborn et al., 2023). Measures such as using selective fishing gear, optimizing trawl designs to reduce seabed contact, and implementing spatial or temporal management to protect sensitive habitats can substantially mitigate ecological risks. For example, the bycatch reduction devices (BRDs), turtle excluder devices (TEDs), and mesh size adjustments, have been shown to enhance both ecological and fishery performance (Lively & McKenzie, 2023; Bhanja et al., 2024). Additional innovations, such as semi-pelagic doors, lightweight gear, and real-time vessel monitoring, help reduce seabed damage, while adaptive management integrating habitat sensitivity with fishing effort supports ecological recovery and maintain landing volumes (Lucchetti et al., 2021; Petza et al., 2023; Sin et al., 2024).

Artisanal fisheries, provide over 40% of the global fish supply and support livelihoods in coastal communities, especially in developing regions (Basurto et al., 2025). Artisanal trawling is a widespread small-scale fishing practice in tropical coastal regions, supporting local food security (Batista et al., 2014; Steadman et al., 2021). It can also cause ecological impacts such as habitat degradation, bycatch, and carbon emissions, though it is likely that these impacts are of lower intensity than industrial trawling due to its smaller scale and shorter tow durations (McConnaughey et al., 2020; Hilborn et al., 2023). Regardless of the scale of their impacts, artisanal trawl fisheries—similar to industrial fleets—can achieve sustainability if they are properly managed. However, there remains an urgent need to address the scarcity of quantitative information on small-scale fisheries, which constrains the assessment and implementation of effective management measures (Misund et al., 2002). Moreover, limited access to management resources and policy support further restricts sustainability outcomes and may intensify competition and conflicts with industrial fleets (Batista et al., 2014; Steadman et al., 2021).

Global shrimp production is dominated by aquaculture (~5.6 million t) in comparison with capture fisheries (~3.4 million t), with Asia and Latin America being the major cultured and wild-caught shrimp producers, respectively (Gillett, 2008, de Souza et al., 2021). While shrimp farming and fishing face their own sustainability challenges production is projected to grow in aquaculture, while capture fisheries are expected to remain relatively stable (de Souza et al., 2021). Shrimp production in Mexico is positioned third in terms of volume among all fisheries; however, in terms of economic value, it ranks first. Between 2014 and 2023, the total shrimp production (cultured and fished) has shown fluctuations, reaching a peak of 270,807 t in 2020 and slightly declining to 249,364 t in 2023. The main producing states are **Sinaloa** and **Sonora**, contributing consistently the largest shares, while smaller contributions come from Nayarit, Tamaulipas, Colima, Campeche, Baja California Sur, Veracruz, and Baja California. Over the last decade, the average annual growth rate of shrimp production (cultured and fished) was **5.19%**, reflecting both the expansion and stabilization of shrimp in Mexico (CONAPESCA, 2023).

The shrimp fishery along the Pacific coast of Baja California Sur, Mexico, is a vital economic and social activity, predominantly targeting **blue shrimp (***Penaeus stylirostris***)**, **brown shrimp (***Penaeus californiensis***)**, **white shrimp (***Penaeus vannamei***)**, and **pink shrimp (***Penaeus brevirostris***)** (García-Borbón et al., 2021). The artisanal fishery in the lagoon system of Bahía Magdalena-Almejas is the most important in the state, directly employing around 900 fishermen with 450 small boats and indirectly generating at least another thousand jobs, underscoring its critical role in local employment and community livelihoods (García-Borbón et al., 2021). This fishery operates seasonally from September–October to March–April, with peak catches in the first three months, representing about 70% of total landings (García-Borbón et al., 2021). Although artisanal shrimp fisheries along the Pacific coast represents the most important fishery in Mexico in terms of income and social value, while their ecological impacts remain less studied (García-Borbón et al., 2021).

Evaluating the ecological consequences of trawling is essential for the sustainable management of fisheries, since this information can help to draw a base line and design targeted interventions. As mentioned before, both industrial and artisanal trawling can significantly modify benthic habitats, alter species composition, and influence population dynamics through direct physical disturbance of the seabed and indirect ecosystem effects (Kaiser et al., 2006; Hiddink et al., 2017; Sciberras et al., 2018). Variability in environmental conditions, site-specific habitats, and species population dynamics complicates impact assessment, highlighting the need for standardized methodologies to enable robust, comparable evaluations across regions.

The present technical report addresses this gap by evaluating spatial and temporal effects on benthic habitats using spatial mapping and quantitative analyses of trawling effort, providing evidence-based insights for local fisheries management in the Bahía Magdalena, BCS, Mexico context. The report includes validated fishing zone boundaries; technical profiles of fishing gear; habitat maps; ecological descriptions of typical benthic fauna; simulations of seabed recovery; and the assessments of habitat resilience and vulnerability within artisanal shrimp-influenced fishing grounds.

4. Methodology

Study area characteristics

Bahía Magdalena, located on the Pacific coast of Baja California Sur, Mexico, is the largest lagoon system in the region, encompassing approximately 2,200 km² of shallow waters, mangroves, and wetlands, with depths typically under 20 m and reaching up to 50 m in the main channels (Figure 1). The bay lies within the Magdalena Transition Zone, a biogeographic region influenced by seasonal upwelling, which creates high temporal variability in water temperature and nutrient availability (Cervantes-Duarte et al., 2018).

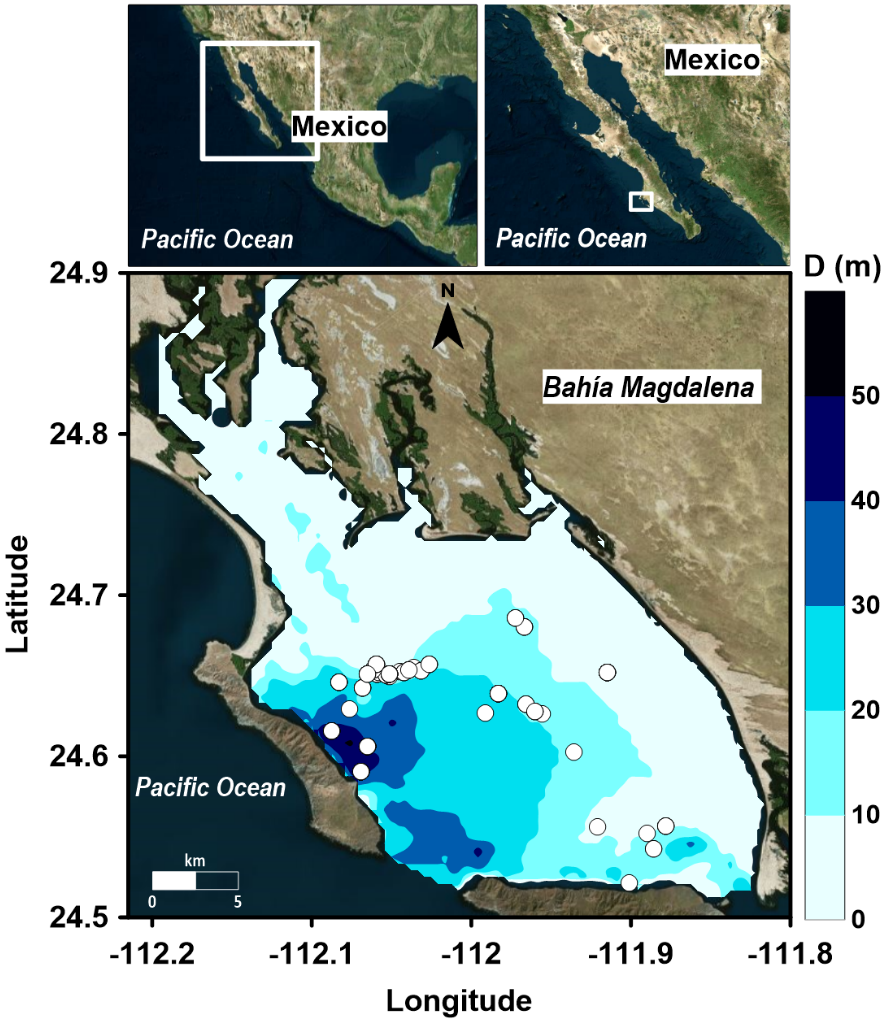

Figure 1. Geographic location of Bahía Magdalena, Baja California Sur, Mexico. Depth (D) in meters; IMIPAS loogbook records (dots).

Ecologically, Bahía Magdalena supports extensive mangrove forests, seagrass beds, and sandy flats that serve as critical nursery habitats for a diverse assemblage of marine species, including fish, crustaceans, mollusks, sea turtles, seabirds, and migratory gray whales (Cruz-Escalona et al., 2017).

The food web structure is characterized by a relatively low connectance index (CI = 0.2), indicating moderate trophic interactions, and is largely controlled by benthic primary producers, which contribute over half of the total ecosystem ascendancy. This indicator reflects the ecosystem's degree of organization and efficiency in processing energy and matter through its trophic network. The high contribution of benthic producers to ascendancy indicates that seafloor primary production underpins a stable, well-structured benthic-dominated food web (Cruz-Escalona et al., 2017).

Economically, the Bahía Magdalena–Almejas system is a major fishing hub in Baja California Sur, accounting for over 50 % of the state's fishery, landings between 2001 and 2013, with both industrial (i.e., small pelagic fishery) and small-scale sectors contributing significantly to employment and income in communities like Puerto San Carlos and Puerto López Mateos (Cota-Nieto et al., 2016).

Major traits and characteristics of the artisanal shrimp fishery in Bahía Magdalena

The shrimp fishery in Bahía Magdalena–Almejas has shown relative stability in its annual catches over the past three decades. Brown shrimp (*Penaeus californiensis*) captures ranged from approximately 3,500 tons in 1990 to 4,200 tons in 1995, maintaining a range of 3,500 to 4,100 tons in subsequent years (García-Martínez & Chávez-Ortiz, 2007; García Borbón, 2009; Borbón, 2019; De la Rosa Meza, 2005; Ramírez-Rodríguez et al., 2011). In contrast, blue shrimp (*Penaeus stylirostris*) exhibited more pronounced variability in its catches. Between 2000 and 2018, blue shrimp captures fluctuated between 401 tons and 2,526 tons, averaging 1,116 tons. The highest captures occurred in the 2014–2015 and 2020–2021 seasons, while the lowest were in the 2000–2001 and 2013–2014 seasons (García-Borbón & Rábago-Quiroz, 2023). This variability in blue shrimp captures may be attributed to environmental factors such as upwelling index, sea surface temperature, and regional circulation, which influence the distribution and recruitment of the species (García Borbón et al., 2023). Regarding relative participation, blue shrimp accounted for an average of 46% of total shrimp captures in the region over the last five seasons, with an increase to 57% in the 2022–2023 season (García-Borbón & Rábago-Quiroz, 2023). This alternation in the abundance of both species reflects the fishery's flexibility to adapt to fluctuations in resource availability.

Shrimp fishing in the Bahía Magdalena lagoon complex targets shrimp using mostly bottom trawl nets deployed from fiberglass vessels measuring 18 to 23 feet in length and powered by 40 to 75 HP outboard engines. Operations occur at night and involve crews of two or three fishers, while fishing takes place between depths of 6 and 50 meters, over muddy, sandy, or silty substrates. Trawling activities are conducted from the stern (De la Rosa-Meza, 2005). The gear is manually retrieved, and the catch is sorted onboard, retaining shrimp and select fin-fish species; the remainder is discarded back to the sea (García-Borbón et al., 1996). In 1999, the Mexican Institute for Sustainable Fisheries and Aquaculture Research (IMIPAS, by its acronym in Spanish) conducted paired comparisons between the traditional "angel wing" net and a new prototype named "Magdalena I" (Annex 1) (García-Borbón, 2019). This new gear type featured a double headline and incorporated both a rigid turtle excluder device (TED) and a fish excluder device (FED). As of 2000, the "Magdalena I" net was officially authorized for shrimp exploitation in the area (Diario Oficial de la Federación, June 2001).

Fishing Gear Characteristics

The “Magdalena I” trawl net is an artisanal fishing gear designed for selective shrimp capture in the Bahía Magdalena–Bahía Almejas lagoon system, Baja California Sur, this net is adapted to the local substrate and fishing depth. (García-Borbón et al., 2019). This net feature a system of trawl doors and a weighted footrope with chains and metal discs, ensuring that the net’s mouth remains in constant contact with the seafloor. The total weight of the footrope and its attachments vary depending on substrate type and fishing conditions, but it is sufficient to maintain bottom contact without causing significant penetration. Penetration into the substrate is generally superficial, limited to the top 1–5 cm of soft sediment, minimizing environmental impact compared to industrial trawls. This design optimizes shrimp capture while reducing bycatch, contributing to more sustainable fishing in the region.

The Magdalena I trawl net, designed for artisanal shrimp fishing in Bahía Magdalena, features a head-rope length of 13.5 m (44.3 ft) and an overall net length of approximately 15.7 m (51.5 ft) (Annex 1a). Constructed from polyamide (PA) or polyethylene (PE) in both mono and multifilament forms, the net incorporates 44.45 mm (1 ¾") mesh in the wings and body and 41.28 mm (1 5/8") mesh in the codend. Its short-tunnel body is achieved through precise panel cuts and layout. To comply with bycatch reduction requirements, as mentioned before, the gear includes a rigid turtle exclusion device (TED) and a fish exclusion device (FED), known locally as “ojo de pescado”, consisting of stainless-steel rods (6.35–15.90 mm thick) shaped into an elliptical frame with a major axis of ≥32 cm, a minor axis of ≥13 cm, and three extensions each measuring 34 cm.

The trawl train (**¡Error! No se encuentra el origen de la referencia.**b) is equipped with a 16 m, 6 mm Ø polyethylene second footrope linked to the lower footrope via bridles at least 20 cm high and spaced no more than 40 cm apart. It also carries 21 sets of 10 cm Ø rubber discs, PVC tubing, and lead weights of 50 g each plus 80 g at both ends. Wooden or sheet-metal doors (1.15 × 0.65 m; max. 13 kg each) provide spreading force during towing. The gear is deployed under strict operating conditions: maximum tow duration of 60 minutes, prohibition of trawling at lagoon mouths, estuary mouths, or river inlets connecting with the bay, and vessel restrictions limiting fishing units to 7.62 m (25 ft) in length with a single net and engines not exceeding 75 HP. Annex 1 (a-d) illustrate the configuration and components of this selective fishing system (Diario Oficial de la Federación, June 2001).

Habitat characteristics review

*Ba*thymetric profiles and sediment type

Bathymetric data used to create contour maps were obtained from the GEBCO Compilation Group (2025). The spatial distribution of phi (φ) values, a logarithmic scale ($\varphi = -\log_2 d$) where coarser grains have lower or negative values and finer grains higher values, was derived from georeferenced data from Rodríguez-Meza (2005), which were interpolated using the Krigging method and displayed as contour maps; all data was analyzed and visualized using QGIS v3.40.4. The characterization and distribution of fine sediments in Bahía Magdalena was described using the georeferenced contour maps described above and complemented with a combination of theoretical criteria, such as hydrodynamic sediment transport models and empirical analyses derived from field observations and granulometric data (Obeso-Nieblas et al., 2007; Rodríguez-Meza et al., 2007; Bizzarro, 2008; Sánchez et al., 2010).

Benthic ecological characteristics

The benthic ecological characteristics of the Bahía Magdalena–Almejas lagoon system were analyzed through a systematic review of published scientific literature, with sources listed in **¡Error! No se encuentra el origen de la referencia.**. This review synthesized data on species abundance, geographic distribution, and life-history traits of key benthic taxa, including polychaetes, economically important and high value mollusk species, and demersal-benthic fishes. By integrating habitat-specific recovery rates, resilience patterns, and species longevity, this approach allowed a comprehensive assessment of the ecological dynamics and recovery potential of benthic communities in response to artisanal trawling.

Validated fishing areas

Data source

As a **representative sample** to characterize area use and the dynamics of fishing activity 186 records of shrimp trawling operations compiled in the IMIPAS logbooks from the shrimp fishing seasons 2022, 2023, and 2024 were used. The following key variables from the logbooks were included in the analysis: geographic coordinates (start and end coordinates per haul); number of hauls; working hours; haul depths and swept area (calculated from data). After analyzing this sample, the results were **scaled using official fishing notices** to represent overall fleet activity. Fishing effort data consisted of the number of effective fishing days per month reported by the artisanal shrimp trawl fleet through catch records (Official landing notices) for the 2022, 2023, and 2024 fishing seasons, available online from CONAPESCA (2025), and listed in the Annex 3. The data include 2457 fishing trips records, corresponding to 72 economical units which operates in the bay area. The distribution of fishing trips per season shows the higher records in the 2023 season (1322), representing the

53.8% of the total; the second behind was the 2024 season (706), with the 28.7% of the records and followed by the 2022 season (429), accounting for the 17.5% of the total fishing trips recorded. The brown and blue shrimp were the most captured species according to the records, with 54.1% and 37.1% of the records respectively. The fishing gear description was taken from government official technical documents (Diario Oficial de la Federación, June 2001).

Classification methodology

The lagoon system was subdivided into four cardinal quadrants using the median latitude and longitude of logbook entries as a central point, assigning each fishing event into four sectors: Northwest, Northeast, Southwest, or Southeast (Figure 2). Building on this, the lagoon system was subdivided into four cardinal fishing areas creating spatially explicit zones that enable precise assessment and support informed management decisions: Northeast (NE), comprising estuarine waters and shallow channels near San Carlos and interior mangroves; Northwest (NW), including northern barrier islands; Southeast (SE), encompassing deeper interior channels near Bahía Almejas; and Southwest (SW), covering deep inner-bay channels influenced by outer coastal areas and Pacific-facing inlets.

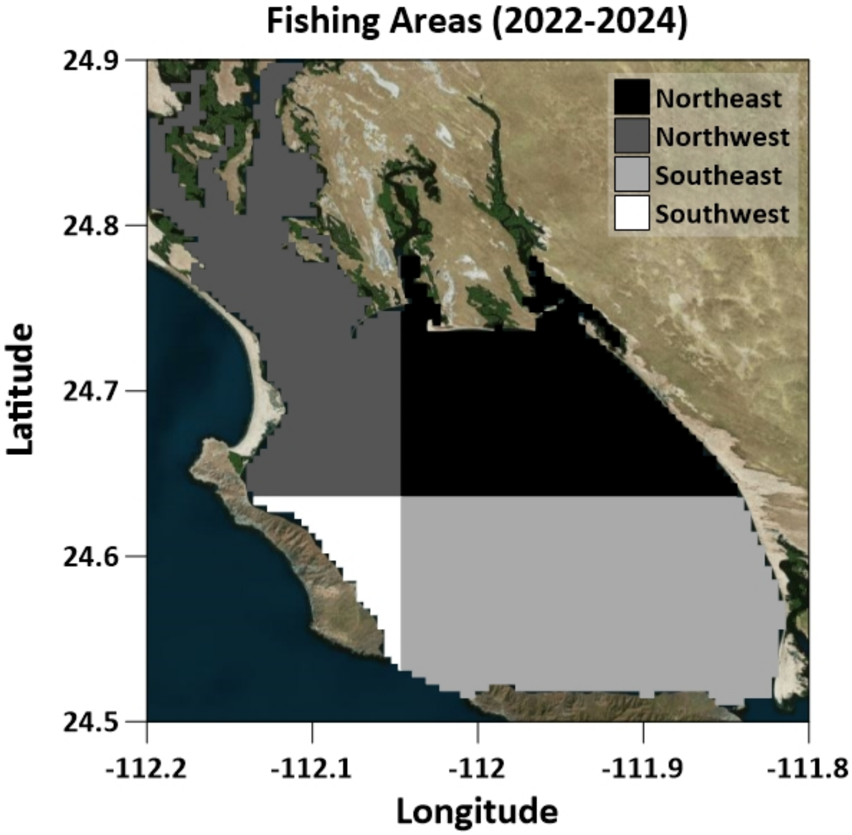

Figure 2. Fishing areas of Bahía Magdalena, BCS, classified into four sectors (NE, NW, SE, SW) based on the median latitude and longitude of logbook entries; shown in grayscale.

Geo-referenced database of fishing effort

Estimation of the Swept Area (SA)

Fishing effort was expressed using the Swept Area method (SA, expressed in km²). Observed SA was spatially reconstructed in a GIS environment based on logbook data from the fishing seasons of 2022, 2023, and 2024, with the sample data subsequently scaled using catch records. A sample track consists of a cleaned GPS trajectory (with initial and final coordinates) showing a vessel towing a fixed-width net in several consecutive tows of defined duration and distance, from which the swept area is calculated as the product of net width and towing distance, then summed across all tows for the day (Figure 3). For each trawl track, the following parameters were analyzed: start and end coordinates, duration, depth, speed, and gear type.

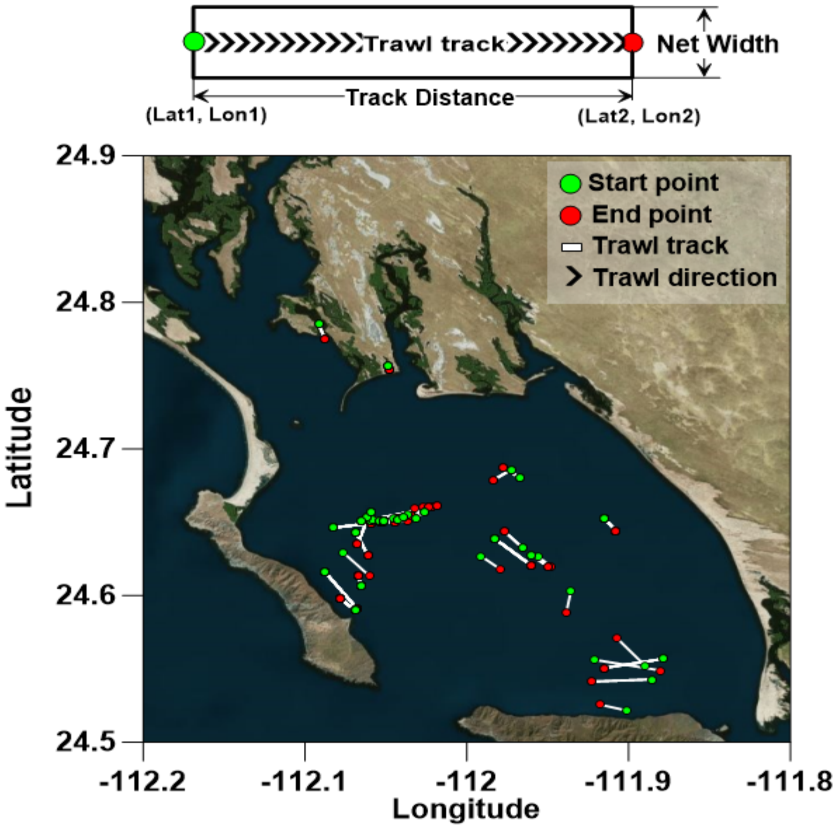

Figure 3. Sample trawl track diagram and map of observed fishing effort based on logbook data from the seasons, prior to scaling with catch records.

The track distance trawled (d) was estimated using the Haversine formula, which calculates the great-circle distance between two geographic coordinates (Noviarianto et al., 2023):

Equation 1:

$$\mathrm{d} = 2\mathrm{R} * \arcsin\left(\sqrt{\sin^2(\frac{\Delta\varphi}{2}) + \cos(\varphi 1) * \cos(\varphi 2) * \sin^2(\frac{\Delta\varphi}{2})}\right)$$

Where d = distance between two points (m), R = Earth's radius (6,371 km), ϕ_1, ϕ_2 = start and end latitudes (radians) and λ_1, λ_2 = start and end longitudes (radians). Swept area was computed by multiplying trawled distance (**d**) by the effective net width of the gear:

Equation 2:

$$\mathrm{SA} = \mathrm{d} * \mathrm{NtW}$$

Where SA = swept area (m^2, later converted to km^2), di = trawl track distance (m), NtW = effective net width of the gear (m).

Estimation of daily, monthly and seasonal observed Swept Area Ratio (SAR).

The total Swept Area Ratio (SAR) for each fishing season of the artisanal shrimp trawl fleet was estimated from direct spatial tracking of trawl operations recorded in fishing activity logbooks (facilitated by IMIPAS), using effective fishing days for the calculation of a SAR-per-day coefficient. The information collected from the logbooks allowed us to characterize the operation and analyze the geographic distribution of fishing effort in the Magdalena Bay area but represents a sample of the actual activity of the artisanal shrimp fleet. The catch data included in the landing notices were used to scale the impact by months during each season, using the effective fishing days as the main variable in the analysis, a methodology described in the following section.

The observed swept area ratio per day (SAR/day) was obtained through spatial reconstruction of trawling operations based on fishing logbooks facilitated by IMIPAS, integrating vessel tracks and trawling activity for each sampled day. For reference and validation, trawl gear specifications were considered, including a trawl width of 16 m, an average towing speed of 4 knots (≈ 7 km/h), and typical daily towing duration, ranging from 4 to 8 hours. For validation purposes, the theoretical swept area per day can be approximated using the formula:

Equation 3

$$\mathrm{SAR/day} = \frac{\mathrm{NtW} * \mathrm{V} * \mathrm{T}}{1{,}000{,}000}\,\mathrm{km}^2/\mathrm{day}$$

where NtW is the trawl width (m), V is the towing speed (km/h), and T is the daily towing duration (hours). For example, with a trawl width of 16 m, a towing speed of 7 km/h, and a towing duration of 6 hours/day, the calculation yields:

Equation 4

$$\mathrm{SAR/day} = \frac{16 * 7 * 6}{1{,}000{,}000} = 0.672\ \mathrm{km}^2/\mathrm{day}$$

In this analysis, however, empirical $\mathrm{SAR/day}$ values obtained from logbook-based spatial tracking are used directly (date, start and end coordinates, duration, gear type), providing more accurate estimates for the artisanal shrimp trawl fleet in Bahía Magdalena.

Estimation procedure.

The monthly swept area ($SARmonth$) was calculated as the product of the effective fishing days in each month ($Dmonth$) and the swept area per day (SAR/day). Effective fishing days per month were calculated from catch data (Annex 3) $SARmonth$ was expressed as:

Equation 5

$$SARmonth = Dmonth * SAR/day$$

where $Dmonth$ represents the number of effective fishing days in the month, and SAR/day is the daily swept area in km², derived from spatial tracking data. Seasonal totals ($SARseason$) were obtained by summing the monthly values for all months within a given fishing season:

Equation 6

$$SARseason = \sum_{\mathrm{month} \in \mathrm{Season}} SARmonth$$

This approach provides cumulative estimates of seabed area impacted by trawling at monthly and seasonal scales.

Benthic Impact Assessment.

The benthic impact of shrimp trawling in Bahía Magdalena was assessed using the MSC Benthic Impacts Tool (BIT), a modeling framework designed to predict the ecological consequences of fishing gear and vessel activity on the seafloor (Whitton & Hiddink, 2023). The tool was developed by the University of Bangor and was published alongside Version 3 of the MSC Fisheries Standard in October 2022 as part of the Fisheries Standard Toolbox, which contains procedures, like risk based methods, that can be used to support the assessment of a fishery against the MSC fisheries standard. The **BIT-derived results predict the impacts of bottom trawling on sedimentary habitats and their potential for recovery** by quantifying the relative intensity of trawling activity and combining it with habitat-specific sensitivity parameters to estimate both the **extent of benthic impact** and the **likelihood of recovery**. These outputs support a **risk-based evaluation of habitat status** under **PI 2.4.1 (Ecosystem outcome)** and enhance the **quality and transparency of habitat information** required for **PI 2.4.3 (Ecosystem information)**, enabling assessors to make more consistent and evidence-based judgments across different fisheries. The BIT user manual and tool can be found in the following links:

1. Benthic Impact Tool https://shiny.bangor.ac.uk/benthic/

2. BIT user manual https://www.msc.org/docs/default-source/default-document-library/for-business/program-documents/chain-of-custody-supporting-documents/msc-benthic-impacts-tool-user-manual.pdf?sfvrsn=a5bd7039_17

Spatial data included habitat layers derived from sediment profiles, fishing effort grids from IMIPAS logbooks and CONAPESCA catch data records (2022, 2023, 2024), and theoretical ecological parameters such as recovery rates and species longevity (Hiddink et al., 2017; Hiddink et al., 2019). All spatial data were harmonized in a GIS environment to allow accurate overlay of fishing footprints and habitat polygons.

The spatial extent of trawling effort was quantified using the **Swept Area Ratio (SAR)** approach at a grid resolution of 0.01º×0.01º, scale of grid-cell sizes typically used (Pitcher et al., 2017). This scale provides sufficient resolution to capture localized fishing effort while ensuring compatibility with habitat classification layers.

Swept Area Ratio per Grid Cell (SARcell)

The BIT-derived swept area ratio was calculated for each grid cell as the proportion of the grid area swept by trawl gear per year (i.e., fishing season):

Equation 7

$$\mathrm{SARcell} = \frac{Aswept}{\mathrm{Acell}}$$

where $\mathrm{SARcell}$ is the swept area ratio for a grid cell (season $^{-1}$), Aswept is the area swept by trawl gear within the grid cell (km²), and Acell is the total grid cell area (km²). This metric quantifies the relative intensity of trawling disturbance on the seafloor surface within each cell.

Proportion of Habitat Overlap (Ph)

The extent of trawling impact on specific habitats was expressed as the proportion of habitat area overlapped by fishing effort:

Equation 8

$$\mathrm{Ph} = \frac{\mathrm{Ofh}}{\mathrm{Ah}} * 100$$

where Ph is the proportion of the total habitat area overlapped by trawling, Ofh is the total area were fishing effort occurs within the habitat polygons (km²), and Ah is the total area of the habitat (km²). The overlap area (Ofh) was estimated by overlaying mapped habitat polygons with the SAR grid, calculating the intersecting area per cell, and summing across all cells. To ensure consistency with actual fishing distribution, cells were weighted by their SAR values, such that grid cells with SAR=0 contributed no overlap. This procedure ensures that the **habitat proportion trawled** (Ph) reflects the share of habitat area exposed to at least one trawling event per year (i.e., grid cells where SAR>0). The approach follows the guidelines of the MSC Benthic Impacts Tool (MSC, 2023) and is consistent with similar applications in benthic status assessments (Pitcher et al., 2017; Hiddink et al., 2017; Katara, 2019).

Depletion rates

The depletion rate (d) represents the fraction of benthic biomass removed per trawl pass, derived from gear penetration depth and sediment type (Hiddink et al., 2017). The BIT provides default generic depletion values for otter trawl gear (0.06), category that includes the *Magdalena I* trawl net used in the fishing activities. This generic d value was modified using SAR, sediment type and depth (integrated into habitat types of map). Habitat types in Bahía Magdalena were assigned to these sediment classes: NE_CSM and SE_CMS as sand, NW_SFM and SW_SMDC as mud. SAR values were then linked to habitat-specific depletion and recovery functions. The estimated d value for each habitat type was as follows: Mud d=0.12, (12% biomass loss per trawl); Sand d=0.05 (5% biomass loss per trawl) (Sciberras et al., 2018; Hiddink et al., 2019 & Pitcher et al., 2022). These values reflect the higher sensitivity of mud habitats compared to sandy substrates. The values of d used in the evaluation are included in the Annex 4.

Recovery rates

Recovery rates are related to the longevity of an organism; species that live longer have a slower recovery rate (Hiddink et al., 2018). Recovery trajectories incorporated sediment stability, species longevity, and turnover rates, using the unimpacted equilibrium state of habitat as base line (Pitcher et al., 2017; Hiddink et al., 2018). A global meta-analysis of comparative studies on trawling impacts estimated the lower confidence interval of recovery (r) for whole benthic communities with a typical longevity distribution to be 0.42 (Hiddink et al., 2017). This value reflects the intrinsic recovery potential of benthic assemblages after disturbance. In the BIT software you have 3 options available for recovery rates, depending on what data and information you have available about the communities in your assessment area. The mentioned options are the *Input longevity distribution parameters*, *Input species data* or *Use a default setting,* the present evaluation was carried out using the default settings option (i.e., r=0.42) since habitat-specific longevity or recovery rates are not available

Relative Benthic Status (RBS)

The Relative Benthic Status (RBS) method provides a quantitative estimate of habitat condition relative to an unfished baseline, offering a data-efficient tool to assess risks to benthic habitats from towed bottom-fishing gears. The approach is derived from the logistic population growth model solved at equilibrium (Pitcher et al., 2017) and integrates fishing intensity, habitat type, and parameters for depletion and recovery. **Relative Benthic Status (RBS)** represents the **percentage of ecological recovery of a habitat toward its unfished state within a year** following a disturbance. The values range from 0 (fully degraded) to 1 (unfished reference) and are calculated for each grid cell using the following equation:

Equation 9

$$\mathrm{RBS} = 1 - \frac{SARcell * d}{r}$$

Where d (Depletion rate) represents the fraction of benthic biomass removed per trawl pass, r (Recovery rate) relates to the ability of the community to recover after disturbance and $\mathrm{SARcell}$ (Swept area ratio) represents the fishing effort calculated for the three seasons al together. Average RBS per habitat was calculated as the mean of all grid cells, while minimum RBS identified the most heavily impacted locations (Pitcher et al., 2017). All outputs were analyzed spatially to produce SAR maps, habitat overlap maps (Ph), and RBS maps, providing a quantitative assessment of trawling impacts and cumulative ecological risk.

Recovery time and MSC score.

Habitat resilience in Bahía Magdalena was assessed by projecting recovery trajectories if the fishing activities were to cease. Relative Benthic Status (RBS), calculated from fishing intensity, habitat type, and depletion (d) and recovery (r) parameters, provided probabilistic estimates of recovery after 20 years. These trajectories informed indicative MSC scores, with higher resilience corresponding to a lower probability of failing to reach 80% of the unfished state (SG100: <20%, SG80: <30%, SG60: <40%, fail: >40%). Finally, the tool estimates the expected recovery time, expressed as the number of years required for biomass to return to 80% of carrying capacity (RBS = 0.8). This was used to generate indicative MSC scores for the outcome status performance indicator of the MSC Fisheries Standard v3.1; 2.3.1.a (MSC, 2021; Whitton & Hiddink, 2023).

Assumptions and limitations.

The analysis assumes that the IMIPAS logbook sample is representative of the fleet dynamics for each season, that fishing gear specifications and trawling behavior are consistent across the fleet or appropriately stratified by vessel type, and that reported days correspond to effective fishing days during which trawling occurred.

In this sense, logbooks from the IMIPAS program (2022, 2023, 2024) provided internal technical documentation and detailed vessel track analyses, allowing for an accurate characterization of operations for part of the fleet. These logbooks are treated as a representative sample of fishing effort, but having the data for all the artisanal vessels that participate in this fishery is desirable, but they are not obliged to submit logbooks or carry VMS. To address this gap, the spatial resolution of fishing effort was scaled using official catch data available online, which helped extrapolate fleet-wide activity and estimate the overall impact throughout the zone. This approach may not fully capture fishing activity in other areas that were not represented. On the other hand, concentrating the estimated effort (and therefore potential impact) in specific zones makes the assessment more **precautionary**, reducing the risk of underestimating habitat impacts and supporting more **conservative management decisions**.

Limitations include the assumption of uniform fishing efficiency and constant operation within each effective fishing day, the potential loss of intra-seasonal variability due to monthly effort aggregation, and the lack of explicit accounting for variability in fishing practices or habitat use unless stratified. In addition, the Relative Benthic Status (RBS) calculations rely on recovery and depletion parameters derived from other regions and fleets. As these are not calibrated to Bahía Magdalena's ecological conditions or the specific operational characteristics of the artisanal trawl fleet, results should be interpreted as indicative ranges rather than definitive estimates of benthic impact. Although, applying these **globally standardized default values** to a local fishery may not perfectly match local habitat or species characteristics, they tend to be **conservative**, providing a **precautionary estimate of potential impacts**. The premise that default values in fisheries management are conservative stems from their design to prioritize caution in the face of uncertainty. These values are typically set at the lower end of observed or theoretical ranges to minimize the risk of over-exploitation when specific data are lacking. This precautionary **principle approach**, advocates for management actions that err on the side of safety to prevent potential harm to fish populations and ecosystems (De Bruyn, Murua, & Aranda, 2013; Gerrodette, Dayton, Macinko, & Fogarty, 2002; Garcia, 1994).

Resilient benthic habitats are typically characterized by coarse or mixed sediments, strong hydrodynamic activity, and communities dominated by fast-growing, opportunistic species with high reproductive output and dispersal capacity. These conditions promote rapid recolonization and functional recovery following trawling disturbance. In contrast, vulnerable habitats occur in fine, muddy, low-energy environments that support long-lived, slow-growing, and sessile or burrowing species with limited dispersal, where disturbance leads to prolonged structural damage and slow recovery of ecological functions (Pitcher et al., 2017; Hiddink et al., 2019). The discussion of the vulnerability, recovery and resilience potential of the habitats encountered in the present evaluation was conducted following this rationale.

5. Results

Bathymetric and sediment-based habitat characterization

The bathymetric structure of Bahía Magdalena (Figure 1), ranging from shallow estuarine flats to deep central channels, interacts closely with sediment type, directly influencing the penetration depth of trawl gear and the resilience of benthic habitats. Substrate type were categorized based on dominant sediment classes using the phi (φ) scale (Figure 4).

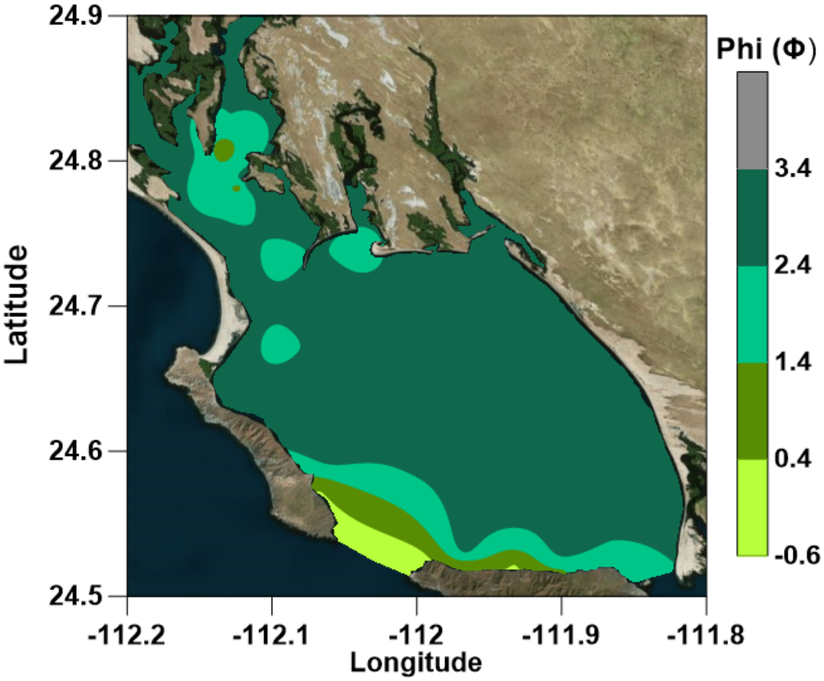

Figure 4. Spatial distribution of dominant sediment types in Bahía Magdalena, classified according to the phi (φ) grain size scale. Colors correspond to phi values, with lower values representing coarser sediments (e.g., sand) and higher values representing finer sediments (e.g., silt and clay)..

Using the bathymetric profiles and the granulometric data and literature findings, an habitat map was compiled, including the classification of bottom types, later used in the analysis of the sensitivity to trawling impacts. Benthic habitats were classified into three categories: sand-dominated, typically found in shallow NE and SE zones; muddy-dominated, prevalent in the deeper NW and SW zones and mixed sediments, dominant in transitional areas. Yhe classification of the habitat was as follows : NE_CSM = Northeast Coarse Sand Mixed; NW_SFM = Northwest Silt and Fine Mud; SE_CMS = Southeast Coarse Marine Sand; SW_SMDC = Southwest Soft Mud Deep Channels (Figure 5).

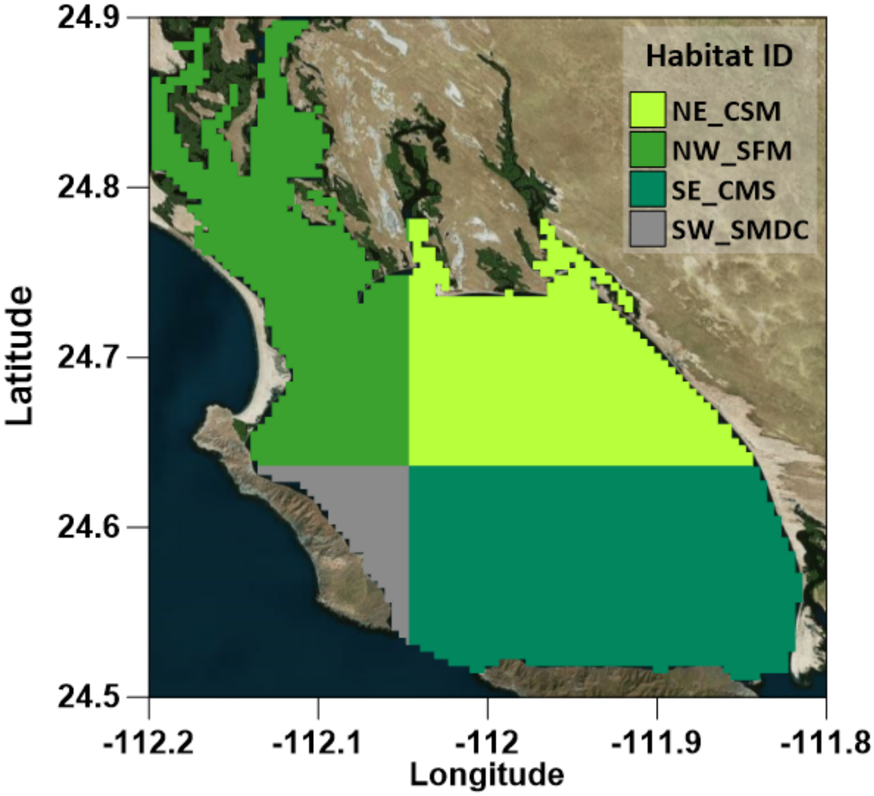

Figure 5. Habitat map of the Magdalena Bay area. NE_CSM = Northeast Coarse Sand Mixed; NW_SFM = Northwest Silt and Fine Mud; SE_CMS = Southeast Coarse Marine Sand; SW_SMDC = Southwest Soft Mud Deep Channels.

Benthic Community Structure and Characteristics

The Bahía Magdalena–Almejas lagoon system exhibits marked spatial heterogeneity in depth, sediment type, and benthic community composition. Depth ranges from shallow estuarine flats (6 m) in the NE to deep central channels (up to 50 m) in the SW, while substrates range from coarse sands to fine muds, which strongly influence trawl gear penetration and benthic resilience (Hiddink et al., 2017).

The Northeast quadrant (NE, 6–20 m) shows shallow flats dominated by coarse marine sands, providing structurally stable habitats that limit trawl penetration. These conditions favor short-lived, fast-growing polychaetes (e.g., Nereididae, Capitellidae), which typically live 1–3 years and recolonize rapidly (0.7–1.0 yr^{-1}), restoring biomass within 0.5–1.4 years (Díaz-Castañeda et al., 2014; Hiddink et al., 2017). Economically important bivalves such as the Catarina scallop (Argopecten ventricosus) and chocolata clam (*Megapitaria squalida*) occur at variable densities. *A. ventricosus* primarily inhabits sandy banks in central and northern sectors, benefiting from stable sediments and high phytoplankton productivity, which enhance larval settlement and growth (Martínez et al., 2000; Morales-Zárate, 2008). Its medium lifespan and relatively early maturation allow moderate recovery rates (~0.13–0.33 yr^{-1}), with populations restoring within 3–8 years under low disturbance conditions (Hiddink et al., 2018). The NE quadrant thus acts as a rapid recovery refuge, supporting both opportunistic polychaetes and moderately resilient bivalves.

The NW quadrant (10–30 m) is characterized by fine muddy sediments and moderate depths near barrier islands. Sediment softness increases susceptibility to trawling, creating highly sensitive habitats. This area supports dense populations of *M. squalida*, pen shells (*Pinna rugosa*, *Atrina maura*), and the chiluda clam (*Panopea globosa*)—the latter representing one of the most economically important bivalves in the region (González-Peláez et al., 2013; Félix-Pico et al., 2024). *P. globosa* inhabits soft-sediment sub-tidal areas (10–25 m), overlapping spatially with the shrimp trawl fishery that operates across muddy bottoms in the northwestern and southwestern sectors of the lagoon. Trawl gear typically penetrates the upper 5–10 cm of the sediment, while *P. globosa* burrows slightly deeper (10–15 cm), indicating partial but significant habitat disturbance. This overlap suggests potential disruption of long-lived bivalve populations, which exhibit low recruitment and slow recovery, typically requiring 5–10 years to restore biomass (Hiddink et al., 2018).

Demersal fishes, including bycatch species such as sanddab (*Citharichthys sordidus*), exhibit intermediate recovery (~2–5 years), whereas long-lived batoids, including the thornback guitarfish (*Platyrhinoidis triseriata*) and **diamond stingray (***Dasyatis dipterura***)**, may require more than 10 years to reestablish populations (Lefebvre et al., 2016; Escobar-Sánchez et al., 2022; Hiddink et al., 2018, 2019). Both elasmobranchs' species are occasionally captured as bycatch in artisanal shrimp trawls, with *D. dipterura* among the most common rays recorded in the lagoon, emphasizing the sensitivity of long-lived species to bottom trawling.

Deeper interior channels in the SE (20–45 m) contain coarse sands but are subjected to lower energy and slower sediment turnover. Benthic assemblages include polychaetes, *A. ventricosus*, and demersal fish, although bivalve densities are lower and patchier than in NE banks (Martínez et al., 2000). Polychaetes recover at moderate rates (~0.4–0.6 yr^{-1}), with biomass restoration in 1.7–2.5 years, while bivalves follow a 3–8-year recovery trajectory depending on local conditions and trawling intensity (Hiddink et al., 2017, 2018; Morales-Zárate, 2008).

The SW quadrant (25–50 m) comprises deep, soft mud channels hosting long-lived species such as *M. squalida*, pen shells, and *P. globosa*. This zone corresponds to the southern limit of *Panopea globosa*'s Pacific distribution, as reported in Bahía Magdalena (24°38′ N), where it replaces the temperate species *P. generosa* (González-Peláez et al., 2013). Sediment softness, low hydrodynamic energy, and the dominance of long-lived organisms result in the slowest recovery rates in the lagoon (~0.1–0.2 yr^{-1}). Key bivalves require 5–10 years to restore populations, and some elasmobranchs may take over 15 years (Hiddink et al., 2018; Félix-Pico et al., 2024). The presence of bycatch species such as the thornback guitarfish and diamond stingray highlights the vulnerability of long-lived, slow-recovering benthic species to artisanal trawl disturbance.

Swept Area Ratio (SAR).

The four-panel figures present monthly maps for each fishing season, illustrating the spatial variation of observed SAR (km^2/month) across Magdalena Bay. Each panel overlays SAR data as colored squares on a satellite image with bathymetric contours, where water depth ranges from shallow (light cyan) to deep (dark blue/black). The SAR color scale spans from white (6 km^2/month) to dark red (108 km^2/month). All data was aggregated by arithmetic sum to a 0.01 decimal degree square grid.

In the 2022 season, the higher fishing effort was concentrated nearshore in moderate depth zones (Figure 6). Spatial patterns reveal peak activity in the northwest bay during October and January, more dispersed effort including eastern bay areas in December, and intensified nearshore trawling around specific points in February. These maps highlight temporal and spatial dynamics of artisanal shrimp trawling effort within the bay.

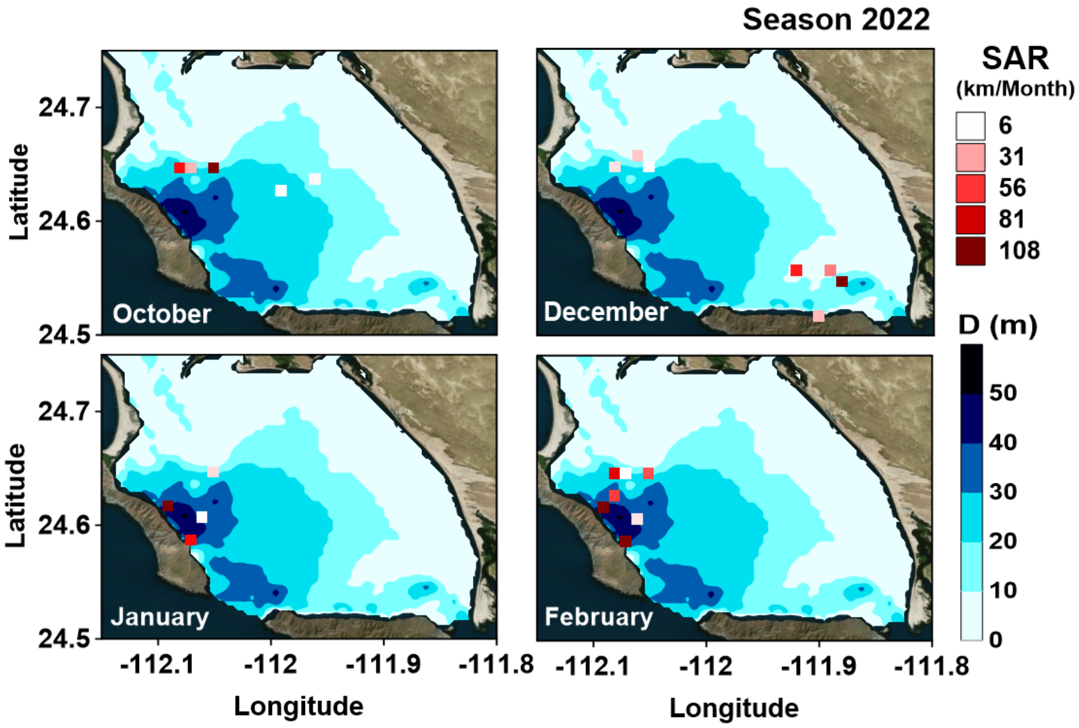

Figure 6. Spatial distribution of observed Swept Area Ratio (SAR) scaled by month during the 2022 artisanal shrimp trawling season in Magdalena Bay. D (m) represents the depth in meters.

In September and October, high SAR values concentrate in the northwest bay, with October showing an extended offshore band of activity for the 2023 fishing season (Figure 7). November displays a more dispersed distribution including eastern bay locations, while December effort is focused closer to shore and along specific depth contours.

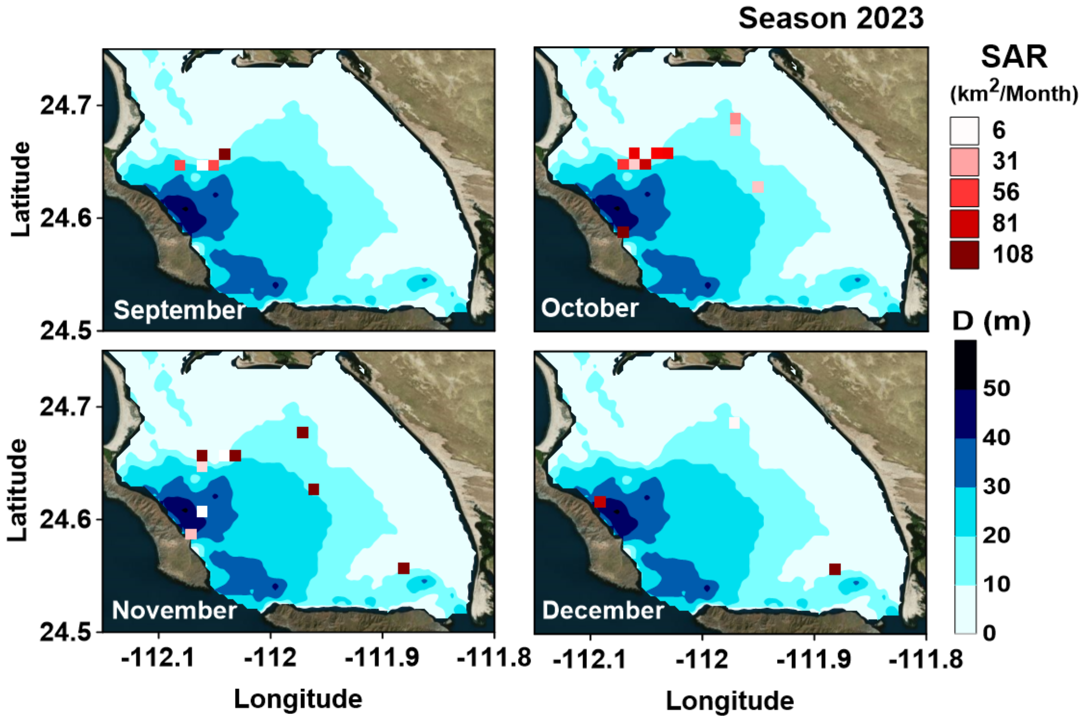

Figure 7. Spatial distribution of observed Swept Area Ratio (SAR) scaled by month during the 2023 artisanal shrimp trawling season in Magdalena Bay.D (m) represents the depth in meters.

In September and October of the 2024 fishing season, effort is concentrated in the northwest bay, with October showing a broader offshore distribution (Figure 9). November activity is more dispersed, including in eastern bay areas, while December effort is focused nearshore in moderate depths.

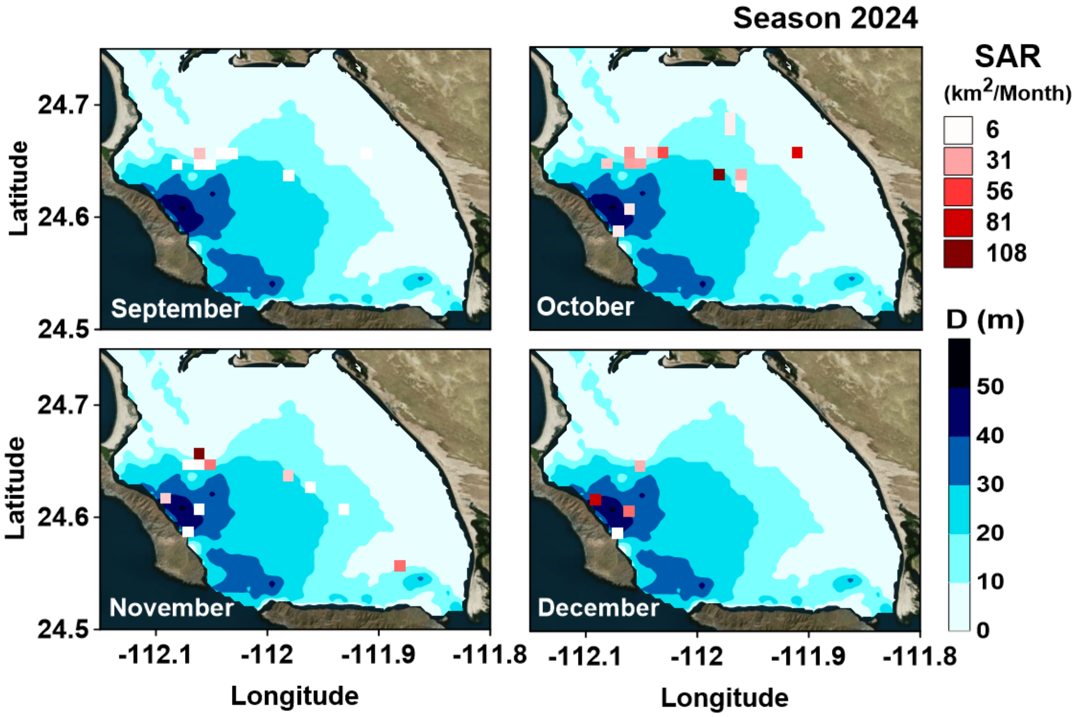

Figure 8. Spatial distribution of observed Swept Area Ratio (SAR) scaled by month during the 2024 artisanal shrimp trawling season in Magdalena Bay. D (m) represents the depth in meters.

The bar plots show the mean of observed SAR (km²/month) across four depth categories: <10 m, 10–20 m, 20–30 m, and >30 m, for the months corresponding to each fishing season: dark purple, cyan, light cyan, and gray-blue. The error bars represent variability in SAR within each category.

The 2022 season fishing patterns indicates that in shallow waters (<10 m) and mid-depths (10–20 m), December recorded the highest fishing effort, markedly exceeding other months (Figure 9). At 20–30 m depths, SAR peaked in February and October, while December was lower. In deeper waters (>30 m), January and February showed moderate SAR, with October and December exhibiting reduced effort.

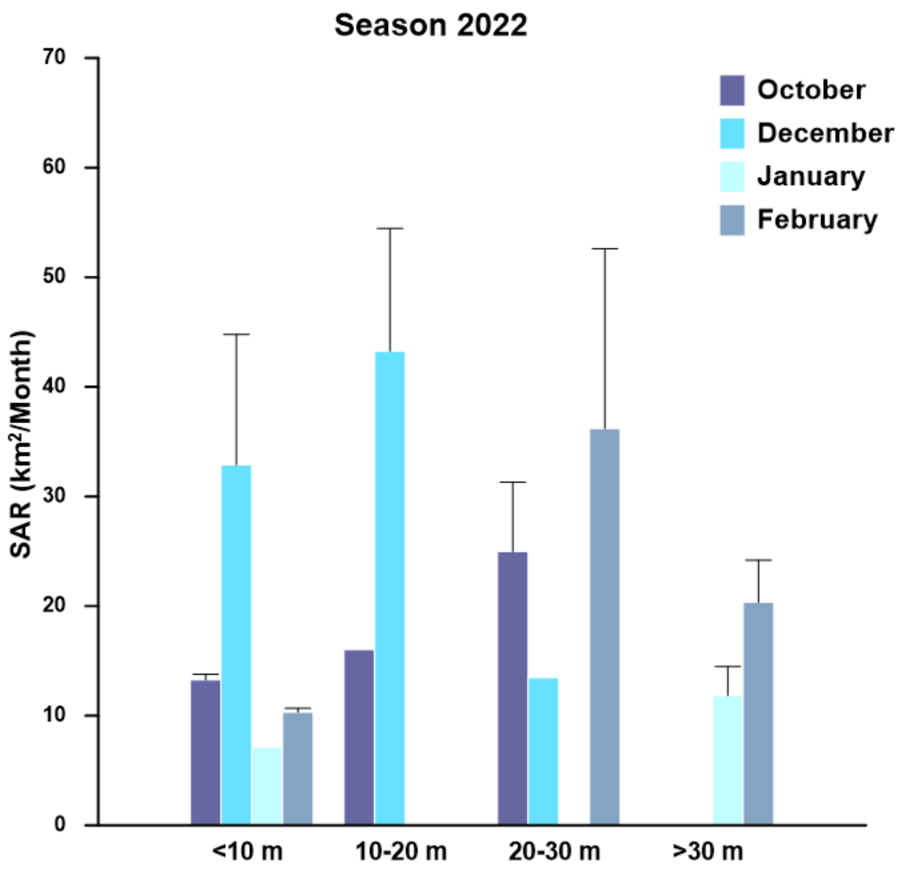

Figure 9. Distribution of Swept Area Rate (SAR) by depth category and month during the 2022 artisanal shrimp trawling season in Magdalena Bay.

For the 2023 fishing season, SAR in shallow waters (<10 m) peaks sharply in November and December, while mid-depth zones (10–20 m) show highest values in October and November (Figure 10). At 20–30 m, SAR is relatively stable across months, with slightly elevated values in September and October. Deep areas (>30 m) show a marked December peak.

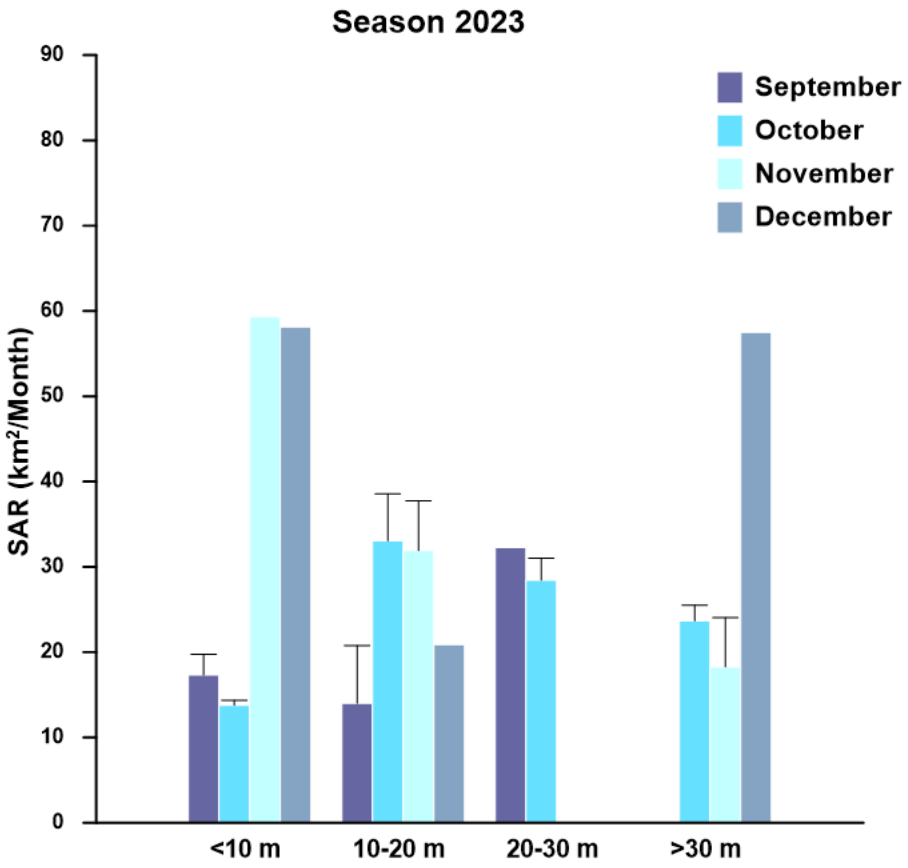

Figure 10. Distribution of Swept Area Ratio (SAR) by depth category and month during the 2023 artisanal shrimp trawling season in Magdalena Bay.

For the 2024 fishing season, November records the highest SAR, followed by October (Figure 11). The 20–30 m category shows pronounced peaks in October and November, while deeper areas (>30 m) exhibit relatively low and stable SAR values throughout the season.

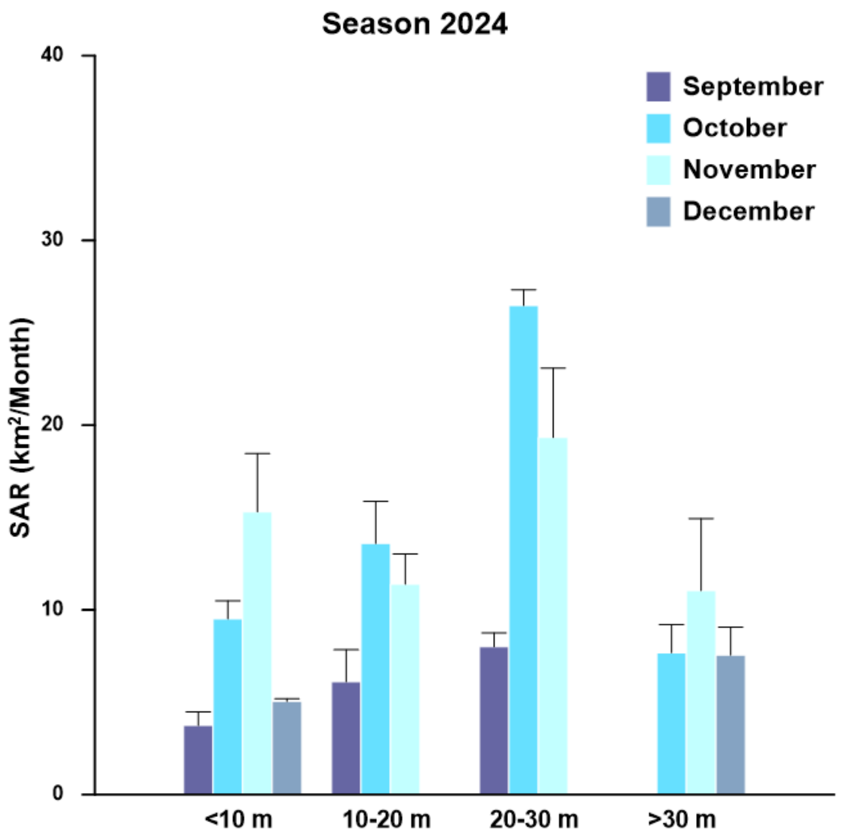

Figure 11. Distribution of Swept Area Rate (SAR) by Depth Category and Month during the 2024 Artisanal Shrimp Trawling Season in Magdalena Bay.

BIT assesstment

Spatial Distribution of cumulative Swept Area Ratio ($SARcell$)

The Swept Area Ratio ($\mathrm{SARcell}$) analysis revealed that shrimp trawling in Magdalena is spatially localized, with the highest intensity concentrated in shallow sandy lagoon channels and nearshore deep mudflats targeted by the artisanal fleet during all the three seasons combined. Figure 12 shows the spatial distribution of the Swept Area Ratio (SAR) during the shrimp seasons. Across that period, most grid cells exhibited low SAR values close to 0 per year, indicating that most of the seafloor experienced infrequent or null disturbance. Peaks of cumulative seasonal SAR (above 400) were observed in narrow fishing corridors, particularly in the SW_SMDC and NW_SFM habitats, where sandy sediments are more accessible and favored by the fleet. On average, the Southwest Soft Mud Deep Channels (SW_SMDC) recorded the highest SAR (16.07), indicating repeated disturbance and multiple seasonal sweeps of the seabed. The Northeast Coarse Sand Mixed (NE_CSM) and Northwest Silt and Fine Mud (NW_SFM) exhibited intermediate SAR values (5.76 and 5.37, respectively), while the Southeast Coarse Marine Sand (SE_CMS) showed the lowest average SAR (2.45). These values confirm that trawling effort is relatively low, not uniformly distributed but disproportionately concentrated in mud-dominated habitats Annex 5).

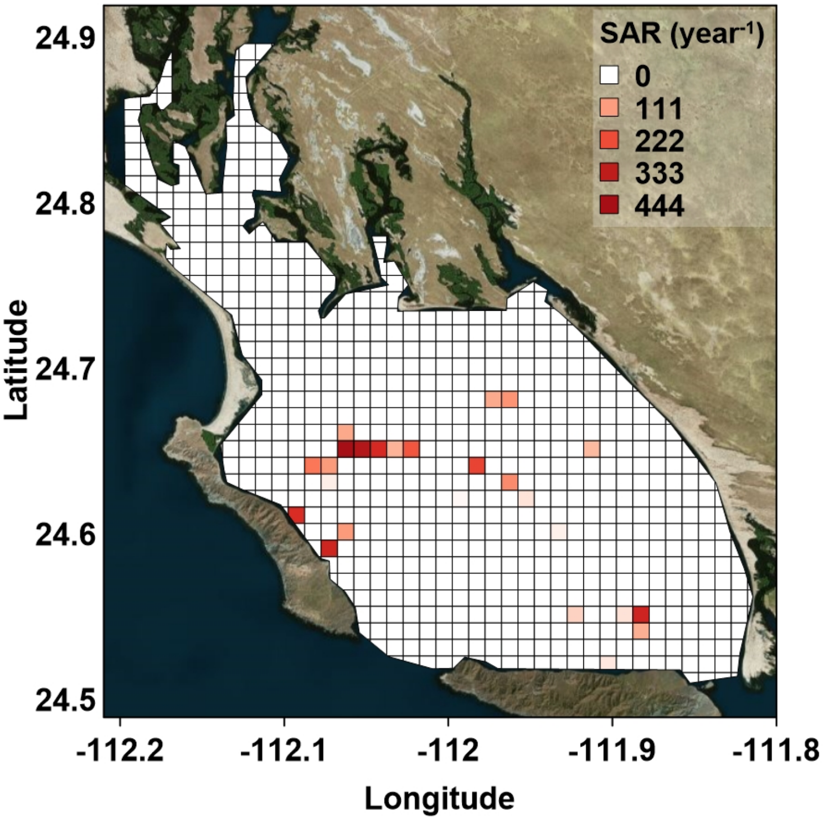

Figure 12 Spatial distribution of cumulative Swept Area Ratio (SAR) for shrimp trawling in Bahía Magdalena, for the seasons of. Darker red shading indicates higher SAR values per grid cell.

Habitat Proportion Overlap (Ph)

Shrimp trawling in Bahía Magdalena (2022, 2023, 2024) was assessed by intersecting swept area ratio (SAR) grids, with habitat polygons. This analysis quantified the common area per habitat and its proportion of overlap with trawling.

Figure 13 presents the proportion of each habitat area trawled at least once per season (Ph). The analysis shows that SW_SMDC had the highest overlap (11.08% of its 38.9 km² area impacted annually). The sandy habitats, NE_CSM and SE_CMS, showed lower overlap proportions (4.13% and 3.36%, respectively), while NW_SFM had the lowest (2.99%). These findings indicate that, although sandy habitats are more extensive, a much higher proportion of mud habitat is persistently exposed to trawling. This persistent trawling overlaps with areas preferred by shrimp (*F. californiensis* and *L. stylirostris*), providing optimal conditions for harvest but also posing risks of habitat degradation (García-Borbón et al., 2021).

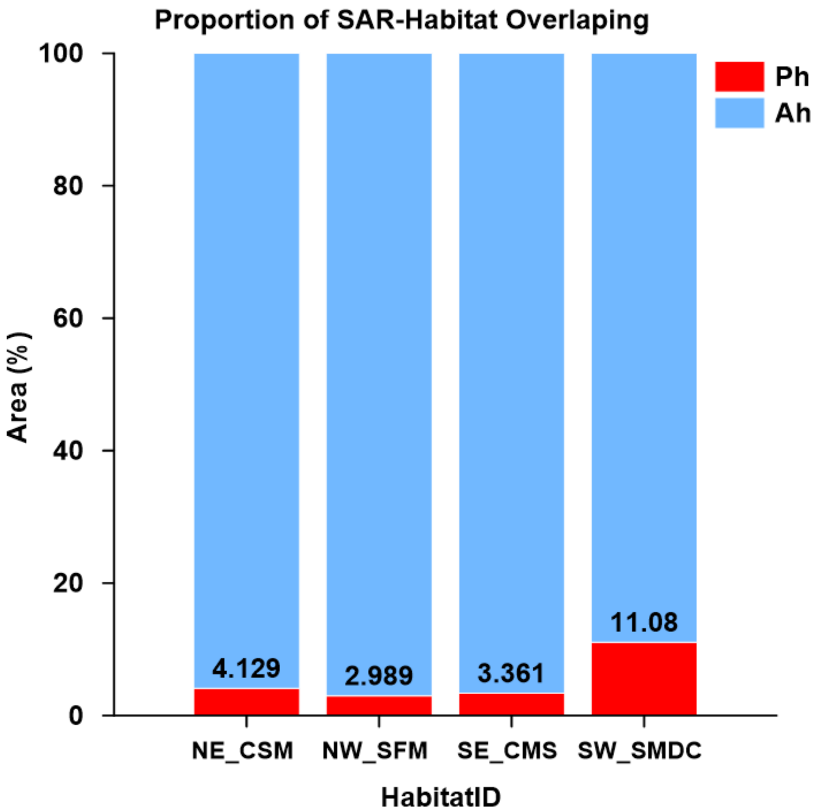

Figure 13. Habitat proportion overlap (Ph), indicating the percentage of each habitat area impacted at least once per year by shrimp trawling. Total habitat area (Ah).

Relative Benthic Status (RBS)

Relative Benthic Status (RBS) was estimated for each grid cell by combining fishing intensity (SAR), habitat type, depletion and recovery parameters. Values range from 0 (degraded) to 1 (unfished baseline). Figure 14 shows the Relative Benthic Status (RBS) across habitats. On average, sandy habitats maintained high benthic integrity, with SE_CMS (0.968) and NW_SFM (0.966) showing the best ecological status, followed by NE_CSM (0.956). In contrast, SW_SMDC exhibited the lowest RBS (0.900), reflecting repeated disturbance.

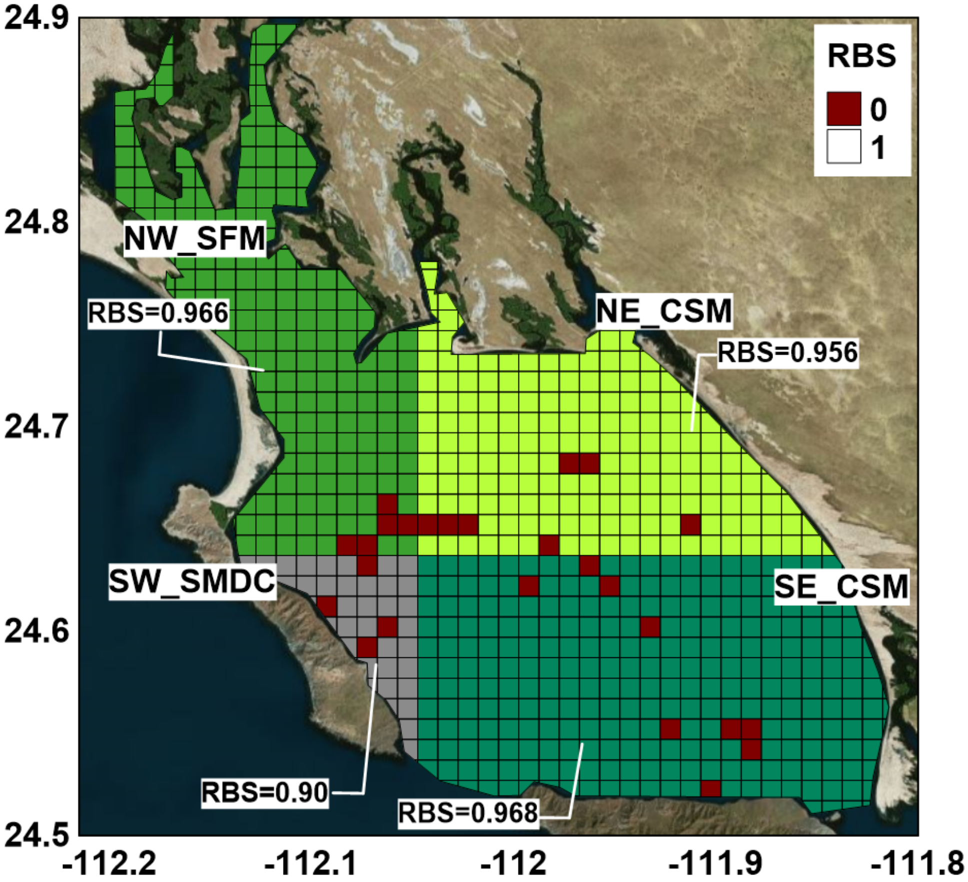

Figure 14. Relative Benthic Status (RBS) map, showing habitat-specific condition and minimum RBS hotspots in Bahía Magdalena, for the shrimp trawling seasons 2022, 2023, 2024. Lower values indicate higher impact: 0 (completely degraded-dark red) to 1 (unfished reference). Habitat categories showed in color as in Figure 5. Square boxes show mean RBS values per habitat.

Habitat-Specific Recovery Trajectories

Habitat resilience in Bahía Magdalena was assessed by projecting recovery trajectories under 20 years ceased fishing period. Relative Benthic Status (RBS), based on fishing intensity, habitat type, depletion (d) and recovery (r) parameters, provided probabilistic estimates of recovery and expected time to reach 80% of habitat natural carrying capacity and unfished undisturbed state. Figure 15 illustrates predicted recovery trajectories for the four dominant habitats within the bay where the fishing activities take place on regular bases.

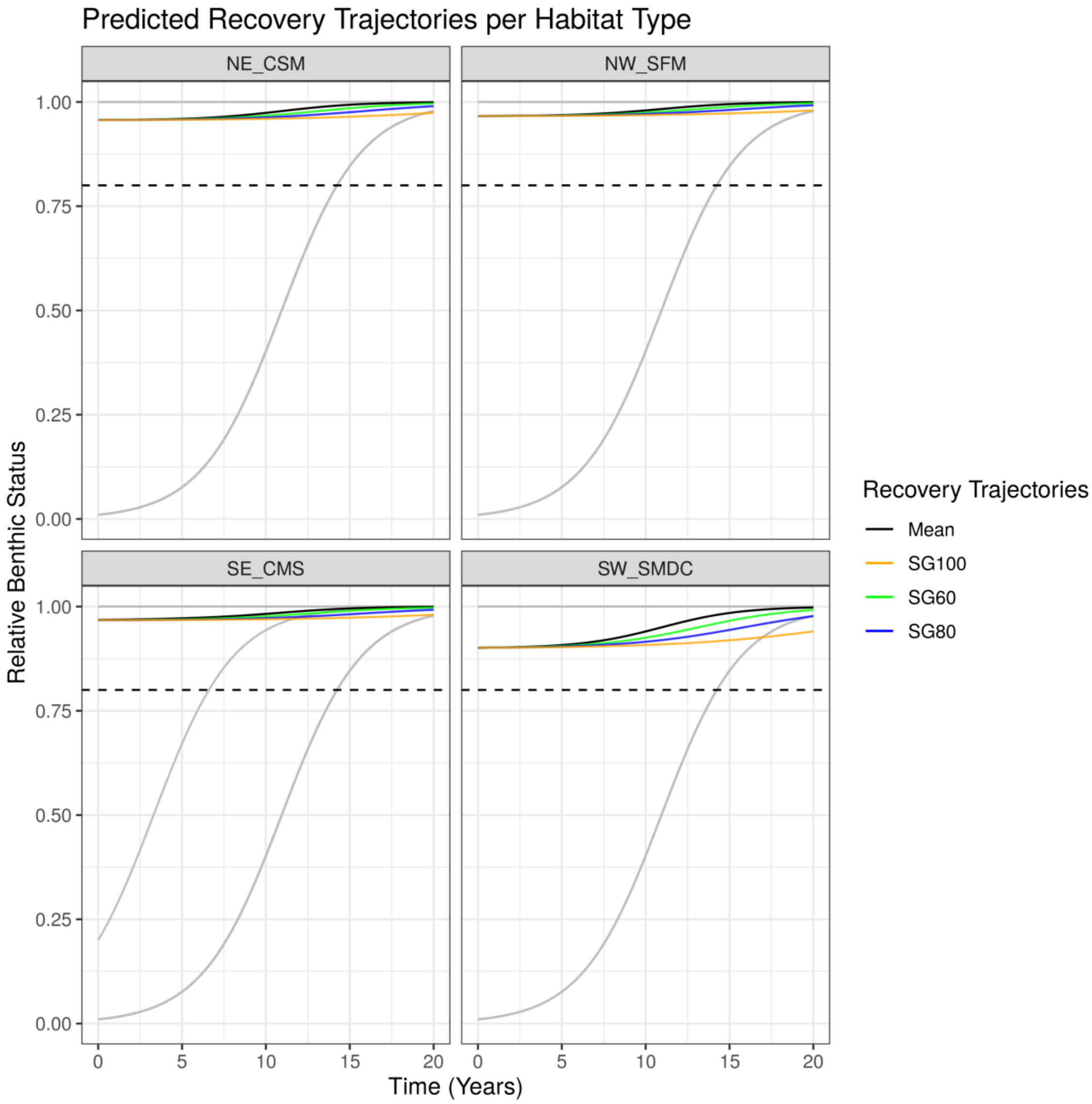

Figure 15. Predicted recovery trajectories per habitat type. Trajectories correspond with BIT based estimated recovery times for 2022, 2023, 2024 shrimp trawling seasons in Bahía Magdalena.

The grey lines illustrate the recovery trajectory for biomass in each individual grid cell affected for the cumulative fishing effort. The black line indicates the mean recovery trajectory of all species biomass together across each habitat. The dashed line indicates an RBS of 0.8, or 80% carrying capacity. Each indicative MSC score relates to uncertainty in the recovery trajectory - to score SG100, there must be high certainty that the species biomass would recover to 80% within 20 years.

The sandy habitats (NE_CSM and SE_CMS) showed the highest resilience, reaching 80% recovery within approximately 7 and 5 years, respectively, and stabilizing above RBS = 0.95 even after disturbance. The NW_SFM habitat recovered more slowly, attaining 80% of baseline after about a decade and stabilizing around RBS ≈ 0.97. In contrast, the SW_SMDC habitat exhibited the lowest resilience, requiring 12–13 years to reach 80% recovery and stabilizing only near RBS ≈ 0.90. These patterns explain the lower RBS values observed in Figure 15 and highlight the higher vulnerability of muddy habitats to cumulative trawling impacts. Nonetheless, all habitats remained above the RBS 80% threshold throughout the analysis period, reflecting the combined effect of high intrinsic resilience and relatively low fishing pressure.

6. Discussion

The SAR metric quantifies the portion of seabed physically contacted by trawl gear and serves as a key indicator of fishing pressure and potential habitat disturbance in coastal and marine spatial planning. While spatially explicit tracking systems such as GPS or Vessel Monitoring Systems (VMS) are ideal for determining trawl footprints, this study employed standardized swept area per day values, obtained from logbook-derived spatial analyses of monitored vessels, allowing extrapolation of cumulative seabed impact across monthly and seasonal scales using catch data from official records of the artisanal shrimp fleet operating in Bahía Magdalena.

The spatial, temporal, and habitat-specific analyses of Swept Area Rate (SAR – observed) reveal detailed patterns of artisanal shrimp trawling in Magdalena Bay across 2022, 2023, 2024 fishing seasons, showing both persistent fishing activity in certain areas and notable seasonal shifts. Fishing effort varied with depth and substrate, and within seasons, reflecting the fleet's adaptive strategy in response to shrimp availability and environmental conditions. In 2022, effort alternated between shallow and mid-depth zones, with occasional forays into deeper areas later in the season. The 2023 season exhibited strong peaks in shallow and mid-depth zones during the middle and late season, while deep-water activity remained limited. In 2024, effort concentrated primarily in mid-depth zones, with seasonal expansions into both shallow and deeper areas. One of the main shrimp fishing sequences occurs in estuarine areas, where juvenile blue and brown shrimp are caught with cast nets and suriperas; this sequence is not included in the analysis as it does not involve trawling (García-Borbón et al., 2021).

Monthly SAR (observed) patterns highlight consistent seasonal dynamics. Early-season trawling consistently concentrated in the northwest bay (NW_SFM) and gradually spread southeastward over time. In 2022, SAR peaked in NW_SFM during October and January, shifted to NE_CSM in December, and moved nearshore by February. The 2023 season began with NW_SFM activity (September–October), including deeper waters inside the bay activity, followed by more diffuse effort in November and concentrated nearshore fishing in SW_SMDC in December. In 2024, early NW_SFM focus gave way to inshore expansion in October, movement toward SE_CMS in November, and nearshore concentration in December. Across all seasons, SAR (observed) values ranged from approximately 6 to 108 km^2/month, illustrating pronounced spatio-temporal shifts in fishing effort shaped by depth, habitat type, and adaptive fleet behavior.

The use of the Benthic Impact Tool provides a complementary and standardized perspective. SAR (BIT-derived) values confirmed the same spatial contrasts observed in the seasonal analysis but expressed them as normalized disturbance rates relative to habitat type. For example, SW_SMDC recorded mean SAR (BIT-derived) values >15, equivalent to multiple annual sweeps, mirroring the SAR (observed) hot spot detected in the same zone. Conversely, SE_CMS sandy habitats averaged <3 in SAR (BIT-derived), reinforcing their low trawling intensity and rapid recovery potential. Together, SAR (observed) and SAR (BIT-derived) validate each other, showing that while pressure is concentrated in specific habitats, the overall scale of the fishery remains within ecological buffering capacity.

Depth and substrate strongly modulated these patterns. Shallow coarse-sand zones like NE_CSM experienced comparatively low SAR (observed and BIT-derived) making them suitable for low-impact harvesting supported rapid recovery due to resilient invertebrate communities and sediments (Díaz-Castañeda et al., 2014; Hiddink et al., 2019). In contrast, muddy and deeper areas such as NW_SFM and SW_SMDC sustained the highest SAR (observed and BIT-derived) and recovered more slowly, highlighting their relative ecological vulnerability. The SE_CMS zone, composed of deeper coarse sand, exhibited moderate SAR (observed and BIT-derived) and recovery potential, representing a balance between fishing activity and benthic resilience.

The distribution of artisanal shrimp trawling effort in Bahía Magdalena closely follows substrate type, with higher effort concentrated on soft-bottom sediments such as sands, silts, and clays, where *Penaeus* species is reported to prefer and reach higher densities and are more susceptible to capture (Hendrickx, 1986, 1996; García-Borbón et al., 1996, 2021). These sediment preferences facilitate both shelter and feeding for shrimp, making fine and mixed sediments the primary targets for the artisanal fleet while coarser sandy areas experience comparatively lower trawling pressure despite supporting shrimp populations.

The evaluation of benthic impacts in Bahía Magdalena highlights how trawling interacts with habitat characteristics to define ecological integrity, resilience, carrying capacity, and recovery after disturbance. By integrating SAR (observed and BIT-derived), Ph, RBS (observed and BIT-derived), recovery trajectories, and MSC scores, habitat-specific risks and management opportunities were identified.

SAR hotspots were detected in the southern lagoon, particularly in SW_SMDC, where mean SAR (observed) reached 16.07, indicating multiple annual sweeps. Such localized intensity is known to cause depletion of long-lived benthic fauna (Hiddink et al., 2019). In contrast, sandy habitats such as SE_CMS experienced much lower SAR (observed) (~2.45), demonstrating uneven distribution of effort across habitats (Rijnsdorp et al., 2018). These findings were reinforced by SAR (BIT-derived) estimates, which provided standardized values that closely matched observed patterns while contextualizing them within habitat-specific recovery dynamics.

Habitat proportion overlap (Ph) results showed that all habitats remained below the 20% threshold, which, according to the Standard's guidance, can justify a score of 100 for "less sensitive" habitats without the need to perform recovery simulations, provided that habitat structure and function are understood to be broadly consistent between fished and unfished areas. (GSA 3.12.4 page 79; MSC, 2024). The highest Ph was in SW_SMDC (11.08%), significant given its small extent, while sandy habitats showed much lower values (<5%).

RBS (observed) values confirmed these patterns. Sandy habitats maintained high ecological integrity (RBS > 0.95), while SW_SMDC recorded the lowest value (0.900). This demonstrates that even below the Ph threshold, sensitive habitats can show cumulative impacts due to slower recovery rates and persistent disturbance (Hiddink et al., 2017; Sciberras et al., 2018). In parallel, RBS (BIT-derived) values confirmed the same trends, but explicitly linked resilience trajectories to benthic community characteristics, further emphasizing the high stability of sandy zones and the increased vulnerability of muddy channels.

The resilience and recovery potential of benthic communities in the Bahía Magdalena–Almejas lagoon are largely governed by sediment type, hydrodynamics, and species life-history traits. Sandy habitats with strong hydrodynamic activity support fast-growing, opportunistic species capable of rapid recolonization, while muddy, low-energy areas harbor long-lived, slow-maturing bivalves and demersal fishes whose recovery is slower but stable over time, reflecting a gradient of ecological resilience across the lagoon system (Pitcher et al., 2017; Díaz-Castañeda et al., 2014; Cruz-Escalona et al., 2017).

The recovery trajectories and habitat condition indicators demonstrate that all benthic habitats in Bahía Magdalena maintain a status consistent with high performance under MSC PIs 2.3.1 (v 3.1) and 2.4.1.(v 2.01) The sandy habitats (NE_CSM and SE_CMS) show the highest resilience, reaching 80% of baseline condition within 5–7 years and stabilizing above RBS = 0.95, suggesting minimal long-term alteration from trawling. The NW_SFM habitat presents moderate resilience, achieving 80% recovery after about a decade and stabilizing near RBS ≈ 0.97, reflecting steady recovery in fine sediment environments. The SW_SMDC habitat exhibits the slowest recovery—12–13 years to reach 80%—consistent with its soft, low-energy muddy composition and higher ecological sensitivity. Despite these differences, all habitats remained above the RBS 0.80 threshold from the initial assessment period, indicating that benthic structure and function remain within acceptable limits of natural variation. These outcomes confirm that even with trawling activity, habitat conditions in Bahía Magdalena remain above the minimum acceptable state expected if fishing were to cease. This favorable situation is supported by a combination of high intrinsic resilience, spatially limited fishing effort, and overall low trawling intensity—meeting the SG100 performance range for habitat outcome indicators.

Overall, the integration of SAR (observed and BIT-derived), Ph, RBS, recovery trajectories, and MSC scores confirms that Bahía Magdalena's habitats are maintaining ecological stability under current fishing pressure. The combined analyses demonstrate that artisanal shrimp trawling, although locally intensive, operates at a scale much smaller than the ecological capacity of the system to absorb disturbance without significant long-term effects. Overall, maintaining current low impact levels and preventing any increase in disturbance represents the most effective approach to ensure the long-term sustainability of Bahía Magdalena's benthic habitats.

7. Conclusions

The artisanal shrimp fishery in Bahía Magdalena–Almejas, targeting brown (*Farfantepenaeus californiensis*) and blue shrimp (*Litopenaeus stylirostris*), has historically operated within a restricted and stable area (García-Martínez & Chávez-Ortiz, 2007; Borbón, 2019; García Borbón et al., 2023). The analysis of trawling patterns demonstrates clear habitat-dependent resilience: shallow sandy areas the associated taxa trend to display rapid recovery (0.5–1.4 years), while muddy, deeper channels could require more than a decade for full recovery of sensitive benthic species. These findings underscore the influence of habitat characteristics and species longevity on resilience, while also showing that the overall magnitude of disturbance from this fishery remains low and consistent, with minimal disruption to benthic structure and function (De la Rosa Meza, 2005; Ramírez-Rodríguez et al., 2011).

The integration of the Benthic Impact Tool (BIT) further strengthens these observations by providing recovery trajectories and resilience estimates that contextualize the artisanal fishery's footprint. BIT outputs confirm that sandy habitats are capable of rapid rebound under the current scale of fishing activity, whereas muddy and deeper habitats show longer recovery trajectories. Importantly, the cumulative disturbance quantified by BIT indicates that overall ecosystem functioning is not compromised, validating that the artisanal fleet's swept area ratio operates within resilience boundaries. Together, the combined evidence reveals that although vulnerability is habitat-specific, the fishery's ecological imprint is modest compared to the system's capacity to absorb and recover from disturbance.

The convergence of observed indicators (SAR, RBS, Ph, MSC scores) with BIT-derived resilience assessments suggests that Bahía Magdalena has a high potential for ecological recovery, with benthic habitats capable of buffering localized pressures from artisanal shrimp trawling. While the fishery concentrates effort in soft-bottom areas, the system's predicted recovery trajectories indicate that trawling impacts are likely to remain limited, supporting compatibility between shrimp harvesting and the bay's long-term ecological stability.

Collectively, the habitat outcome, status, and management indicators demonstrate that Bahía Magdalena's benthic habitats maintain a high level of ecological integrity and resilience, consistent with MSC sustainability benchmarks for trawl fisheries operating within well-managed, low-impact ecosystems.

Ultimately, the application of BIT method of evaluation illustrates the value of integrating standardized, predictive tools into fisheries assessments, moving beyond descriptive analyses to resilience-based management. For this case study, by quantifying recovery trajectories and confirming the robustness of benthic habitats under artisanal trawling, BIT highlights both the sustainability of the current fishing practices and the importance of science-driven approaches to ensure future ecosystem health. The overarching lesson is that tools like BIT empower fisheries science to demonstrate not only the presence of resilience but also the capacity of ecosystems to sustain artisanal fisheries without compromising ecological balance—turning resilience from a theoretical concept into a practical foundation for sustainable management.

8. Recommendations for Improvement

Future assessments should expand fishing effort monitoring by increasing logbook coverage and deploying low-cost tracking tools across as many vessels as possible (at least 20% of the fleet), ensuring the availability and quality of spatial data. Catch reports must be fully integrated with effort data to enhance fleet-wide representativeness.

Experimental studies on gear penetration depth and sediment disturbance would improve understanding of the physical footprint of trawling under local conditions. Currently, the evaluation parameters are based on globally standardized investigations from the industrial fleet, which may overestimate impacts relative to the artisanal fleet. While this does not necessarily underestimate ecological risk, calibrating these parameters to better reflect artisanal practices would enhance the accuracy and representativeness of the results. Additionally, recovery and depletion rates should be adjusted to local benthic habitats through targeted surveys, supported by a more spatially precise description of habitat types across Bahía Magdalena to provide appropriate ecological context. Complementary indicators, such as biodiversity indices and sediment thresholds, should also be incorporated to strengthen the ecological relevance of the assessment.

Regular application of the Benthic Impact Tool as part of the monitoring process, combined with replication of assessments in other regions, will facilitate comparative analyses and support the development of standardized, resilience-based benchmarks for sustainable fisheries management, all conducted under a participatory framework with key stakeholders.

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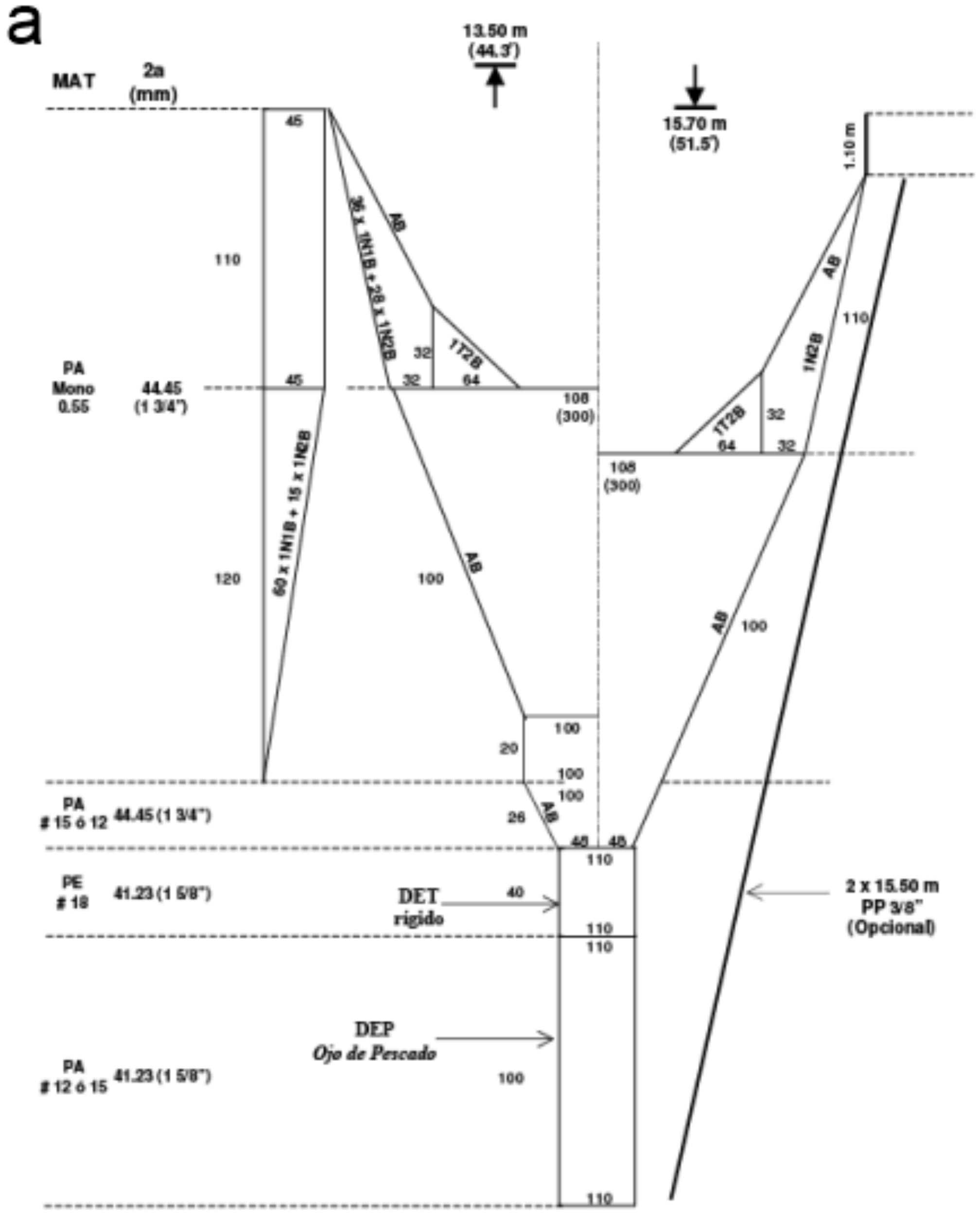
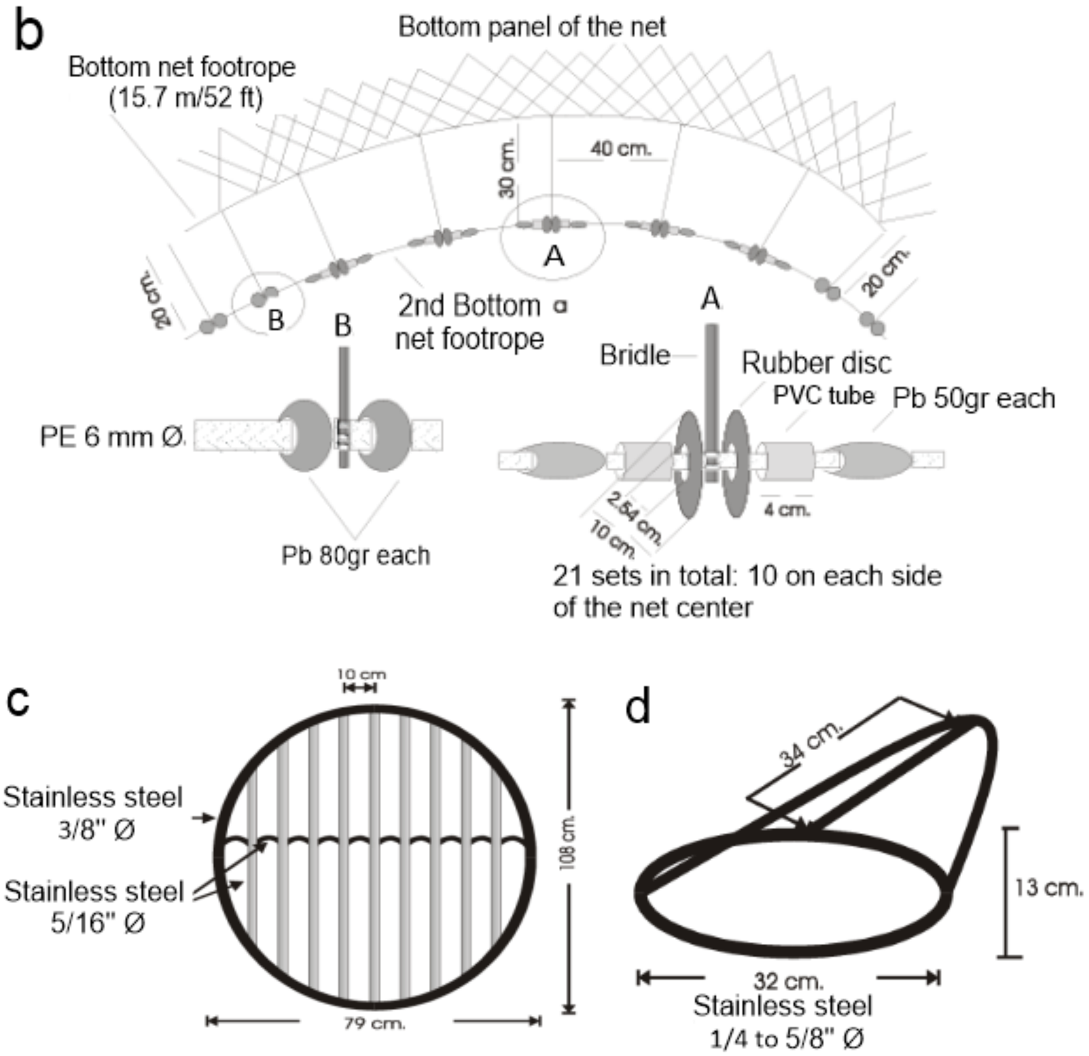
10. Annexes

Annex 1. Diagram of the "Magdalena I" net configuration. a: Technical blueprint. b: Trawl train. c: Turtle Excluder Device (TED). d: Fish Excluder Device (FED) (Modified from Diario Oficial de la Federación, June 2001).





Annex 2. References used for benthic group use in the ecological description of the benthic community of Magdalena Bay.

Group / Taxon	**Aspects Covered**	**Key Reference (Author–Year)**	**Notes & Source Highlights**
Polychaetes / macrobenthos	Abundance & composition	Díaz-Castañeda, de León-González & Solana-Arellano 2014	Species-rich polychaete assemblages; densities reported for sandy vs. muddy habitats; baseline for community structure in Bahía Magdalena.
Polychaetes / macrobenthos	Spatial distribution (habitat)	Bizzarro 2008	Summarizes polychaete-rich soft-bottom communities across lagoon sub-basins and

Group / Taxon	Aspects Covered	Key Reference (Author–Year)	Notes & Source Highlights
			depth zones; sediment type–community linkages.
Polychaetes / macrobenthos	Ecological characteristics (recovery, drivers)	González-Ortiz et al. 2021	Links benthic community changes to sediment type and hydrography; seasonal and environmental drivers shaping polychaete assemblages.
mollusks – Almeja chocolata (*Megapitaria squalida*)	Production trends, abundance	Amezcua-Castro et al. 2015	Fishery trends and production levels in Bahia Magdalena-Almejas; sandy bottom habitat (~2 ind/m²).
mollusks – Almeja catarina (*Argopecten ventricosus*)	Population distribution	Maeda-Martínez et al. 2000–2001	Population distributions across Bahía Magdalena biological activity centers; depth 6–35 m.
mollusks – Almeja catarina (*A. ventricosus*)	Fishery overview, life-cycle/reproduction	Félix-Pico et al. 2024; Jiménez-Quiroz et al. 2021	Seasonal spawning, short lifespan (~1–2 years), fishery gear impacts; commercial importance and resilience.
mollusks – Almeja chiluda (*Panopea generosa*)	Distribution & fishery importance	Rodríguez-Meza 2005; Rodríguez-Meza et al. 2007	Confirms presence in Bahía Magdalena and Gulf of California; habitat and population connectivity.
Fish – Demersal/epibenthic	Abundance (trophic / biomass)	Cruz-Escalona et al. 2017	Quantifies trophic groups including demersal fishes; context for abundance on trawl-able soft bottoms.
Fish – Demersal/epibenthic	Geographic distribution	Bizzarro 2008, Lefebvre et al., 2016; Escobar-Sánchez et al., 2022	Synthesizes distribution of key demersal fishes (sanddab, skates/guitar-fishes) by depth and substrate type.
Fish – Bycatch assemblages	Abundance & composition (trawl-associated)	De la Rosa-Meza 2005	Species lists and relative abundances of bycatch associated with shrimp trawling grounds; ecological co-occurrence data.
Longevity / Recovery traits	Seabed biota depletion & recovery	Hiddink et al. 2017	Relationships between trawling pressure and

Group / Taxon	Aspects Covered	Key Reference (Author–Year)	Notes & Source Highlights
			recovery time; foundational for resilience evaluation.
Longevity / Recovery traits	Longevity-based impact assessment	Hiddink et al. 2019	Community sensitivity to longevity spectra; slow recovery in muddy/deep habitats dominated by long-lived taxa.
Longevity / Recovery traits	Global meta-analysis of benthic recovery	Kaiser et al. 2006	Response and recovery trajectories across gear and habitat types; used to benchmark recovery ranges in Bahía Magdalena.

Annex 3. Effective fishing days per month for the Fishing Season 2022, 2023 and 2024. Data obtained from catch data (CONAPESCA, 2025)

Season	Month	Effective fishing days
2022	OCTUBRE	259
	DICIEMBRE	152
2023	SEPTIEMBRE	358
	OCTUBRE	436
	NOVIEMBRE	404
	DICIEMBRE	396
	ENERO	220
	FEBRERO	278
2024	SEPTIEMBRE	81
	OCTUBRE	223
	NOVIEMBRE	208
	DICIEMBRE	144

Annex 4. Generic and sediment specific depletion rate (d) per habitat type used by the BIT.

Habitat ID	Generic Gear d	Sediment Type	Sediment Specific d
NW_SFM	0.06	mud	0.115
SW_SMDC	0.06	mud	0.115
NE_CSM	0.06	sand	0.047
SE_CMS	0.06	sand	0.047

Annex 5. Summary table of all key habitat-specific results from your data for Bahía Magdalena. SAR: cumulative trawl intensity (higher = more disturbance); Ph: proportion of habitat impacted (higher = more exposure); RBS: ecological status (closer to 1 = healthy, 0 = degraded); Recovery Time: years to reach 80% of unfished baseline.

Habitat	SAR (km²)	Ph (%)	RBS	Recovery Time (yrs)	Vulnerability / Resilience
NE_CSM	5.76	4.13	0.956	7	Low-Medium vulnerability, High resilience
NW_SFM	5.37	2.99	0.966	10	Medium vulnerability, Moderate resilience
SE_CMS	2.45	3.36	0.968	5	Low vulnerability, High resilience
SW_SMDC	16.07	11.08	0.900	12–13	High vulnerability, Low resilience