UNIVERSIDAD AUTÓNOMA DE BAJA CALIFORNIA
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RESILIENCIA DE SISTEMAS SOCIO-ECOLÓGICOS: ANÁLISIS DE INTERACCIONES POTENCIALES ENTRE PESCA INDUSTRIAL Y TORTUGAS MARINAS EN LA ZONA MEDIA DEL GOLFO DE CALIFORNIA

T E S I S

PARTE DE LOS REQUISITOS PARA OBTENER EL GRADO DE

MAESTRA EN CIENCIAS EN OCEANOGRAFÍA COSTERA

PRESENTA

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RESUMEN

Esta investigación se llevó a cabo en la zona media del Golfo de California, abarcando las Reservas de la Biosfera Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes, e Isla San Pedro Mártir. El objetivo fue analizar las interacciones espaciales entre la pesca industrial y las tortugas marinas, combinando dos fases complementarias: una primera enfocada en la caracterización del sistema socioecológico (SES) y una segunda orientada al análisis espacial de zonas de interacción potencial.

Durante la primera fase, se aplicó el Marco General de Ostrom para descomponer el SES en sus componentes fundamentales. El sistema de recursos incluye ecosistemas marino-costeros con alta diversidad biológica y zonas críticas utilizadas por cinco especies de tortugas marinas. Las unidades de recurso se definieron por las poblaciones de tortugas que utilizan la región para alimentación, tránsito o residencia estacional, con énfasis en juveniles de Chelonia mydas. Entre los usuarios se identificaron tres tipos de flotas pesqueras industriales (pelágicos menores, camarón y multiespecie), pescadores ribereños, autoridades ambientales y grupos comunitarios. El sistema de gobernanza abarca normativas pesqueras, decretos de ANP, programas de manejo y esquemas de vigilancia institucional y comunitaria. Se destaca el papel del Grupo Tortuguero de Bahía de los Ángeles como actor clave en el monitoreo local y la participación ciudadana en conservación marina.

La segunda fase consistió en un análisis espacial para identificar zonas de solapamiento entre la actividad pesquera industrial y la distribución de tortugas marinas. Se integraron datos del Sistema de Monitoreo Satelital de Embarcaciones

(VMS), registros científicos, información de monitoreo participativo y conocimiento local, proyectados sobre una cuadrícula uniforme de 1 km de diametro. Se identificaron zonas con alta interacción espacial en Bahía San Rafael y al este de Isla Ángel de la Guarda, donde coinciden rutas de pesca con áreas utilizadas recurrentemente por tortugas. Si bien solo la flota de pelágicos menores cuenta con autorización para operar dentro de las ANP, también se registró actividad de flotas de camarón y multiespecie en zonas restringidas.

Los resultados evidencian que las interacciones potenciales entre pesca industrial y tortugas marinas están espacialmente concentradas y vinculadas a zonas permitidas de pesca, lo que plantea retos para la vigilancia y el cumplimiento de normativas. La integración de herramientas de análisis socioecológico, monitoreo satelital y participación comunitaria aporta elementos técnicos para mejorar la planificación espacial marina, orientar el manejo adaptativo y reforzar la conservación de especies protegidas dentro de las Áreas Naturales Protegidas del Golfo de California.

Palabras clave: sistema socioecológico, análisis espacial, manejo adaptativo, gobernanza.

ABSTRACT

This research was conducted in the mid-Gulf of California region, encompassing two marine protected areas (MPAs): the Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes Biosphere Reserve, and the Isla San Pedro Mártir Biosphere Reserve. The objective was to analyze spatial interactions between industrial fishing and sea turtles through two complementary phases: a socio-ecological system (SES) characterization, and a spatial analysis of potential interaction zones.

In the first phase, Ostrom's General Framework was applied to break down the SES into key components. The resource system includes diverse marine-coastal ecosystems and critical habitats used by five sea turtle species. The resource units were defined by sea turtle populations that rely on the area for foraging, migration, or seasonal residency, with an emphasis on juvenile green turtles (Chelonia mydas). Identified users included three types of industrial fleets (small pelagics, shrimp, and multispecies), artisanal fishers, environmental authorities, and community groups. The governance system comprises fisheries regulations, MPA management programs, and institutional and community-based surveillance. The Tortuguero Group of Bahía de los Ángeles plays a key role in participatory monitoring and local conservation initiatives.

The second phase involved a spatial analysis to identify overlap between industrial fishing activity and sea turtle distribution. Data from the Vessel Monitoring System (VMS), ecological records, participatory monitoring, and local knowledge were integrated over a standardized 1 km^2 hexagonal grid. Results highlighted spatial interaction hotspots in Bahía San Rafael and east of Isla Ángel de la Guarda, where fishing routes coincided with areas frequently used by sea turtles. While only the small pelagics fleet is authorized to operate within the MPAs, activities by shrimp and multispecies fleets were also recorded in restricted areas.

Findings show that potential interactions between industrial fishing and sea turtles are spatially concentrated and often occur within authorized fishing zones, posing challenges for enforcement and regulatory compliance. The integration of socio-ecological analysis, satellite monitoring, and community-based data provides technical

inputs to improve marine spatial planning, guide adaptive management, and strengthen the conservation of protected species within marine protected areas in the Gulf of California.

Keywords: socio-ecological system, sea turtles, industrial fishing, marine protected areas, spatial analysis, governance.

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3. INTRODUCCIÓN GENERAL

La zona media del Golfo de California alberga una de las concentraciones de biodiversidad marina más importantes del Pacífico oriental tropical, lo que ha motivado el establecimiento de múltiples instrumentos de protección ambiental. En esta región se encuentran dos Áreas Naturales Protegidas (ANPs) de alta relevancia: la Reserva de la Biosfera Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes, y la Reserva de la Biosfera Isla San Pedro Mártir (CONANP, 2005; Sandoval-Lugo *et al*., 2020). Ambas forman parte del sistema nacional de ANPs y se caracterizan por una compleja interacción entre ecosistemas marinos altamente productivos, especies protegidas de amplia distribución, comunidades costeras y flotas pesqueras industriales con presencia activa en el área (Danemann y Ezcurra. 2008; Noriega, 2023).

Este espacio ha sido reconocido como hábitat crítico para cinco especies de tortugas marinas: *Chelonia mydas*, *Lepidochelys olivacea*, *Caretta caretta*, *Eretmochelys imbricata* y *Dermochelys coriacea* (Seminoff. 2000). Las tortugas utilizan esta zona tanto para alimentarse y descansar como para migrar, y en menor medida para anidar (Seminoff, *et al*. 2002). La relevancia de estas especies como indicadores ecológicos y su valor como especies sombrilla hacen que su conservación tenga implicaciones amplias para otros componentes del ecosistema (Gallegos-Fernández *et al*., 2023). Sin embargo, su distribución espacial coincide con zonas de pesca industrial activa, lo que genera potenciales interacciones que requieren atención desde una perspectiva integrada (Danemann y Ezcurra. 2008).

El presente trabajo de investigación se estructuró en dos capítulos que, en conjunto, buscan ofrecer una comprensión integral del sistema socioecológico marino presente en la zona media del Golfo de California. El primer capítulo consistió en una caracterización del sistema socioecológico (SES), a partir del marco conceptual propuesto por Ostrom (2009), que permite descomponer la complejidad del sistema en sus componentes principales: sistema de recursos, unidades de recurso, actores o usuarios, y sistema de gobernanza. Esta caracterización fue aplicada a las dos ANPs mencionadas, con énfasis en la interacción entre las tortugas marinas y las actividades pesqueras, principalmente de tipo industrial (Zentner *et al*., 2023). El segundo capítulo consistió en un análisis espacial de las interacciones potenciales entre pesca industrial y tortugas marinas, utilizando herramientas de monitoreo satelital (VMS), registros ecológicos, mapeo participativo y datos comunitarios, consolidado en forma de artículo científico.

Marco conceptual: el sistema socioecológico

El General Framework for Analyzing Sustainability of Social-Ecological Systems de Ostrom (2009) constituye una herramienta robusta para estudiar la sostenibilidad y gobernanza de sistemas complejos. Aplicado a esta investigación, permitió descomponer y analizar de forma estructurada los siguientes elementos:

Sistema de recursos (RS): El sistema de recursos de las ANPs analizadas está constituido por ecosistemas marinos costeros altamente interconectados: praderas de algas, arrecifes rocosos, fondos bentónicos, islas y canales profundos (CONANP, 2007). Esta configuración topográfica y ecológica proporciona hábitats críticos para numerosas especies marinas, incluyendo tortugas, mamíferos, peces y aves

(Danemann y Ezcurra. 2008). Las condiciones oceanográficas específicas de esta región mezcla inducida por vientos, surgencias, batimetría compleja promueven una alta productividad primaria, sustentando redes tróficas que benefician tanto a especies residentes como migratorias (Amador-Castro *et al*., 2021).

La Reserva de la Biosfera Bahía de los Ángeles, junto con Isla San Pedro Mártir, conforma una unidad ecológica funcional que favorece la conectividad entre hábitats de alimentación, tránsito y descanso para las tortugas marinas, en especial *Chelonia mydas*, que encuentra en esta zona abundantes recursos como algas rojas (*Gracilaria*, *Gracilariopsis*), verdes (*Ulva*, *Chaetomorpha*) y pardas (*Sargassum*) (CONANP, 2007).

Unidades de recurso (RU): Las unidades de recurso analizadas fueron las cinco especies de tortugas marinas registradas en la región (Seminoff *et al*., 2002). Se documentaron sus patrones de residencia, alimentación, descanso y tránsito. En el caso de *Chelonia mydas*, se identificaron áreas clave de forrajeo y hibernación, con desplazamientos diarios de entre 4 y 15 km en busca de alimento (Danemann y Ezcurra. 2008). La tortuga golfina ha sido observada en playas como El Rincón y La Mona, donde se han registrado eventos esporádicos de anidación . Por su parte, la tortuga carey utiliza áreas rocosas ricas en esponjas (Martínez-Estévez *et al*., 2021), mientras que *Caretta caretta* y *Dermochelys coriacea* emplean la zona como corredor migratorio y espacio de alimentación (Benson *et al.*, 2011; Bojórquez-Tapia *et al*., 2017.

Se integraron registros científicos, comunitarios y satelitales, así como mapas de rutas migratorias, para representar de manera precisa el uso del espacio por estas especies.

Este análisis permitió establecer con claridad que Bahía de los Ángeles no es únicamente un refugio temporal, sino un espacio funcional para distintas fases del ciclo de vida de las tortugas.

Actores o usuarios (A): La caracterización de actores se centró en las flotas pesqueras industriales que operan en la región. Se analizaron 77 empresas registradas entre 2018 y 2023, con base en datos VMS, permisos y códigos RNP. Se encontró una fuerte presencia de flotas dirigidas a pelágicos menores, camarón y pesca multiespecie, muchas de las cuales figuran con puertos base en estados distintos a Baja California, lo que evidencia una disociación entre el puerto administrativo y el operativo. Esta falta de trazabilidad limita la vigilancia efectiva.

Se detallaron también los tipos de permisos combinados y el acceso práctico a la zona, revelando que la ANP funciona de facto como un sistema de acceso abierto, dada la escasa regulación, fiscalización y claridad normativa. Este hallazgo es relevante para explicar la recurrencia de actividades no autorizadas y la presencia de artes de pesca que no deberían operar en zonas sensibles.

Además, los atributos socioeconómicos de los usuarios muestran una estructura desigual en el acceso y aprovechamiento de los recursos. Grandes empresas integradas verticalmente dominan el mercado, mientras que los usuarios locales cuentan con menor capacidad de incidencia en la toma de decisiones. También se documentó la historia de uso del recurso, incluyendo la transición de la pesca intensiva de tortugas marinas a las actuales prácticas industriales, con una presión creciente sobre especies y ecosistemas clave.

Sistema de gobernanza (GS)

El sistema de gobernanza fue abordado mediante un análisis de los marcos normativos, institucionales y operativos que rigen las actividades dentro del Área Natural Protegida . En el caso de la zona media del Golfo de California que comprende tanto la Reserva de la Biosfera Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes, como la Reserva de la Biosfera Isla San Pedro Mártir, la gobernanza involucra una red compleja de actores federales, estatales, comunitarios y de la sociedad civil.

Entre los actores institucionales formales destacan la Comisión Nacional de Áreas Naturales Protegidas (CONANP), responsable directa del manejo de ambas ANP; la Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT); la Procuraduría Federal de Protección al Ambiente (PROFEPA); la Secretaría de Marina (SEMAR); la Secretaría de Agricultura y Desarrollo Rural (SADER); y la Comisión Nacional de Acuacultura y Pesca (CONAPESCA), encargada de regular las actividades pesqueras. Estas entidades operan bajo marcos legales como la Ley General del Equilibrio Ecológico y la Protección al Ambiente (LGEEPA), la Ley de Pesca y Acuacultura Sustentables, el decreto de creación de las ANP, sus respectivos Programas de Manejo, y normas técnicas específicas como la NOM-062-PESC-2007 (VMS) y la NOM-059-SEMARNAT-2010 (especies en riesgo) (Danemann y Ezcurra. 2008).

No obstante, la sola presencia institucional no garantiza el cumplimiento de los objetivos de conservación. En la práctica, se ha documentado una implementación desigual de las regulaciones, vacíos en la vigilancia, superposición de competencias entre dependencias y limitaciones presupuestales que debilitan la operatividad de los instrumentos de gestión (Guill *et al*., 2019; O'Farrell *et al.*, 2023). Por ejemplo, aunque los datos satelitales de posicionamiento (VMS) son obligatorios en embarcaciones mayores, su uso efectivo como herramienta de control requiere sistemas integrados de verificación, bitácoras electrónicas y validación cruzada que actualmente no están implementados de forma robusta.

En este contexto, adquiere especial relevancia el papel de la sociedad civil organizada y las iniciativas de gobernanza comunitaria. Uno de los actores más importantes en la zona media del Golfo es el Grupo Tortuguero de Bahía de los Ángeles, una organización con más de veinte años de trabajo continuo en monitoreo, conservación y educación ambiental (Danemann y Ezcurra. 2008). Este grupo ha sido clave para generar conocimiento ecológico local sobre las tortugas marinas, identificar áreas de uso crítico (alimentación, descanso, agregación), y desarrollar procesos de vigilancia participativa y sensibilización ambiental tanto con pescadores como con operadores turísticos.

El Grupo Tortuguero realiza monitoreos en agua durante los meses de mayor actividad biológica, mantiene bases de datos propias con observaciones georreferenciadas, y colabora activamente con instituciones académicas, gubernamentales y ONGs para fortalecer estrategias de conservación (Danemann y Ezcurra. 2008). Además, ha impulsado vedas comunitarias, protocolos de código de conducta, formación de jóvenes en educación ambiental, y ha documentado la persistencia de amenazas como la captura incidental y la contaminación marina (Seminoff *et al*., 2002).

Su experiencia no solo aporta datos valiosos, sino que ha generado estructuras locales de corresponsabilidad y vigilancia, que complementan las limitaciones del Estado. A través del diálogo con autoridades, la implementación de recorridos de sensibilización en temporada alta y el fortalecimiento del monitoreo, el Grupo Tortuguero representa un ejemplo concreto de gobernanza adaptativa desde lo local (Danemann y Ezcurra. 2008).

El abordaje detallado del sistema socioecológico en la zona media del Golfo de California, particularmente en las Reservas de la Biosfera Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes e Isla San Pedro Mártir, permitió identificar los principales elementos que configuran la relación entre tortugas marinas y actividades humanas. A partir de este diagnóstico integral se reconocieron los nodos críticos de interacción, las debilidades institucionales en la vigilancia y monitoreo, y la relevancia de la participación comunitaria como componente clave del sistema de gobernanza.

Sobre esta base, el segundo capítulo de la tesis se orienta hacia un análisis técnico-científico más específico, enfocado en la identificación de interacciones espaciales potenciales entre la pesca industrial y las tortugas marinas dentro de ambas ANP. Esta sección, estructurada como un artículo científico, emplea herramientas de análisis geoespacial, datos satelitales de posicionamiento (VMS), registros científicos y monitoreo comunitario para mapear zonas de solapamiento entre hábitats críticos y esfuerzo pesquero.

El estudio considera la operación de distintas flotas industriales (pelágicos menores, camarón y multiespecie), evaluando su coincidencia con áreas utilizadas por cinco especies de tortugas marinas, incluidas zonas de alimentación, tránsito y agregación. El enfoque integrador del artículo no solo revela zonas de posible captura incidental o colisión, sino que además propone insumos concretos para el manejo adaptativo, la planificación marina espacial y la mejora de las estrategias de vigilancia (Lucchetti *et al*., 2016).

Esta transición metodológica y temática entre capítulos refleja el diseño integral del proyecto de tesis: primero comprender el sistema socioecológico en toda su complejidad estructural (actores, recursos, normas), y posteriormente focalizar el análisis en una de las principales fuentes de presión ecológica identificadas: la pesca industrial (Bojórquez-Tapia *et al*., 2017). El conjunto de ambos capítulos busca aportar al conocimiento científico aplicado, ofreciendo herramientas útiles para la toma de decisiones, el fortalecimiento del manejo de Áreas Naturales Protegidas y la conservación efectiva de especies marinas protegidas en el Golfo de California.

4. CAPÍTULO ll

Potential interactions between industrial fishing and sea turtles in marine protected areas of the Gulf of California "the world's aquarium"

Interactions between fishing and sea turtles in MPAs

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Abstract

Using a compilation of historical and recent geospatial data for multicriteria analysis, this study assessed potential interactions between sea turtles and industrial fishing activities within two marine protected areas in the Gulf of California an ecologically significant and biodiverse region. Vessel Monitoring System (VMS) data, local ecological knowledge, data mining, and satellite telemetry were integrated to identify spatial overlaps between industrial fishing grounds and areas of recurrent sea turtle presence. Industrial fleets were categorized into three target fisheries (small pelagics, shrimp, and multispecies) and weighted based on the level of potential interaction with sea turtles. The areas of highest interaction coincided with zones where small pelagic fishing is officially authorized; however, evidence of activity by fleets operating with unauthorized gear was also documented, particularly along the eastern coast of Isla Ángel de la Guarda and in Bahía San Rafael, indicating regulatory noncompliance. These findings highlight the presence of critical habitats that overlap with extractive activities, and underscore the need to revise current management practices. Specific recommendations include participatory monitoring, dynamic or seasonal closures, and targeted studies focusing on particular sea turtle species and fleet types to enhance adaptive management and spatial planning in marine protected areas.

Keywords: Spatial analysis, adaptive management, fisheries planning, Potential interactions, socio-ecological systems.

Highlights

- Spatial analysis revealed overlap between fishing activity and sea turtle habitats
- High potential interaction zones matched areas permitted for small pelagic fishing
- Unauthorized gear types were detected operating within regulated marine areas
- Proposals include dynamic closures and participatory monitoring strategies

1. Introduction

Marine ecosystems are dynamic socio-ecological systems where ecological, economic, cultural, and food security processes converge (Refulio Coronado *et al*., 2021). One of the most pressing challenges for marine sustainability is to balance biodiversity conservation with resource use. Addressing this challenge requires not only the protection of critical habitats, but also the transformation of governance systems towards adaptive, participatory, and evidence-based approaches (Cinner *et al*., 2020).

Industrial fishing is among the most influential human activities affecting these systems. In the Gulf of California, industrial fisheries are a major economic driver both nationally and internationally, in terms of landings and their impact on regional economies (Ojeda-Ruiz *et al*., 2022; Noriega, 2023). Their expansion into biodiversity-rich areas has underscored the urgent need to strengthen monitoring and traceability mechanisms, particularly within and around marine protected areas (MPAs), to ensure long-term ecological sustainability (Arreguín-Sánchez *et al*., 2017; Ramírez *et al*., 2024).

In this context, the concept of socio-ecological resilience is especially relevant. It refers to the capacity of human and ecological systems to adapt and recover from multiple stressors (Folke *et al*., 2010). Promoting resilience in marine governance entails integrating ecological, technological, and social variables into management frameworks that are equitable, efficient, and sustainable (Faulkner *et al*., 2018).

Marine turtles are emblematic and protected species in the Gulf of California, using the region for feeding, migration, and residence. Five species *Chelonia mydas*, *Caretta caretta*, *Lepidochelys olivacea*, *Eretmochelys imbricata*, and *Dermochelys coriacea* have been recorded, all protected under Mexican law and international treaties (DOF, 1990; DOF, 2019; UICN, 2025). Each species exhibits distinct spatial-use patterns depending on life stage, suggesting that their potential interactions with human activities must be analyzed with species-specific considerations.

Potential interactions between sea turtles and industrial fishing are defined here as the spatiotemporal overlap between turtle presence and industrial vessel operations, which may result in bycatch, entanglement, or behavioral disruption (Calderón-Alvarado *et al*., 2023; Wallace *et al*., 2025). While these interactions are not always directly observable, they can be inferred through spatial analysis combining species distribution and fishing effort data (Cuevas *et al*., 2018; Calderón-Alvarado *et al*., 2023). This approach has proven effective in anticipating interactions and supporting decision-making in various international contexts (Putman *et al*., 2020; Cuevas *et al*., 2018).

Globally, numerous studies have documented the effects of industrial fishing gear on sea turtles. Bottom trawl nets, especially those used in shrimp fisheries, are among the most harmful due to high levels of incidental capture (Wallace *et al*., 2013; Wallace *et al*., 2025). Although the use of Turtle Excluder Devices (TEDs) is mandatory in Mexican shrimp trawls (NOM-061-SAG-PESC/SEMARNAT-2016; DOF, 2016), implementation remains weak in some regions, which has led to international sanctions (MND, 2021). Longlines also represent a threat, as turtles can be attracted to the bait and become hooked, often suffering serious injury (Hochscheid *et al*., 2019). Gillnets are particularly dangerous due to their low visibility and passive drift (Vera *et al*., 2021). In addition, high-speed vessel traffic can result in collisions or alter turtle behavior (Work *et al*., 2010; Schoeman *et al*., 2020).

These threats are also evident in Mexico. In the Gulf of Ulloa, interactions between artisanal gillnet fleets and loggerhead turtles (*Caretta caretta*) have led to mortality events and prompted emergency closures, gear modifications, and adjustments in management plans (Bojórquez-Tapia *et al*., 2017). This case demonstrates that even regulated fleets may lead to harmful interactions if not subject to effective, evidence-based monitoring and control measures.

To address these challenges, multiple strategies have been promoted, including the designation of MPAs, certification of fisheries, deployment of satellite-based vessel monitoring, and the engagement of local communities in monitoring efforts (Arafeh-Dalmau *et al*., 2023). However, the effectiveness of these strategies depends on their integration into adaptive governance frameworks. Internationally, the degree of impact varies by gear type, seasonality, operational scale, and intensity (Wallace *et al*., 2013; Wallace *et al*., 2025). Therefore, the use of spatial analysis and remote sensing tools is critical for anticipating potential interacting scenarios (Fuentes *et al*., 2023).

Combining Vessel Monitoring System (VMS) data with species distribution records and local ecological knowledge offers a powerful approach to enhancing spatial planning and maritime surveillance (Chang, 2011). This integration helps identify potential interaction zones between protected species and industrial fleets, contributing to more informed and responsive marine management (Lucchetti *et al*., 2016; Zentner *et al*., 2023).

This study was conducted within a marine polygon located in the mid–Gulf of California, encompassing two UNESCO Biosphere Reserves: Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes, and Isla San Pedro Mártir. These reserves are recognized for their exceptional biodiversity, the presence of endangered species, and their strategic role within the Gulf of California's conservation system (Danemann and Ezcurra, 2007; Soria *et al*., 2014; Villalejo-Fuerte *et al*., 2020; Amador-Castro *et al*., 2021).

In this context, the aim of this study was to spatially analyze potential interactions between industrial fishing activities and sea turtle presence within the mid–Gulf of California polygon, with the objective of informing adaptive management. The study followed a three-step approach: (i) mapping the spatial distribution of sea turtles in the study area; (ii) generating a spatial representation of industrial fishing activities and characterizing their intensity; and (iii) identifying zones of potential interaction based on spatial overlap between the two datasets.

The results provide technical evidence to support spatial planning and decision-making in marine areas under high biodiversity and fishing pressure. Additionally, the proposed methodology offers a replicable model for other regions where extractive activities and conservation goals must coexist, contributing to more transparent, science-based marine governance.

2. Materials and methods

2.1 Study Area

The study area encompasses a marine polygon off the eastern coast of the Baja California Peninsula, covering two federally designated Marine Protected Areas (MPAs): the Bahía de los Ángeles, Canales de Ballenas y de Salsipuedes Biosphere Reserve (RBBDLA) and the Isla San Pedro Mártir Biosphere Reserve (RBISPM) (CONANP, 2005). RBBDLA includes coastal zones, islands, channels, and continental shelf segments near Bahía de los Ángeles. Spanning approximately

3,879.56 km², it was designated in 2007 to preserve marine biodiversity and ecological processes. It is noted for its seasonal upwelling, high primary productivity, and critical roles as feeding and nursery areas for marine species (CONANP, 2005; Danemann & Ezcurra, 2007).

RBISPM, established in 2002 off the coast of Sonora, covers about 302 km² including the island and surrounding marine area. Its ecological value lies in supporting abundant populations of cetaceans, pelagic fish, seabirds, and sea turtles, many of which are nationally and internationally protected (NOM-059-SEMARNAT; CITES; IUCN). Although relatively remote, the area supports artisanal fishing, recreational use, and scientific tourism (CONANP, 2007).

Between the two MPAs lies an unprotected marine corridor. This intermediate zone, ecologically significant as a transit route for sea turtles, pelagic fish, and marine mammals, also experiences regular industrial fishing traffic. It was included in the study as a reference zone to assess spatial interactions both within and outside protected areas.

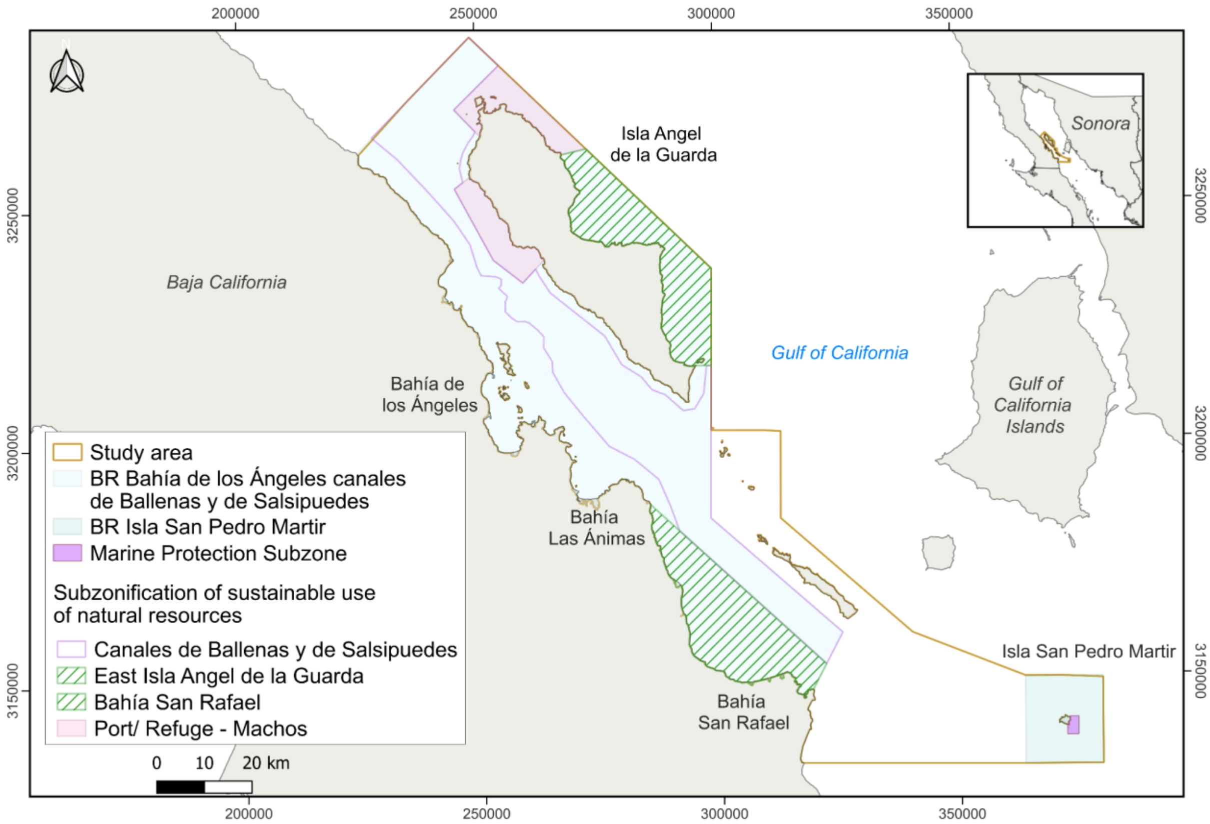


Figure 1. Study area in the central Gulf of California. The brown polygon shows the marine portions of two Natural Protected Areas (NPAs): the Bahía de los Ángeles Reserve (north) and the Isla San Pedro Mártir Reserve (south). The Marine Protection Subzone (dark pink) is exclusive to San Pedro Mártir. The Sustainable Use Subzones (hatched or outlined) are located within Bahía de los Ángeles and include Bahía San Rafael, East Isla Ángel de la Guarda, Canales de Ballenas y de Salsipuedes, and Port / Refuge – Machos.

Both MPAs are managed by CONANP under zoning schemes that balance conservation and human use. Subzones include core, sustainable use, public use, and restoration areas, each with defined activity rules. This zoning, backed by the General Law of Ecological Balance and Environmental Protection (LGEEPA), informed the spatial interpretation of industrial fishing activity and the assessment of compliance within the study area (CONANP, 2005; 2007; Danemann & Ezcurra, 2007).

2.2 Spatial analysis

A hexagonal grid with 1 km diameter cells was used as the base unit to standardize spatial resolution across all layers. This resolution, previously applied in sea turtle distribution studies in the Gulf of Mexico (Uribe-Martínez *et al*., 2021), follows the kernel utilization distribution method originally proposed by Worton (1989), and enables consistent comparisons across datasets. All geospatial analyses were conducted using QGIS 3.28 and RStudio 2023. Three primary spatial layers were generated: (1) sea turtle distribution, (2) industrial fishing activity derived from VMS data, and (3) a potential interaction layer resulting from the weighted combination of the first two.

2.2.1 Sea turtle distribution layer

The spatial distribution of sea turtles was constructed using six complementary data sources, including georeferenced scientific literature, satellite telemetry, community monitoring, and participatory mapping (Table 1). Sixteen published maps of different sea turtle species were georeferenced using QGIS, and local monitoring records (2003–2023) from Grupo Tortuguero de Bahía de los Ángeles were digitized.

Table I. Sources of sea turtle information used in this study, including type of data, species, and primary ecological or management use.

No.	Source	Year	Species	Data type	Primary use
1	Seminoff et al. (2002). Home range *Chelonia mydas* Bahía de los Ángeles	2002	*Chelonia mydas*	Georeferenced MCP	Residence / feeding
2	Hart et al. (2015). Multinational Tagging Efforts	2015	*Chelonia mydas*	Georeferenced migration routes	Migration

3	Sandoval-Lugo et al. (2021). Movements of *Caretta caretta*	2021	*Caretta caretta*	Georeferenced migration routes	Migration
4	Collaborative satellite data (unpublished)	2002	*Chelonia mydas*	Satellite tracking with coordinates	Residence / feeding
5	Grupo Tortuguero Bahía de los Ángeles. In-water monitoring	2003 - 2023	Various species	Presence and abundance records	Presence / feeding
6	Grupo Tortuguero Bahía de los Ángeles. Participatory mapping	2023	Various species	Mapping of key areas	Local knowledge

The dataset integrated known residence areas of *Chelonia mydas* (Seminoff *et al*., 2002), multinational satellite tracks for *C. mydas* (Hart *et al*., 2015), and migration patterns for *Caretta caretta* (Sandoval-Lugo *et al*., 2021). Unpublished tracking data for *C. mydas* (Seminoff *et al*., 2002) and results from participatory mapping conducted in 2023 enriched the ecological coverage with local knowledge.

Each information source was transformed into an individual layer projected onto the 1 km hexagonal grid. Point-based data were aggregated as counts per hexagon, while track-based data were intersected with grid cells. All sublayers were merged to form a unified attribute table.

A differentiated weighting was applied according to the type of spatial use: 0.65 was assigned to records related to residence or foraging, and 0.35 to migratory transit or occasional presence. This weighting is based on empirical data from Seminoff and

Jones (2006), who found that *C. mydas* in Bahía de los Ángeles spend over 68% of their time in foraging areas, while migration comprises less than 32% of activity. These findings support the prioritization of habitats with prolonged use.

Accordingly, a turtle interaction index (**Idx_{iTM}**) was constructed using the following equation:

$$Idx_{TM} = \left(\sum_{n=1}^{4} Area_{Estancia} * \lambda_{Est} \right) + \left(\sum_{m=1}^{2} Conteo_{Mig} * \lambda_{Mig} \right)$$

$Area_{Estancia}$: refers to residence or foraging zones from four independent sources (n = 4), including satellite telemetry, community monitoring, and participatory mapping.

$Conteo_{Mig}$: represents migratory routes or occasional presence events from two sources (m = 2)

$\lambda_{Est/\lambda_{Mig}}$: are weighting coefficients assigned according to spatial use: 0.65 for residence/foraging records and 0.35 for migration/occasional use.

The resulting index generated a continuous spatial layer reflecting the relative presence of sea turtles per analysis cell, with emphasis on habitats with prolonged use. Finally, cumulative values per cell were rescaled between 0 and 1 to standardize magnitudes across sources and avoid biases related to data density or origin. The final product was a layer of weighted density, representing the integrated spatial distribution of sea turtles within the study area.

2.2.2 Industrial fishing activity

Data on fishing activity within the study area were obtained from the Vessel Monitoring System (VMS) managed by the Mexican National Commission of Aquaculture and Fisheries (CONAPESCA) (https://www.gob.mx/conapesca/es/acciones-y-programas/sistema-de-monitoreo-satelital-de-embarcaciones-pesqueras). This open-access system provides georeferenced information on industrial fishing fleets operating in Mexican waters and has been widely applied for monitoring and research (NOM-062-PESC-2007; DOF, 2008).

Matrices covering the period 2018–2023 were downloaded, representing six years of fleet activity in the Gulf of California. These datasets were clipped to the study area using RStudio and filtered to remove non-fishing records. The resulting fishing activity points were then linked to official operational data arrival, landing, and production reports also published by CONAPESCA (https://conapesca.gob.mx/wb/cona/avisos_arribo_cosecha_produccion).

Each VMS entry includes date and time, national fishing registry number (RNP), vessel name, operating company, administrative homeport, latitude, and longitude. By matching records through shared fields (RNP, vessel name, company), each trip was associated with its declared catch, resulting in an integrated dataset that combines spatial and operational attributes, including the reported fishery.

Based on the declared fishery, vessels were classified into three categories:

- Small pelagic: vessels exclusively reporting catches of sardine, mackerel, or other small pelagic species, typically associated with purse seine nets.

- Shrimp: vessels exclusively reporting shrimp catches, usually operating with trawl nets.
- Multispecies: vessels reporting diverse catches, including demersal fish, sharks, rays, jack mackerel, red snapper, and shrimp, suggesting the use of various fishing gears such as longlines, gillnets, or combinations thereof.

This classification enabled an analysis of the diversity of fishing gears employed and their varying potential for interaction with sea turtles.

2.2.3 Classification of activity fishing vs. transit

The final fishing activity matrix was processed following a vessel movement analysis approach, as proposed by Frawley *et al*. (2021), Freitas *et al*. (2012), Uribe-Martínez *et al*. (2021), and Uribe-Sandoval (2025). Records were grouped by trip, chronologically ordered, and speed (km/h) was calculated. Based on operational patterns of industrial fleets in the Gulf of California and descriptive statistics, fishing was defined as speeds ≤1 km/h, while transit involved speeds >1 km/h.

A supervised classification was also conducted on 200 complete trips to validate and refine the methodology. Visual inspection in QGIS revealed typical patterns: active fishing showed semicircular or clustered trajectories, while transit displayed straight or smooth routes (Fig. 2). This review enabled full dataset classification with an estimated accuracy of 75% for fishing and 78% for transit (Anderson *et al*., 2003). Although further refinement is possible, this method provides sufficient confidence for analyzing spatial patterns and potential sea turtle interactions.

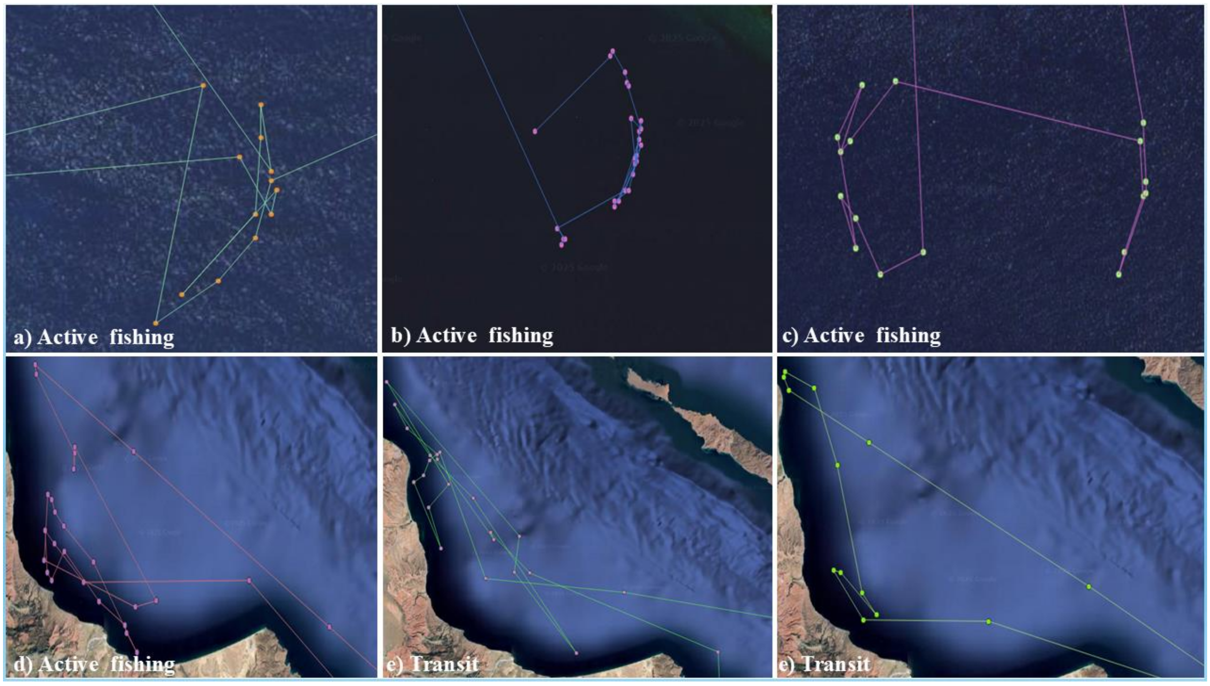


Figure 2. Representative spatial patterns of active fishing and vessel transit. Subfigures a–d illustrate vessel trajectories classified as active fishing, showing spatial concentration, return loops, and semicircular movements typical of purse seine operations by the small pelagic fleet. Subfigures e–f show linear, extended tracks consistent with transit activity. Classification was based on VMS data (2018–2023) processed in QGIS 3.28. Gear types could not be confirmed due to the lack of complementary data (e.g., logbooks or onboard observers).

2.2.4 Spatial analysis and threat weighting

A weighted fishing effort layer was generated from the classified VMS data using the same 1 km hexagonal grid. Records were categorized by fishery type (small pelagics, shrimp, multispecies), activity (fishing vs. transit), and year. Each point received a relative pressure score based on a dual-weighting scheme informed by literature on interaction potential with sea turtles (Wallace *et al.*, 2010):

- **Fishery weights**: small pelagics (purse seines) = 0.14; shrimp (trawls) = 0.50; multispecies (longlines, gillnets, mixed gear) = 0.36.

- **Activity weights**: fishing = 0.65; transit = 0.35.

Final point values were calculated as the product of both weights (e.g., 0.14 × 0.65 = 0.091). These were then rescaled to a 0–1 range to ensure comparability across spatial layers. The resulting output represents a continuous, weighted estimate of fishing pressure, accounting for gear type and operational phase.

2.3 Potential interactions

The final interaction layer was generated by spatially combining the two previously constructed layers: weighted sea turtle distribution and weighted industrial fishing effort. Both layers had normalized values (0–1) within the same hexagonal grid.

For each cell, potential interaction (PI_i) was calculated as:

Ec.(A.2) $$\mathbf{PI_i = TM_i \times FE_i}$$

Where $\mathbf{TM_i}$ is the weighted sea turtle value and $\mathbf{FE_i}$ is the cumulative fishing effort value, including both fishing and transit activities.

This approach assumes that both operational phases exert complementary pressures on sea turtles: active fishing entails the possibility of incidental capture, while transit may contribute to behavioral disturbance, underwater noise, or collisions. Therefore, cumulative effort was used to reflect the full spatial footprint of industrial fishing.

By multiplying both layers, the index highlights areas of significant spatial overlap, where the likelihood of potential interactions is greater, and downplays areas where one or both variables are low. Final values were not rescaled to preserve their relative magnitude.

Table 2. Score categories of potential interaction values between industrial fishing effort and sea turtle distribution.

Value range	Interaction potential
0 -0.042	Moderate
>0.042 -0.129	Intermediate
>0.129 -0.315	Elevated
>0.315 -0.799	High

3.1 Sea turtles distribution

Sea turtle presence was documented throughout the marine corridor connecting the RBBDLA and RBISPM, occupying 20.49% of the study area. The species recorded include *C. caretta*, *L. olivacea*, *E. imbricata*, *D. coriacea*, and *C. mydas*, the latter showing the broadest spatial representation, particularly in coastal and insular foraging areas.

Transit routes of *C. mydas* and *C. caretta* were also identified across oceanic regions between both MPAs, highlighting their broad spatial use. Although these tracks had limited coverage, they suggest active use of the area by highly mobile individuals.

Participatory mapping allowed to document recurrent sightings of *C. mydas* near the coast and occasional records of *D. coriacea* and *E. imbricata* offshore. While the data reflects presence/absence rather than abundance, the convergence of sources strengthens the reliability of key areas identified.

The spatial analysis of the integrated layer (Fig. 3) revealed high weighted presence values in the northern coastal area of Bahía de los Ángeles, within the bay near the town, in the Canal de Ballenas, and south of Bahía San Rafael areas with more frequent turtle records.

Intermediate values appeared in coastal and insular regions such as Bahía Las Ánimas, Isla Ángel de la Guarda, and the unprotected marine strip between both MPAs. Lower values (blue) were distributed across most of the polygon and should not be interpreted as absence, but rather as areas with fewer records or reduced monitoring effort. **Figure 3.** Relative distribution of sea turtles in the study area. The map integrates six independent data sources. High-density areas (red) are concentrated in the northern coast of Bahía de los Ángeles, the Canal de Ballenas, and southern Bahía San Rafael. Intermediate values (green and orange) are observed in coastal and insular zones such as Bahía Las Ánimas, the southern tip of Isla Ángel de la Guarda, and the marine corridor between the Bahía de los Ángeles and San Pedro Mártir reserves. Low values (light blue) correspond to areas with limited monitoring and should not be interpreted as turtle absence.

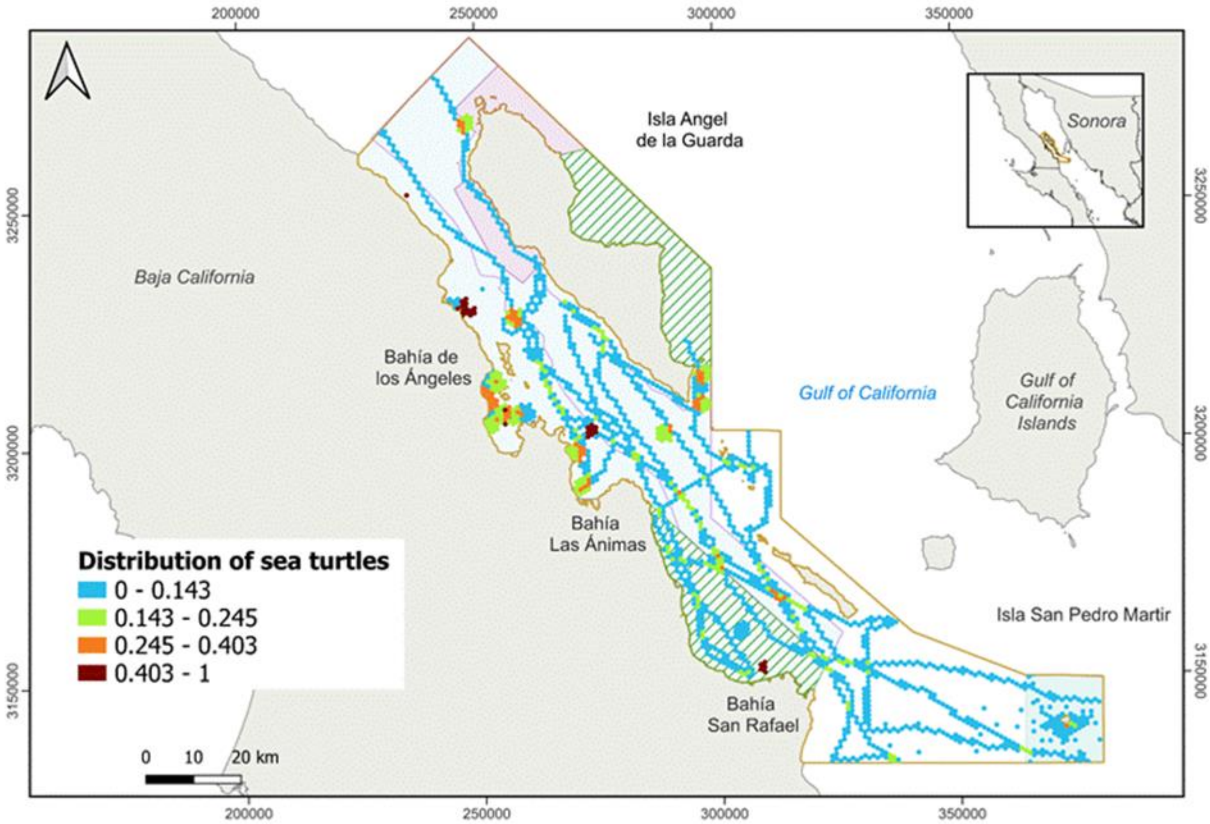
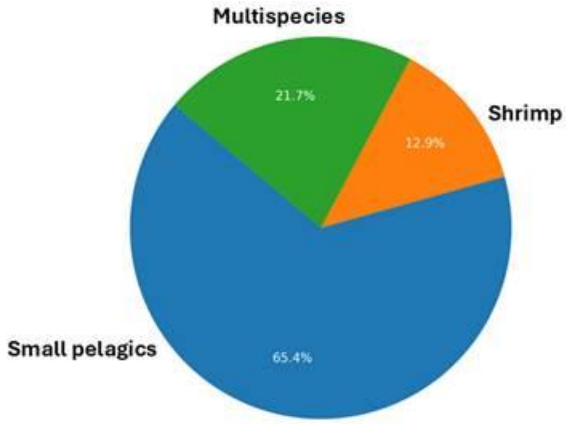


Figure 3. Relative distribution of sea turtles in the study area. The map integrates six independent data sources. High-density areas (red) are concentrated in the northern coast of Bahía de los Ángeles, the Canal de Ballenas, and southern Bahía San Rafael. Intermediate values (green and orange) are observed in coastal and insular zones such as Bahía Las Ánimas, the southern tip of Isla Ángel de la Guarda, and the marine corridor between the Bahía de los Ángeles and San Pedro Mártir reserves. Low values (light blue) correspond to areas with limited monitoring and should not be interpreted as turtle absence.

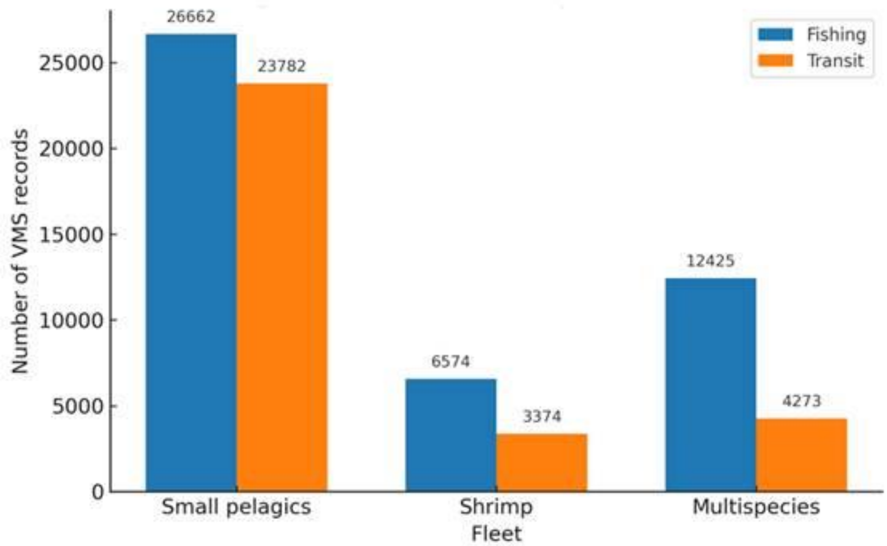
The presence of sea turtles was recorded across multiple subzones within both NPA, encompassing areas designated for both conservation and sustainable use. In RBBDLA, records were concentrated in sustainable use subzones of high ecological importance, such as Bahía San Rafael, the eastern sector of Isla Ángel de la Guarda, and the Ballenas and Salsipuedes channels. In RBISPM, sea turtle presence was documented within the marine protection subzone, underscoring the significance of these areas in supporting habitat use by protected species.

3.2 Industrial fishing activity patterns

A total of 77,090 VMS records from industrial fleets operating in the study area between 2018 and 2023 were analyzed. Small pelagic vessels accounted for most records, followed by multispecies and shrimp fleets. While the overall effort was nearly balanced between fishing (51.7%) and transit (48.3%), fleet-specific patterns varied: shrimp and multispecies fleets showed a greater proportion of active fishing events, whereas the small pelagic fleet presented a more even distribution between fishing and transit. These differences reflect operational characteristics inherent to each fishery (Fig. 4).



a. Percentage of VMS records by industrial fleet during the 2018–2023 period in the study area.



b. Total number of fishing and transit events by industrial fleet.

Figure 4. Industrial fishing VMS records in the study area during 2018–2023. (a) Percentage of total records by fleet type: small pelagics, shrimp, and multispecies. (b) Number of events classified as fishing or transit, disaggregated by fleet.

Spatial distribution of industrial fishing activity

The spatial distribution of industrial fishing activities revealed distinct patterns among fleets, along with areas of recurrent overlap. All three fleets exhibited low-intensity fishing values (blue) across most of the study area, indicating broad spatial coverage but low event frequency. However, higher-intensity zones (green to red) varied in location and extent by fleet (Fig. 5).

Bahía San Rafael emerged as a hotspot for all fleets particularly shrimp and small pelagic both in fishing and transit records. The eastern coast of Isla Ángel de la Guarda also showed frequent fishing activity, especially for small pelagic and multispecies fleets, albeit at lower relative intensity.

Transit patterns differed across fleets. The small pelagic fleet displayed a continuous coastal corridor of intermediate to high values, linking the southern polygon to northern fishing grounds. The shrimp fleet followed a similar route, concentrated in the south, while the multispecies fleet showed a more scattered distribution, with no dominant path likely reflecting higher variability in origin and destination.

In the marine protection subzone of Isla San Pedro Mártir, all fleets showed very low or sporadic activity, consistently in the lower intensity range. Most records were concentrated on sustainable use subzones and the unprotected marine corridor connecting the two PNAs.

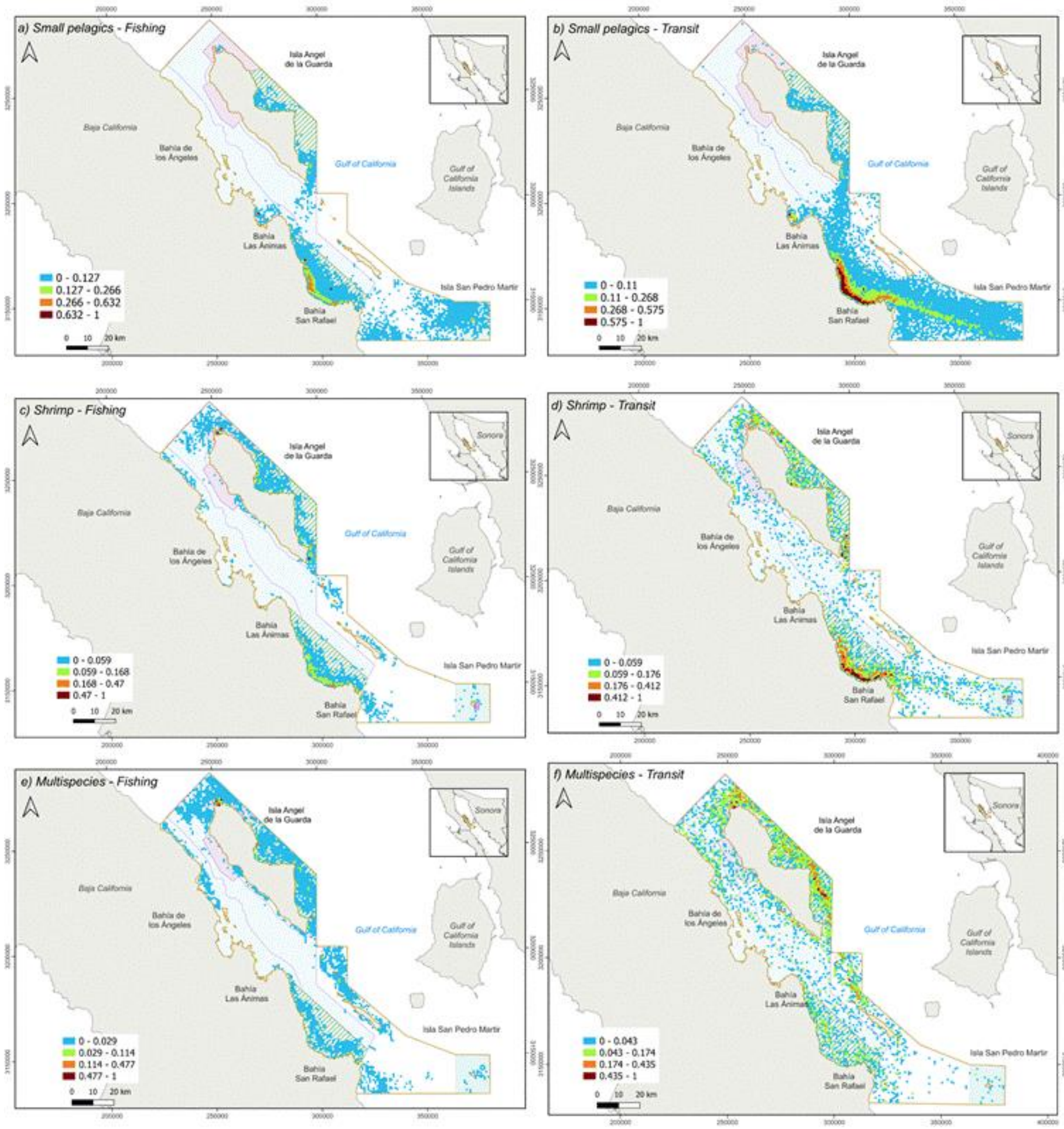


Figure 5. Spatial distribution of industrial fishing activity intensity (2018–2023), by fleet type and activity. The maps show fishing (left) and transit (right) for the small pelagic fleet (a–b), shrimp fleet (c–d), and multispecies fleet (e–f). All values were rescaled from 0 to 1 to enable spatial comparison. The color gradient indicates relative effort: blue = low, green = moderate, red = high intensity.

According to landing reports, the small pelagic fleet primarily targeted sardines, anchovy, and mackerel, using purse seine nets. The shrimp fleet focused on three penaeid shrimp species, all captured with bottom trawls. The multispecies fleet showed greater taxonomic diversity, including demersal finfish (e.g., grouper, croaker, jack) and elasmobranchs (e.g., mako and silky sharks, mobulid rays), reflecting the use of various gears such as bottom longlines, gillnets, and entangling nets. The lower number of VMS records and higher operational heterogeneity made it difficult to classify the spatial patterns of this fleet with precision.

3.3 Potential Interactions

The spatial overlap between sea turtle distribution and industrial fishing activity revealed defined patterns of potential interaction, classified into four levels: moderate, intermediate, elevated, and high (Fig. 6). These patterns help identify priority areas where conservation and fisheries management intersect.

High interaction zones were concentrated in the sustainable use subzone of Bahía San Rafael and along the eastern coast of Isla Ángel de la Guarda. Those areas overlapped with intense fishing activity particularly by shrimp and small pelagic fleets and with turtle foraging and transit areas. All three fleets operated here, with varying intensities.

Elevated zones (yellow) surrounded turtle aggregation hotspots, while intermediate zones (green) appeared more fragmented, including parts of the central channel, Bahía Las Ánimas, and areas near MPAs. Moderate zones (blue) dominated most of the study area. Notably, the Canal de Ballenas showed consistent but moderate levels of overlap, indicating shared use by both turtles and fishing vessels.

High and elevated interaction areas clustered in subzones with permitted industrial use, while the strictly protected subzone of Isla San Pedro Mártir showed consistently low values. These results provide a spatial basis for adaptive management measures in areas where protected species and industrial fishing converge.

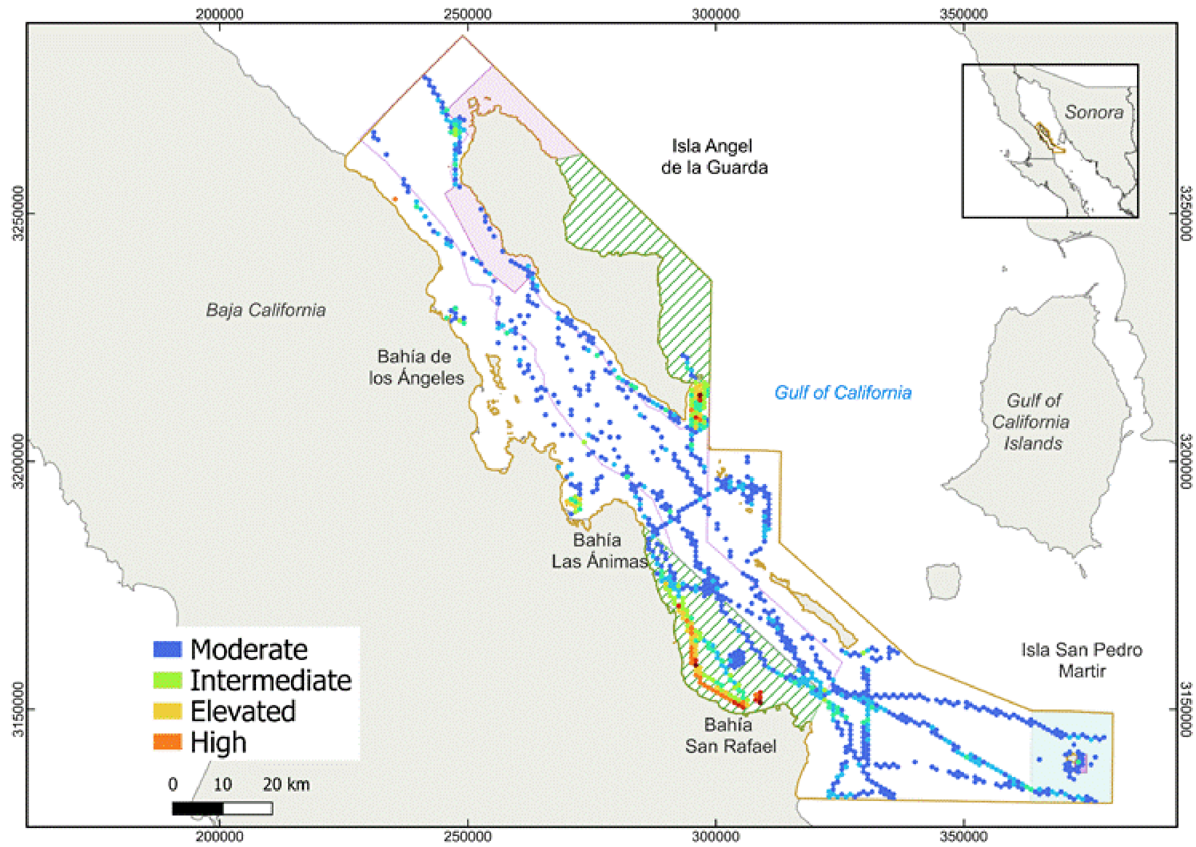


Figure 6. Potential interactions between sea turtle distribution and cumulative industrial fishing effort. The map shows spatial overlap between sea turtle presence and combined fishing and transit activities by industrial fleets during 2018–2023.

4. Discussion

This study integrated multiple spatial data sources scientific, technological, and community-based to identify potential interaction zones between sea turtles and industrial fishing within a marine protected area. By combining satellite vessel monitoring (VMS), ecological literature, community monitoring, and participatory mapping, it was possible to overcome the limitations of single-source data and generate a more comprehensive representation of spatial use by both turtles and fleets. This convergence, especially in areas where conservation and extraction goals intersect, is crucial for informing adaptive management strategies.

4.1 Sea turtle distribution

Spatial analysis confirmed the presence of five sea turtle species across the study area, positioning it as a multi-use habitat in the Gulf of California (Seminoff *et al*., 2002; Martínez-Estévez *et al*., 2021). Historical records, telemetry, and community observations consistently located turtles in coastal and insular sites such as Bahía de los Ángeles, San Rafael, Las Ánimas, and Canales de Ballenas y Salsipuedes. The study area lies near the northern limit of turtle distribution in Mexico (Seminoff *et al*., 2004; Sandoval-Lugo *et al*., 2020).

Turtle presence was documented in ~20% of the polygon, likely an underestimate. *Chelonia mydas*, for example, can travel over 15 km per day (Seminoff & Jones, 2006), suggesting broader habitat use than isolated records indicate. Spatial gaps may reflect data limitations rather than true absence.

Records overlapped with industrial fishing areas, especially within sustainable-use subzones and the unmanaged corridor between MPAs. While overlap does not confirm direct interaction, it indicates zones that warrant targeted monitoring to prevent incidental capture or collisions (Cuevas *et al*., 2018; Putman *et al*., 2023; Calderón-Alvarado *et al*., 2023). Use of these areas beyond core zones highlights the need to include sustainable-use zones in conservation strategies (Uribe-Martínez *et al*., 2021).

Chelonia mydas was most frequently recorded, likely due to resident behavior and conservation recovery. Key areas included Puerto Refugio, San Rafael, and Isla Ángel de la Guarda. Its shallow habitat use increases exposure to shrimp trawls when mitigation is absent (Secretaría CIT, 2006). *Lepidochelys olivacea* was sparsely recorded but likely uses sandy-bottom areas targeted by trawls, particularly where Turtle Excluder Devices (TEDs) are not enforced. *Eretmochelys imbricata* appeared near reefs south of Ángel de la Guarda, vulnerable to longlines and gillnets. *Caretta caretta* was found via telemetry in Canal de Ballenas, a benthic feeder susceptible to trawls and longlines (Wallace *et al*., 2010). *Dermochelys coriacea* was rarely recorded offshore, but is known to interact with longlines and fast vessels (FAO, 1997; Morales-Bojórquez *et al*., 2021), supporting precautionary measures in pelagic zones.

These species use the region for feeding, residency, and migration, each facing distinct interaction scenarios. This underlines the importance of spatial planning that accounts for varying vulnerabilities and overlapping use of marine space (Cuevas *et al*., 2019).

4.2 Industrial fishing activities

Between 2018 and 2023, three industrial fleets operated in the area: small pelagics (purse seines), shrimp (trawls), and multispecies (gillnets, longlines). Only the small pelagics fleet is authorized in the MPAs, but repeated shrimp and multispecies operations suggest ongoing unauthorized activity.

Comparison of satellite and administrative data (RNP codes, ports) revealed inconsistencies and low traceability. The absence of electronic logbooks, observers, or gear verification limits regulatory enforcement and complicates the identification of interactions.

Incidental capture remains a serious threat to sea turtles (Putman *et al*., 2020; Senko *et al*., 2021). Shrimp trawls have caused high mortality in Mexico, particularly in the Gulf of Ulloa (Bojórquez-Tapia *et al*., 2021). While TEDs are mandatory, their effectiveness depends on correct installation and use (FAO, 1997; Campbell *et al*., 2020).

Multispecies gillnets are difficult to detect and often deployed in shallow habitats, affecting *Chelonia mydas* and *Caretta caretta* (Fahlman *et al*., 2017; Miguel *et al*., 2020). Their impact led to closures and gear changes in the Gulf of Ulloa (Bojórquez-Tapia *et al*., 2017). Longlines attract *Dermochelys coriacea* and *C. caretta* to baited hooks, resulting in entanglement and injury (Gilman *et al*., 2017; Báez *et al*., 2019). Although circle hooks and bait modifications can reduce bycatch, implementation is inconsistent.

Purse seines show fewer recorded interactions but may affect turtles when fishing schools associated with non-target fauna (Swimmer *et al*., 2020; MSC, 2024). This fleet is MSC-certified, which improves traceability through audits and public reporting.

Vessel traffic adds further pressure. High-speed transits have been linked to turtle strandings and fatalities (Fuentes *et al*., 2021; Welsh & Witherington, 2023; Mihaljević *et al*., 2024). Studies from Hawaii and Florida indicate that speeds over 10 knots increase the likelihood of lethal strikes, particularly in aggregation zones like Canal de Ballenas (Shimada *et al*., 2017; Welsh & Witherington, 2023).

These findings emphasize the importance of gear-specific mitigation measures and spatial management that considers co-use of habitat by industrial fleets and sea turtles.

4.3 Potential interactions

This study identified interaction zones, notably in sustainable-use subzones of Bahía San Rafael and east of Isla Ángel de la Guarda. These areas are used by all three fleets and serve as key areas for sea turtle activity. The spatial overlap between fleet operations particularly those of the small pelagics fleet and sea turtle presence supports the need for focused monitoring and adaptive management.

Bottom trawls used by the shrimp fleet were identified as the most impactful gear type for turtles. The multispecies fleet appeared less frequently in the data but posed uncertainty due to low traceability. These differences justified the weighting system used in spatial analysis.

A key limitation was the inability to confirm fishing gear or precise behavior from VMS data. While speeds allowed distinction between fishing and transit, the absence of complementary information such as electronic logbooks or field validation limited interpretative precision. Similar limitations have been reported in other regions (Guill *et al*., 2019; O'Farrell *et al*., 2023).

Nonetheless, the 1 km² grid enabled detailed mapping of turtle habitat use beyond core zones. The integration of multiple data sources enhanced the robustness of the spatial overlap analysis and provides valuable input for adaptive marine spatial planning.

Based on these findings and international experiences, several management options are proposed: time-area closures during turtle aggregation periods, early warning systems integrating VMS and turtle sightings, and improved traceability through electronic observation, digital logbooks, and community monitoring. Subzoning schemes within MPAs should be reviewed in light of new spatial evidence (Sarker *et al*., 2019; Read *et al*., 2019)

Certification programs such as MSC provide a framework for improving compliance, but must be informed by localized interaction data and applied across all fleets not just certified ones. Additionally, community-based monitoring, such as that led by Grupo Tortuguero de Bahía de los Ángeles, is critical for validating satellite data and advancing inclusive, evidence-based governance (Trouillet *et al*., 2019).

In sum, addressing not only species presence but spatial overlap with industrial activity is essential for effective management. Identifying interaction hotspots supports stronger enforcement, flexible governance, and refinement of current zoning schemes (Tassetti, Ferrà, & Fabi, 2019; Breen *et al*. 2017).. This calls for improved institutional coordination, local participation, and integrated monitoring systems to ensure the coexistence of conservation priorities and sustainable fisheries.

5. Conclusions

1. This research demonstrated that critical sea turtle habitats spatially overlap with zones authorized for industrial fishing, revealing a misalignment between conservation objectives and permitted uses within Marine Protected Areas (MPAs). This spatial insight highlights the need to revise zoning schemes and implement targeted management measures based on empirical overlap patterns.
2. A key methodological contribution was the integration of satellite, scientific, and community-based data to identify areas of ecological importance often

missed by broader-scale assessments. The resulting tool offers a replicable framework to support spatial planning and monitoring.

3. The study also underscores the importance of species-specific and seasonal analyses to design tailored strategies. Strengthening inter-institutional collaboration, community-based monitoring, and data traceability is essential for participatory and adaptive marine governance.
4. Overall, this research provides a science-based foundation to inform decision-making in MPAs, demonstrating the value of spatially explicit, multisource approaches under real-world information constraints.

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Declaration of competing interest

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

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5. CONCLUSIONES GENERALES

La integración del enfoque socioecológico permitió comprender de manera integral la complejidad del sistema marino en la zona media del Golfo de California, donde interactúan múltiples actores, usos del espacio y elementos ecológicos clave. El uso del Marco General de Ostrom facilitó la identificación de relaciones entre el sistema de recursos, las unidades de recurso, los usuarios y las estructuras de gobernanza, revelando fortalezas como la existencia de normativas específicas para las Áreas Naturales Protegidas (ANP) y debilidades como la limitada trazabilidad de actividades pesqueras industriales.

El estudio confirmó la importancia ecológica de las Reservas de la Biosfera Bahía de los Ángeles y San Pedro Mártir como hábitats críticos utilizados por cinco especies de tortugas marinas. Se documentó el uso del espacio marino por individuos en etapa juvenil o subadulta, así como su presencia en zonas costeras e insulares que coinciden con áreas de aprovechamiento pesquero.

El análisis espacial de datos satelitales (VMS), combinado con registros científicos, monitoreo comunitario y conocimiento local, permitió identificar zonas de interacción potencial entre pesca industrial y tortugas marinas. Las áreas con mayor coincidencia espacial se localizaron principalmente en la subzona de aprovechamiento sustentable de Bahía San Rafael y el este de Isla Ángel de la Guarda.

Aunque solo la flota de pelágicos menores cuenta con autorización para operar dentro de las ANP, se identificó actividad de flotas camaronera y multiespecie en zonas no autorizadas, lo que evidencia la necesidad de fortalecer los mecanismos de vigilancia, control y cumplimiento normativo. Esta situación pone en duda la efectividad de los sistemas actuales de monitoreo satelital si no se acompañan de bitácoras verificables o supervisión directa.

El presente estudio aporta herramientas técnicas y analíticas para apoyar la planificación espacial marina y el manejo adaptativo en ANP. La combinación de enfoques teóricos, tecnológicos y comunitarios permitió traducir información fragmentada en evidencia útil para mejorar la zonificación, la toma de decisiones y la conservación de especies protegidas como las tortugas marinas.

La participación de actores locales, en particular del Grupo Tortuguero de Bahía de los Ángeles, fue fundamental para complementar la información científica y validar los hallazgos espaciales. Su labor demuestra el valor de los esquemas de monitoreo participativo para fortalecer la gobernanza ambiental desde un enfoque de corresponsabilidad.

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