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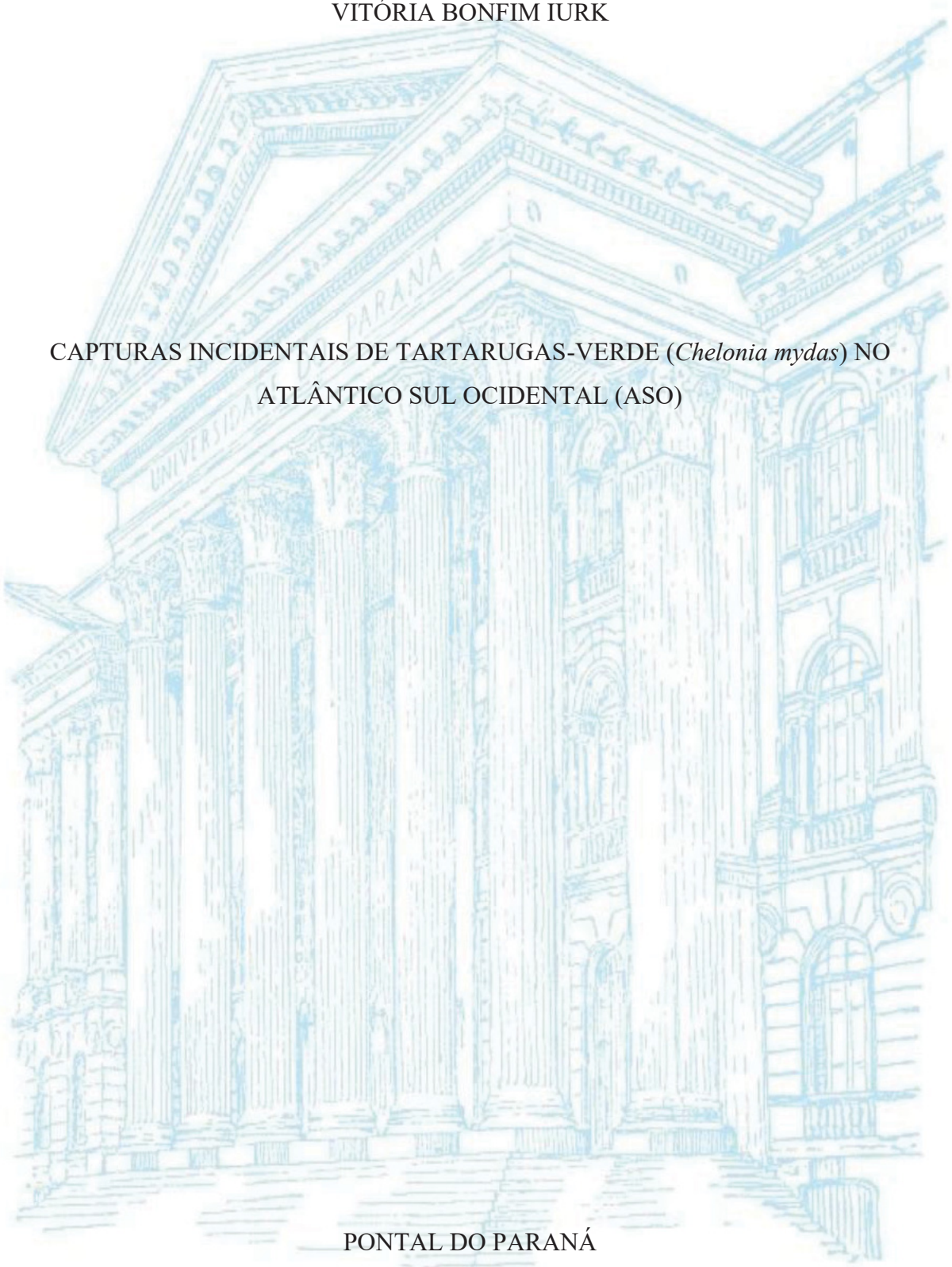

CAPTURAS INCIDENTAIS DE TARTARUGAS-VERDE (*Chelonia mydas*) NO ATLÂNTICO SUL OCIDENTAL (ASO)

PONTAL DO PARANÁ

2025

VITÓRIA BONFIM IURK

CAPTURAS INCIDENTAIS DE TARTARUGAS-VERDE (*Chelonia mydas*) NO ATLÂNTICO SUL OCIDENTAL (ASO)

Dissertação apresentada ao curso de Pós-Graduação em Sistemas Costeiros e Oceânicos, Setor de Ciências da Terra, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestrea em Biologia e Ecologia de Sistemas Costeiros e Oceânicos.

Orientadora: Profa. Dra. Camila Domit
Coorientador: Prof. Dr. Matt K. Broadhurst

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TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação SISTEMAS COSTEIROS E OCEÂNICOS da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **VITÓRIA BONFIM IURK**, intitulada: **CAPTURAS INCIDENTAIS DE TARTARUGAS-VERDE (Chelonia mydas) NO ATLÂNTICO SUL OCIDENTAL (ASO)**, sob orientação da Profa. Dra. CAMILA DOMIT, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de mestra está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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Ao seu Pipo, que precisou partir,

mas deixou comigo o amor pelo mar e os sonhos compartilhados.

"A Vitória será o que ela quiser ser!"

Pai, esse sonho também é seu. Essa conquista é nossa.

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O Senhor dos Anéis: A Sociedade do Anel – *Livro I*

J. R. R. Tolkien

DESTAQUES

1. As ASO-RMU são áreas estratégicas para cinco espécies de tartarugas-marinhas, mas registram alta mortalidade por interações com atividades humanas, principalmente a pesca.
2. Revisão de 41 estudos indica crescimento da produção científica, porém com concentração geográfica e lacunas sobre a pesca costeira de pequena escala.
3. Entre 2016 e 2023, o PMP-BS registrou 42.333 encalhes de *Chelonia mydas* no litoral do RJ ao SC, majoritariamente juvenis e em avançado estado de decomposição.
4. Hotspots de encalhe ocorreram no norte de SP, Complexo Estuarino de Paranaguá (PR) e norte de SC, com maiores taxas no inverno e primavera; pesca e resíduos sólidos foram as principais causas identificadas.
5. Os resultados reforçam a urgência de medidas de mitigação regionais e ações de gestão multilateral coordenadas.

RESUMO

As Unidades de Manejo Regionais do Atlântico Sudoeste (ASO-RMU), que abrangem as Zonas Econômicas Exclusivas de Argentina, Uruguai e Brasil, constituem áreas críticas para a alimentação e o desenvolvimento de cinco espécies de tartarugas marinhas, mas enfrentam ameaças significativas decorrentes de atividades antropogênicas, com destaque para a pesca incidental. Nesse contexto, o presente estudo buscou compreender, por meio de uma abordagem integrada, tanto a evolução do conhecimento científico sobre o tema quanto os padrões espaciais e temporais de mortalidade de tartarugas marinhas na ASO-RMU. No primeiro capítulo, a revisão de 41 artigos revelou um crescimento exponencial da produção científica nas últimas décadas, com destaque para estudos baseados em dados primários obtidos por observadores de bordo. A pesca industrial, especialmente com uso de espinhel, foi a principal atividade associada à captura incidental. As pesquisas concentram-se, principalmente, no sudeste do Brasil e na região do estuário do Rio da Prata (Argentina e Uruguai), com predominância de registros da espécie *Caretta caretta*. Lacunas relevantes foram identificadas, sobretudo em relação à pesca artesanal, atividade amplamente distribuída na região e com elevado potencial de interação com tartarugas marinhas, mas ainda pouco estudada. No segundo capítulo, foram analisados dados de encalhes de *Chelonia mydas* registrados pelo Projeto de Monitoramento de Praias da Bacia de Santos (PMP-BS) entre 2016 e 2023, abrangendo o litoral entre os estados do Rio de Janeiro e Santa Catarina. No total, foram registrados 42.333 encalhes, com predominância de indivíduos juvenis em estado avançado de decomposição (70%). Áreas de maior concentração ("hotspots") foram identificadas no norte de São Paulo, nas proximidades do Complexo Estuarino de Paranaguá (PR) e no norte de Santa Catarina, sendo o Paraná o estado com as maiores taxas de encalhe, especialmente durante o inverno e a primavera. Entre os 11.885 animais em condições de avaliação, interações antrópicas associadas à pesca foram documentadas em 4.418 indivíduos (37,2%). A interação com resíduos sólidos marinhos, como estrangulamento, foi registrada em 4.955 animais (36,0%), enquanto a ingestão de resíduos ocorreu em 4.279 (41,6%). Também foram observadas colisões com embarcações (1.233 casos, 10,4%), agressões (760 casos, 6,4%) e, em menor número, contaminações por óleo (16) e por dragagem (36), ambas com frequência inferior a 1%. Os padrões de encalhe observados parecem estar fortemente relacionados à dinâmica sazonal do esforço pesqueiro, bem como ao comportamento migratório e às demandas energéticas de *C. mydas*. Os resultados reforçam a importância das ASO-RMU como áreas prioritárias para a conservação de tartarugas marinhas no Atlântico sul ocidental e evidenciam a pesca, em suas diversas modalidades, como a principal ameaça à sobrevivência dessas espécies na região. A análise integrada da produção científica e dos dados empíricos de mortalidade por encalhe permitiu identificar padrões espaço-temporais críticos e lacunas significativas de conhecimento, especialmente no que se refere à pesca costeira de pequena-escala. Esses achados destacam a necessidade urgente de ampliar o monitoramento e a regulamentação das atividades pesqueiras, bem como de promover estratégias de mitigação mais eficazes, com foco regional e multilateral. A abordagem adotada neste trabalho contribui para subsidiar políticas públicas e iniciativas de gestão compartilhada voltadas à redução da mortalidade de tartarugas marinhas, enquanto reforça a urgência de estratégias de manejo mais eficazes para a pesca, principalmente a de caráter costeiro.

Palavras-chave: tartaruga marinha, pesca, gestão pesqueira, conservação, mitigação

ABSTRACT

The Southwest Atlantic Regional Management Units (SWAO-RMUs), encompassing the Exclusive Economic Zones of Argentina, Uruguay, and Brazil, represent critical areas for the foraging and development of five sea turtle species. However, these regions face significant threats from anthropogenic activities, particularly incidental capture in fisheries. In this context, the present study aimed to understand—through an integrated approach—both the evolution of scientific knowledge on the topic and the spatial and temporal patterns of sea turtle mortality within the SWAO)-RMUs. In the first chapter, a review of 41 peer-reviewed articles revealed an exponential growth in scientific output over recent decades, with a notable emphasis on studies based on primary data collected by onboard observers. Industrial fishing, especially longline operations, emerged as the main activity associated with bycatch. Research efforts were largely concentrated in southeastern Brazil and the Río de la Plata estuary region (Argentina and Uruguay), with a predominance of records for the species *Caretta caretta*. Significant knowledge gaps were identified, particularly concerning small-scale artisanal fisheries—a widely distributed activity in the region with a high potential for sea turtle interactions but still largely understudied. The second chapter analyzed stranding data for *Chelonia mydas* recorded by the Santos Basin Beach Monitoring Project (PMP-BS) between 2016 and 2023, covering the coastline from Rio de Janeiro to Santa Catarina. A total of 42,333 strandings were recorded, predominantly involving juvenile individuals in advanced stages of decomposition (70%). Stranding hotspots were identified in northern São Paulo, the vicinity of the Paranaguá estuarine complex (Paraná), and northern Santa Catarina, with Paraná exhibiting the highest stranding rates, particularly during winter and spring. Among the 11,885 individuals suitable for assessment, anthropogenic interactions related to fisheries were documented in 4,418 cases (37.2%). Entanglement with marine debris was observed in 4,955 individuals (36.0%), while ingestion of solid waste was recorded in 4,279 cases (41.6%). Collisions with vessels (1,233 cases, 10.4%), physical aggression (760 cases, 6.4%), and contamination from oil (16 cases) and dredging (36 cases) were also reported, each with frequencies below 1%. The observed stranding patterns appear to be strongly influenced by the seasonal dynamics of fishing effort, as well as the migratory behavior and energetic requirements of *C. mydas*. The findings underscore the importance of the SWAO-RMUs as priority areas for sea turtle conservation in the southwestern Atlantic and highlight fisheries—across various modalities—as the primary threat to the survival of these species in the region. The integrated analysis of scientific literature and empirical stranding data enabled the identification of critical spatiotemporal patterns and major knowledge gaps, particularly concerning coastal small-scale fisheries. These insights emphasize the urgent need to expand monitoring and regulation of fishing activities and to implement more effective, regionally coordinated mitigation strategies. The approach adopted in this study contributes to informing public policy and shared management initiatives aimed at reducing sea turtle mortality, while reinforcing the urgency of more effective fisheries management, especially in coastal contexts.

Keywords: sea turtles, fisheries, fisheries management, conservation, mitigation

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LISTA DE ABREVIATURAS OU SIGLAS

ASO	- Atlantico Sul Ocidental
CBD	- Convention on Biological Diversity
CCC	- Comprimento curvilíneo da carapaça
CCL	- Curved carapace length
CCW	-Curved carapace width
CITES	-Convention on International trade in Endangered Species of Wild Fauna and Flora
CMS	-Convention on Migratory Species
EEZ	-Exclusive Economic Zones
GLMM	-Generalizes Linear Mixed Models
IAC	-Inter-American Convention for the Protection and Conservation of Sea Turtles
IBAMA	-Instituto Brasileiro do Meio Ambiente e dos Recursos Naturai
IUCN	-International Union for Conservation of Nature
LED	-Light Emitting Diodes
PAN	-National Action Plan
PEC	-Paranaguá Esturarine Complex
PMAP (BS)	-Projeto de Monitoramento da Atividade Pesqueira (da Bacia de Santos)
PMP (BS)	-Projeto de Monitoramento de Praia (da Bacia de Santos)
RMU	-Regional Management Units
SIMBA	-Sistema de Informação de Monitoramento da Biota Marinha
SWAO	-Southwest Atlantic Ocean
TED	-Turtle Excluder Device
ZEE	-Zonas Econômicas Exclusiva

SUMÁRIO

1 INTRODUÇÃO GERAL

As tartarugas-marinhas são componentes fundamentais dos ecossistemas marinhos há mais de 200 milhões de anos, desempenhando papéis cruciais na manutenção da saúde das ervas marinhas e dos recifes de corais, na transferência de energia na cadeia trófica, na ciclagem de nutrientes e na conectividade entre habitats e espécies (Shaffer et al., 2017; Roche et al., 2021; Carpena-Catoira et al., 2022). Esses organismos apresentam uma distribuição cosmopolita, habitando diversos ecossistemas ao longo de seu ciclo de vida, o que disponibiliza o uso de uma variedade de áreas e recursos (Chatzimentor et al., 2021). Assim, a saúde das tartarugas-marinhas reflete de forma significativa os processos que ocorrem nos ecossistemas marinhos, consolidando sua importância como sentinelas ambientais (Domiciano et al., 2017).

Atualmente, existem sete espécies descritas de tartarugas-marinhas, das quais cinco ocorrem nas águas do Atlântico sul: a tartaruga-verde (*Chelonia mydas*), a tartaruga-cabeçuda (*Caretta caretta*), a tartaruga-de-couro (*Dermochelys coriacea*), a tartaruga-de-pente (*Eretmochelys imbricata*) e a tartaruga-oliva (*Lepidochelys olivacea*) (Marcovaldi & Marcovaldi, 1999). Essas espécies compartilham características biológicas importantes, como maturação sexual tardia, migrações transoceânicas e a alternância entre habitats e recursos alimentares (Seminoff & Shanker, 2008). Embora essas adaptações sejam fundamentais para sobrevivência das espécies, também aumentam a vulnerabilidade das tartarugas-marinhas, especialmente em contextos de impactos ambientais múltiplos e cumulativos (Castro et al., 2021).

As principais ameaças às tartarugas-marinhas incluem a ingestão de resíduos sólidos antropogênicos, colisões com embarcações, contaminação por poluentes químicos, doenças emergentes, poluição sonora, degradação de habitats, atividades portuárias e captura incidental em artes de pesca (Wallace et al., 2010b; Domiciano et al., 2017; Fuentes et al., 2020; Castro et al., 2021). Essas ameaças são diretamente refletidas no risco de extinção global dessas espécies, as quais, segundo as categorias e critérios estabelecidos pela Lista Vermelha da União Internacional para Conservação da Natureza (IUCN, do inglês International Union for Conservation of Nature), são classificadas como “Vulneráveis”, “Em Perigo” ou “Criticamente em Perigo” (IUCN – SSC, 2024).

Visando aprimorar a capacidade de compreensão das ameaças provindas das interações entre as tartarugas-marinhas e atividades antropogênicas, e tornar mais efetivas as ações de mitigação e conservação de suas populações, o Grupo de Especialistas em Tartarugas Marinhas da IUCN e o Grupo de Trabalho de Questões Candentes (MTSG-BI, do inglês Marine Turtle Specialist Group - Burning Issues) propôs a criação de unidades de manejo regionais (RMUs,

do inglês regional management units) para todas as sete espécies, baseando-se em informações que incluíam locais de nidificação individuais, estoques genéticos e distribuições geográficas (Wallace et al., 2010b; Wallace et al., 2023).

Em especial, o oceano Atlântico sul ocidental (ASO), inserido na RMU do Atlântico Centro-sul e Sudoeste, corresponde a uma parcela importante da subpopulação de *C. mydas* da América do sul (Wallace et al., 2010b; Wallace et al., 2023), e representa uma importante região para alimentação e desenvolvimento da espécie (Gama et al., 2016; Tagliolatto et al., 2019b; Cantor et al., 2020; Fuentes et al., 2020). A região engloba as Zonas Econômica Exclusivas (ZEE) da Argentina, Uruguai e principalmente Brasil, caracterizadas pelo desenvolvimento de uma infinidade de atividades antropogênicas (Cabral & Martins, 2018; Miura & Noernberg, 2020) com potencial sobreposição e capacidade de impacto na subpopulação de *C. mydas* do ASO (Fuentes et al., 2020)

A população de *C. mydas* do ASO é composta predominantemente por juvenis com tamanho entre 30 e 60 cm de comprimento curvilíneo da carapaça (CCL). Esses indivíduos, com idades estimadas entre 2 e 8 anos, possuem origem genética de pelo menos 12 diferentes sítios reprodutivos, sendo a Ilha de Ascensão, o Caribe e a costa africana os locais mais prováveis de origem (Prosdocimi et al., 2012; Andrade et al., 2016; Jordão et al., 2015; Savada et al., 2021). Após os primeiros anos em ambiente oceânico, os juvenis migram para áreas costeiras, onde realizando atividades de forrageamento e se desenvolvem, até atingirem a maturidade sexual, entre 20 e 30 anos de idade, dependendo da região (Chaloupka & Limpus, 2004). Na maturidade, os indivíduos de *C. mydas* migram a cada 2 a 5 anos das áreas de alimentação costeiras para as praias e ilhas de origem para reprodução, exibindo forte filopatria (Bolten, 2003).

Apesar do ASO ser uma área crucial de forrageamento e desenvolvimento para *C. mydas*, suas condições ambientais favorecem também o crescimento de múltiplos níveis tróficos, incluindo várias espécies de interesse comercial, como crustáceos e peixes. Essa característica resulta em uma significativa sobreposição entre as áreas de uso de *C. mydas* e zonas de intensa atividade pesqueira (Gallo et al., 2006; Fiedler et al., 2020; Jones et al., 2024). Essa coincidência espacial intensifica os riscos de interações com a pesca, inclusive com as práticas artesanais e de pequena escala, predominantes principalmente ao longo da costa brasileira, aumentando os impactos sobre as populações da espécie (López-Barrera et al., 2012; Tagliolatto et al., 2019b; Fiedler et al., 2020; Fuentes et al., 2020; Castro et al., 2021).

As práticas pesqueiras apresentam ampla heterogeneidade de técnicas de captura, variando ao longo do tempo e espaço. Essa variação é fortemente influenciada por mudanças

sazonais no ambiente e nos diferentes níveis tróficos, que afetam a disponibilidade das espécies-alvo e obrigam os pescadores a ajustarem suas estratégias ao longo do ano. As adaptações incluem a substituição de apetrechos e a modificação do tamanho das malhas das redes (López-Barrera et al., 2012). Na costa brasileira, já foram identificados 18 tipos de pescarias que interagem com diferentes espécies de tartarugas-marinhas, principalmente em áreas costeiras (Marcovaldi et al., 2006). Na Argentina, pelo menos cinco tipos distintos de pescarias foram documentados interagindo com tartarugas-marinhas, principalmente nas áreas estuarinas do Rio de la Plata e El Rincón (Jones et al., 2024). Dessa forma, as taxas de captura incidental também tendem sofrer flutuações em diferentes escalas temporais e espaciais entre os diversos segmentos populacionais (López-Barrera, Longo, Monteiro-Filho, 2012; Tagliolatto et al., 2019a; Cantor et al., 2020).

Obter informações sobre a interação entre tartarugas-marinhas e a pesca permanece um desafio significativo para os países do ASO. Historicamente, os esforços para avaliar o risco de extinção das tartarugas-marinhas têm se concentrado predominantemente em dados relacionados a fêmeas, ninhos e ovos durante as temporadas de nidificação (Wildermann et al., 2018; Robinson et al., 2023). Além de permitir a diferenciação entre estoques genéticos, essa abordagem é amplamente adotada devido à sua menor complexidade operacional e viabilidade financeira, enquanto populações de machos e juvenis, que habitam exclusivamente o ambiente aquático, apresentam maiores dificuldades de monitoramento (Seminoff & Shanker, 2008). Contudo, ignorar as influências das variações populacionais nessa fase de desenvolvimento pode resultar em interpretações equivocadas ou desatualizadas sobre o estado de conservação das espécies (Seminoff & Shanker, 2008; Wildermann et al., 2018).

Também, a obtenção de dados quantitativos sobre as interações com a pesca baseia-se principalmente no monitoramento pesqueiro e em avaliações realizadas por pesquisadores embarcados. No entanto, os dados gerados por esses estudos frequentemente enfrentam limitações substanciais, incluindo altos custos operacionais, desafios logísticos relacionados a programas de bordo, períodos de observação relativamente curtos e cobertura geográfica restrita (Wallace et al., 2010a). Adicionalmente, a ausência de estatísticas precisas e a falta de integração dos dados disponíveis entre diferentes regiões comprometem a capacidade de identificar tendências, lacunas de conhecimento e vieses associados às capturas incidentais no ASO (Bezerra, 2008; Wallace et al., 2010a)

Diante dessas limitações, algumas metodologias têm ganhado destaque como alternativas para superar as lacunas de conhecimento relacionadas às interações entre tartarugas-marinhas e atividades de pesca. Entre elas, os registros sistemáticos de encalhes destacam-se como um

método terrestre mais acessível e econômico, capaz de fornecer informações quantitativas fundamentais sobre a distribuição, estrutura populacional e taxas de mortalidade de tartarugas-marinhas e outras espécies de megafauna marinha (Monteiro et al., 2016; Ten Doeschate et al., 2017; Cantor et al., 2020). No Atlântico Sul Ocidental (ASO), o monitoramento de encalhes de tartarugas-marinhas remonta à década de 1980, com destaque para iniciativas pioneiras na costa sul do Brasil, como as conduzidas pelo Núcleo de Educação e Monitoramento Ambiental (NEMA) e pelo Laboratório de Ecologia e Conservação da Megafauna Marinha (EcoMega), ambos no estado do Rio Grande do Sul (Monteiro et al., 2016). No Uruguai, as iniciativas começaram a surgir no início dos anos 2000, com destaque para o Projeto Karumbé, fundado em 1999, que se tornou uma das principais referências na conservação de tartarugas-marinhas no país (Vélez-Rubio et al., 2013).

A partir de 2010, a eficácia do monitoramento de encalhes contribuiu para o estabelecimento de diversos Projetos de Monitoramento de Praias (PMPs) no Brasil, implementados como condicionantes nos processos de licenciamento ambiental, especialmente em atividades relacionadas à exploração e produção de hidrocarbonetos. Esses projetos abrangem diferentes trechos do litoral brasileiro, desde a região Sul até o Nordeste. Destacam-se, entre eles, os PMPs coordenados pelo Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) e executados pela Petrobras, que monitoram de forma quase contínua a costa entre Laguna, em Santa Catarina, e Conceição da Barra, no Espírito Santo, cobrindo aproximadamente 2.788 km de litoral (https://comunicabaciadesantos.petrobras.com.br/projeto-de-monitoramento-de-praias-pmp-)). Essas iniciativas têm sido fundamentais para a geração de dados robustos sobre a interação de tartarugas-marinhas com atividades antrópicas, incluindo a pesca (Tagliolatto et al., 2019b; Cantor et al., 2020; Fonseca et al., 2024).

De forma semelhante, a aplicação de metodologias sistematizadas de revisão da literatura tem ganhado destaque por facilitar a unificação e análise integrada dos dados disponíveis provenientes de diferentes regiões. Esse tipo de abordagem pode desempenhar um papel fundamental na identificação de tendências, lacunas e vieses na literatura sobre capturas incidentais, permitindo uma compreensão mais abrangente do impacto das atividades pesqueiras na mortalidade de tartarugas-marinhas (Lewison et al., 2004; Pott & Wiedenfeld, 2017; Castro et al., 2021). Também permite a identificação de padrões globais e regionais, evidenciando como diferentes contextos geográficos, socioeconômicos e ecológicos influenciam na problemática. Essa abordagem é especialmente importante em áreas com

recursos limitados, onde os desafios para o monitoramento são mais significativos e os dados disponíveis são frequentemente escassos ou subestimados (Lewison et al., 2014).

Diante dos cenários apresentados, este estudo possui dois objetivos principais, que se complementam e estão organizados em dois capítulos. O primeiro capítulo tem como objetivo integrar e caracterizar a evolução temporal e espacial da literatura relacionada à captura incidental de tartarugas-marinhas no ASO, identificando tendências, lacunas de conhecimento e padrões geográficos dessa problemática. Já o segundo capítulo busca aprofundar o entendimento das lacunas bioecológicas e dos fatores associados aos encalhes de *C. mydas* com evidências de interação com a pesca.

1.1 OBJETIVOS

1.1.1 Objetivos gerais

Capítulo 1: Explorar e avaliar a literatura existente acerca da evolução temporal e espacial da ocorrência de tartarugas marinhas com interação pesqueira (captura incidental), na região que compõem o Atlântico Sul Ocidental (ASO).

Capítulo 2: Caracterizar e avaliar a ocorrência de encalhes de tartarugas-verde (*Chelonia mydas*), com foco nos animais com interação pesqueira, a partir dos dados gerados pelo registro sistemático de encalhes na região sul do Brasil.

1.1.2 Objetivos específicos

Capítulo 1:

- Analisar a distribuição e as características das publicações e autores relacionados a interação entre a pesca e as tartarugas-marinhas de ocorrência na região do oceano Atlantico Sul (ASO).
- Determinar a distribuição espacial e a modalidade dos esforços pesqueiros que interagem com cada espécie de tartaruga-marinha de ocorrência na região do ASO, com ênfase nas regiões costeiras do Brasil, Uruguai e Argentina;
- Determinar quaisquer fatores facilitadores e limitantes chave para a captura incidental de tartarugas marinhas na região;
- Descrever lacunas de informação de elucidação prioritária para mitigação de impactos da captura incidental e conservação de tartarugas marinhas;
- Propor abordagens amplas que possam contribuir para resolver e simplificar, de maneira contínua, as lacunas existentes acerca do tema.

Capítulo 2:

- Avaliar os padrões espaciais e temporais de encalhe, mortalidade, e de interação com atividades pesqueiras, a partir dos dados de *C. mydas* provenientes do registro sistemático de encalhes no sul do Brasil;
- Analisar a estrutura populacional de *C. mydas* com e sem evidências de interação pesqueira, utilizando dados provenientes do registro sistemático de encalhes no sul do Brasil;
- Identificar os tipos de esforços pesqueiros com maior potencial de interação espaço-temporal com *C. mydas* na região;
- Mapear áreas de concentração de encalhes de *C. mydas* com sinais de interação pesqueira, destacando regiões prioritárias para ações de conservação da espécie;
- Avaliar os riscos associados às interações entres atividades pesqueiras e *C. mydas* na região;
- Preencher lacunas no conhecimento sobre *C. mydas* na ASO-RMU, oferecendo dados críticos para subsidiar a formulação de estratégias eficazes de conservação e mitigação dos impactos da pesca e outras atividades antrópicas.

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CAPÍTULO 1

Uma análise sistemática das interações entre as tartarugas marinhas e a pesca no Atlântico Sul Ocidental

A systematic analyses of interactions between marine turtles and fisheries in the southwest Atlantic Ocean

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A systematic analysis of interactions between marine turtles and fisheries in the southwest Atlantic Ocean

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HIGHLIGHTS

1. The SWAO-RMU host five marine turtle species and are subject to substantial impacts from fisheries bycatch.
2. A total of 41 publications (2004–2023) reveal an exponential increase in research, primarily focused on southeastern Brazil and the Río de la Plata region.
3. Industrial fisheries are cited in 51% of studies, with longline operations accounting for 81.8% of recorded bycatch events.
4. Only 22% of publications address mitigation measures, most of which evaluate modifications to industrial fishing gear (e.g., circle hooks and BRDs).
5. There is a paucity of data on coastal and small-scale fisheries, a widespread activity in the region with potentially significant implications for conservation.

RESUMO

As unidades de manejo regionais do Atlântico sul ocidental (ASO-RMU), que abrangem as Zonas Econômicas Exclusivas da Argentina, Uruguai e Brasil, são áreas críticas para a alimentação e o desenvolvimento de cinco espécies de tartarugas-marinhas, mas sofrem pressões significativas da pesca incidental. Neste contexto, o presente estudo teve como objetivo avaliar a evolução temporal e espacial da literatura científica sobre captura incidental de tartarugas-marinhas na região da ASO-RMU. Foram analisados 41 artigos publicados entre 2004 e 2023, revelando um crescimento exponencial da produção científica ao longo das últimas décadas. A maior parte dos estudos baseou-se em dados primários obtidos por coleta *in situ*, principalmente por meio de observadores de bordo. A pesca industrial foi reportada em aproximadamente 51% dos trabalhos, com o espinhel identificado como o petrecho mais frequentemente associado à captura incidental (81,8%). Geograficamente, as pesquisas concentram-se no sudeste do Brasil e na região do estuário do Rio da Prata (Argentina e Uruguai). Todas as cinco espécies que ocorrem na ASO-RMU foram registradas, com *Caretta caretta* presente em 68% dos estudos e *Eretmochelys imbricata* na menor proporção (29%). Apenas 22% dos estudos abordaram estratégias de mitigação, sendo mais de 60% desses focados em modificações de petrechos na pesca industrial, como o uso de anzóis circulares e dispositivos redutores de captura incidental (BRDs). A revisão evidenciou lacunas relevantes no conhecimento, especialmente quanto à escassez de dados relacionados à pesca de pequena escala - atividade amplamente distribuída na região e com potencial de significativa interação com tartarugas-marinhas. Tais resultados reforçam a necessidade de políticas públicas mais abrangentes e do fortalecimento da gestão da pesca de pequena-escala, de modo a subsidiar estratégias de conservação mais efetivas e representativas para a ASO-RMU.

Palavras-chave: pesca incidental, megafauna, espécie não alvo, mitigação, gestão pesqueira

ABSTRACT

In the southwest Atlantic Ocean, the Exclusive Economic Zones of Argentina, Uruguay and Brazil, support important fisheries resources, but are also critical areas for the foraging and development of five sea-turtle species. This co-occurrence manifests as excessive unwanted mortalities among all five species and mostly as discarded bycatch. This study aimed to assess the temporal and spatial trends in scientific literature addressing regional sea-turtle bycatch in the southwest Atlantic Ocean. A total of 41 peer-reviewed articles published between 2004 and 2023 were analyzed, revealing an exponential increase in scientific output over recent decades. Most studies were based on data collected *in situ*, and primarily via onboard observers. Industrial fisheries were reported in approximately 51% of the studies, with longlines identified as the fishing gear most frequently associated with sea-turtle bycatch (82%). Geographically, research efforts were concentrated in southern Brazil and the Río de la Plata estuary (Argentina and Uruguay). All five sea-turtle species were reported, with *Caretta caretta* being the most frequently recorded (68%) and *Eretmochelys imbricata* the least (29%). Only 22% of studies addressed bycatch mitigation strategies, and many of these focused on gear modifications in industrial fisheries, such as the use of circle hooksfor longlines or and bycatch reduction devices for penaeid trawls. The review highlights critical knowledge gaps, particularly the scarcity of data describing small-scale or artisanal fisheries and despite their widespread presence in the region and likely interactions with sea turtles. These findings underscore the need for broader public policies and improved management of small-scale fisheries to support more effective and representative conservation strategies for the southwest Atlantic Ocean.

Keywords: bycatch, megafauna, non-target species, mitigation strategies, fishery management

1 INTRODUCTION

Chelonioid sea turtles have existed in marine ecosystems for >150 million years and subsequently held substantial cultural, traditional, and spiritual importance in human societies for millennia (Campbell, 2002; Godley et al., 2020). Their ecological roles include regulating prey populations and contributing to nutrient cycling, which help to maintain the balance of aquatic ecosystems (Shaffer et al., 2017; Roche et al., 2021; Carpena-Catoira et al., 2022). As key bioindicators, sea turtles provide valuable insights into marine-ecosystem health by reflecting the overall quality of their environment (Domiciano et al., 2017).

Sea turtles exhibit complex life cycles characterized by slow growth, delayed sexual maturity, long juvenile phases, reliance on diverse and spatially dispersed habitats, long lifespans, and extensive migrations; all typical of k-strategists (Castro et al., 2021). Their movements span multiple ecosystems, including oceanic and neritic zones, foraging and breeding grounds, and even terrestrial environments (Bolten, 2003). These life-history traits make sea turtles particularly vulnerable to various human-induced threats, including fishing mortality, habitat degradation, pollution, hunting, poaching, invasive species, diseases, and climate change; which collectively have resulted in global declines in their populations (Domiciano et al., 2017; Fuentes et al., 2020; Castro et al., 2021).

Conserving the ecological roles of sea turtles in coastal and oceanic habitats remains a complex challenge, shaped by socioeconomic, cultural, and environmental factors (Parrott, 2017). To support more effective management strategies, researchers have identified global priorities for sea-turtle conservation (Hamann et al., 2010). The International Union for the Conservation of Nature (IUCN) ‘marine turtle specialist group’ (MTSG) introduced the concept of ‘regional management units’ (RMUs) for sea turtles. These RMUs aim to integrate data describing nesting sites, genetic stocks, and geographical distributions to improve the management and conservation of turtle populations (Wallace et al., 2010b; Wallace et al., 2023).

The RMU comprising the southwest Atlantic Ocean (SWAO), encompasses the exclusive economic zones (EEZs) of Argentina, Uruguay, and Brazil and has been identified as a critical habitat for sea turtle species. However, this region is densely populated and heavily affected by human activities (Wallace et al., 2010b; Wallace et al., 2023). All five sea turtle species inhabiting the SWAO (*Dermochelys coriacea*, *Chelonia mydas*, *Caretta caretta*, *Lepidochelys olivacea*, and *Eretmochelys imbricata* (Pough, Janis, & Heiser, 2011)) are globally classified by the IUCN as either "Vulnerable", "Endangered", or "Critically Endangered". Such classifications highlight severe risks of extinction.

Among the various threats to sea-turtle populations in the SWAO-RMU, the bycatch of non-target species by regional fisheries is widely recognized as being of substantial concern and has necessitated urgent efforts to characterize, monitor, and resolve impacts (Marcovaldi et al., 2006; Wallace et al., 2010; Lewison et al., 2014; Wallace et al., 2023). Documented bycatches of all five sea turtles occur among various fishing methods, including pelagic longlines, demersal trawls, and gillnets (Wallace et al., 2010a; Lewison et al., 2014) which are deployed across critical feeding and developmental areas (López-Barrera rt al., 2012; Tagliolatto et al., 2019b; López-Mendilaharsu et al., 2020). In particular, gillnets and trawls fished across coastal zones of SWAO are especially detrimental to juvenile and subadults of *C. mydas* and *C. caretta* (Tagliolatto et al., 2019a; López-Mendilaharsu et al., 2020).

Although fisheries bycatch is globally recognized as a priority research area, quantitative data remain scarce, largely due to the high costs and logistical challenges associated with onboard observation programs (i.e. recognized as the most accurate census approach; Kennelly, 2021). Most available data originate from short-term industrial fleet-based studies with limited spatial coverage, which undermines their representativeness and hampers comprehensive understanding of the issues (Wallace et al., 2010a). Further, the lack of integration and standardization across different studies underestimates the true scales of bycatch, particularly in developing countries like those along the SWAO where small-scale fisheries predominate, and monitoring and enforcement mechanisms are insufficient (Castro et al., 2021).

In this context, systematic literature reviews have emerged as valuable tools for synthesizing and analyzing available data from different regions in an integrated manner (Lewison et al., 2004; Lewison et al., 2014; Castro et al., 2021). This approach facilitates identifying regional and global trends, gaps, and biases in bycatch data and supports a more comprehensive understanding of the impacts of fishing activities on sea turtle mortality (Lewison et al., 2004; Pott & Wiedenfeld, 2017; Castro et al., 2021). Such analyses are particularly crucial in resource-limited regions, where monitoring challenges are substantial (Lewison et al., 2014).

Considering the challenges outlined above, this study aimed to collect, evaluate, and synthesize available data on sea-turtle bycatch in the SWAO-RMU, providing a foundational resource for future conservation planning. Specifically, five objectives were to: (1) analyze the distribution and characteristics of publications and authors related to sea-turtle bycatch; (2) investigate the spatial distribution and types of fishing activities interacting with sea turtles, in the EEZs of Brazil, Uruguay, and Argentina; (3) identify those key factors that either contribute

to, or reduce, incidental sea-turtle captures in the region; (4) prioritize information gaps requiring clarification to mitigate the impacts of bycatch and protect sea turtles; and (5) develop comprehensive approaches to streamline addressing existing gaps in our understanding of sea-turtle bycatch.

2 METHODS

2.1 REVIEW PROTOCOL

A systematic review was undertaken to facilitate achieving the stated objectives using three bibliographic databases: Consortium for Wildlife Bycatch Reduction (CWBR - https://www.bycatch.org/), Scopus (https://service.elsevier.com/app/overview/scopus/), and Web of Science (WoS - https://clarivate.com/). Keywords from three categories were used: (1) incidental fishing and synonyms ("bycatch" OR "by-catch" OR "fishing" OR "incidental fishing" OR "incidental catch" OR "incidental capture" OR "accidental fishing" OR "accidental catch" OR "accidental capture" OR "fisheries interaction"); (2) sea turtles and synonyms ("sea turtle" OR "seaturtle" OR "marine turtle" OR "green turtle" OR "leatherback turtle" OR "hawksbill turtle" OR "loggerhead turtle" OR "olive ridley turtle"); and (3) Southwest Atlantic Ocean, and synonyms ("Brazil" OR "Uruguay" OR "Argentina" OR "Atlantic Ocean" OR "Southwestern Atlantic" OR "South West Atlantic" OR "South Atlantic" OR "Western Atlantic" OR "Southern Western Atlantic" OR "South Western Atlantic" OR "Western South Atlantic"). The categories were combined using the boolean operator "AND".

Database searches were conducted on October 6, 2023, with citation information, bibliographic information, and Abstracts exported and combined using the software 'Rayyan' (http://rayyan.qcri.org). The eligibility criteria included experimental studies (primary or secondary) without specific language or date restrictions, although review articles were excluded. The eligible species populations included all life stages (hatchlings, juveniles, and adults) and both sexes of the sea-turtle species occurring in the SWAO (i.e., *D. coriacea* (DC), *C. mydas* (CM), *C. caretta* (CC), *E. imbricata* (EI), and *L. olivacea* (LP)). For studies covering additional countries beyond Brazil, Uruguay, and Argentina, only the information related to these three countries was analyzed. Eligible exposures included any type of fishing operation and gear, excluding studies addressing secondary interactions such as ghost fishing or ingestion of fishing debris.

An evidence table was constructed using data extracted from the selected studies. The information included: (a) title; (b) authors; (c) number of authors; (d) name of the first author; (e) year; (f) category (bycatch monitoring, mitigation, ethnobiological studies, and health); (g)

journal; and (h) language of publication; (i) country addressed in the study; (j) geographic coordinates addressed; (k) RMUs (Wallace et al., 2023) addressed; (l) country of the first author; (m) main objectives; (n) sea-turtle species addressed; and (o) biological characteristics (sex and developmental stage); (p) type of fishing addressed (industrial or small-scale); (q) main fishing gear addressed—longline, gillnet, trawl, and others (hook and line, driftnet, etc.); and (r) proposed mitigation measures, classified according to Gupta et al. (2020), and Castro et al. (2021), with some modifications.

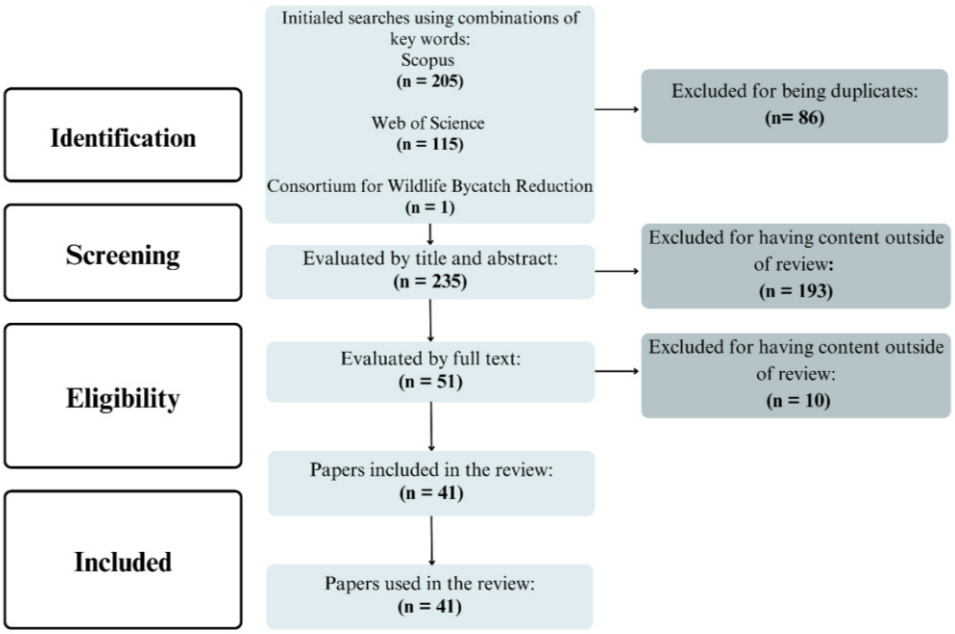
Subsequently, the data generated from the systematic review were statistically analyzed using the R environment (R Core Team, 2017), employing the 'Bibliometrix – Biblioshiny' package (Arya & Cuccurullo, 2017), and Microsoft Office (version 2412, 2024). Additionally, QGIS software (version 3.10.10, 2020) was used to create maps representing the distribution of the publications.

3 RESULTS

3.1 RESEARCH EFFORTS AND APPROACHES

In total, 321 titles were retrieved (Scopus = 205, WoS = 115, and CWBR = 1). After removing duplicate files (86), the remaining articles (235) were screened by reading titles and Abstracts. A total of 51 articles were selected for full-text reading, of which 10 were excluded for non-relevant content, and 41 were included in the data extraction stage (Fig. 1; Supplementary Table 1).

FIGURE 1 - A schematic diagram of methodology applied to the literature considered in the review, with the number of publications (in parentheses) at each stage.



Across the analyzed publications, a total of 167 unique authors were identified, with an average of 5 authors per article. The rate of international co-authorship was 2.5%, calculated as the proportion of publications involving authors from multiple countries. The highest number of contributions by a single author was 10 publications, while the lowest was one. Notably, only 5% (n = 2) of first authors were affiliated with institutions outside the SWAO region. Most (78%, n = 32) of the articles had Brazilian first authors, while only ~10% (n = 4) and 7% (n = 3) originated from Uruguay and Argentina. Nevertheless, 93% (38) of the studies were published in English. The most disseminated journals were North American and English, with Aquatic Conservation: Marine and Freshwater Ecosystems being particularly notable (5–12%), followed by Ocean & Coastal Management (4.0–10%), Marine Policy and Fisheries Research (both with 3 publications or 7%).

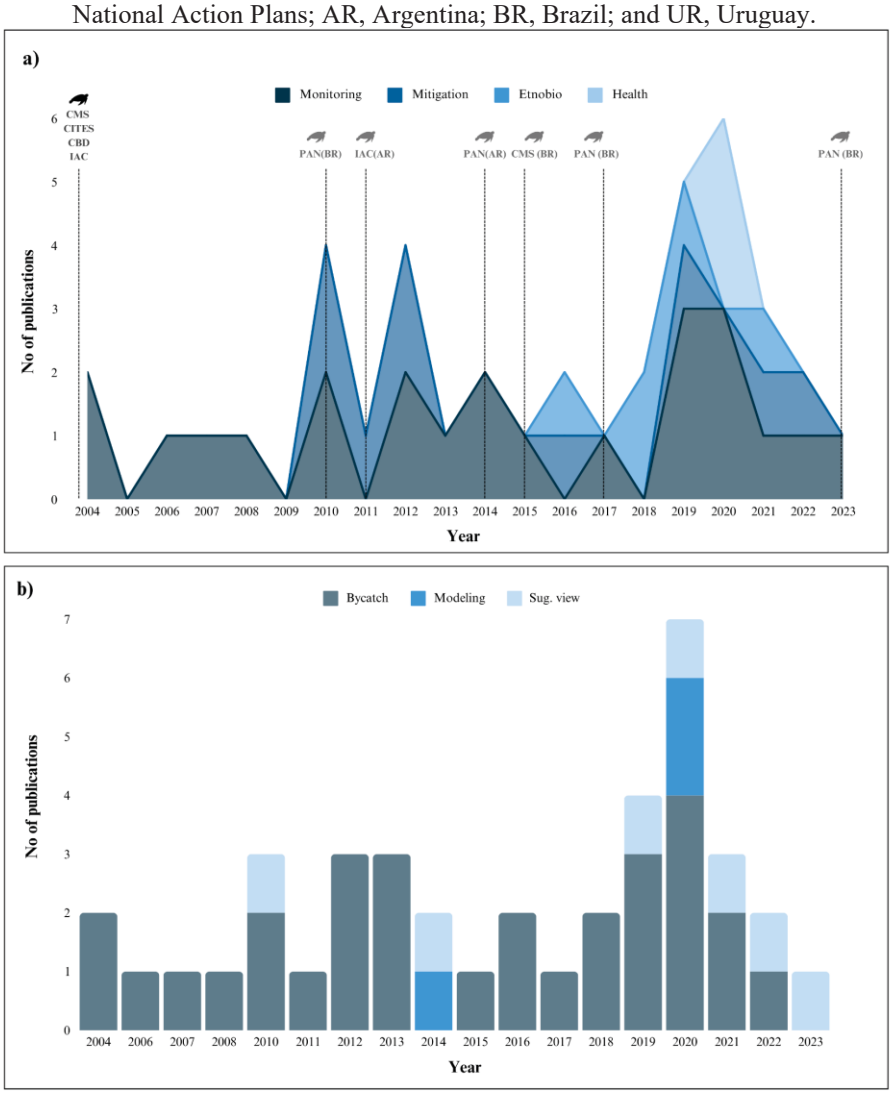
Prior to 2004, no studies meeting the full inclusion criteria for this review were identified through the search engines. However, the annual numbers of relevant publications have increased steadily over time, rising from two in 2004 to seven in 2020 (Fig. 3). Among the studies analyzed, 55% (22) focused on bycatch monitoring, 21% (9) addressed mitigation strategies, 16% (6) consisted of ethnobiological research, and 9% (4) investigated the health impacts of fishing on sea turtles (Fig. 2a).

Bycatch-monitoring studies, defined as those that specifically identified and characterized incidental captures—whether through direct interaction or signs of unintentional

interaction—of marine species during fishing activities targeting other species, have remained prevalent. Studies on mitigation approaches became more prominent in 2010, while ethnobiological studies increased from 2016, and health studies emerged as a focus in 2020 (Fig. 2a).

The standardized studies had an average data collection and availability period of 3.8 ± 3.5 years (mean ± SD), with a range spanning from two months for ethnobiological studies to 15 years for monitoring bycatch studies. The average time to publication, measured from the last data collection date to the article's availability, was 3.7 ± 2.4 years (mean ± SD), with a range of 1 to 11 years. Most studies collected data *in situ* (i.e., onboard studies; Fig. 2b). However, *ex-situ* studies (i.e. utilizing internal and/or external signs of interactions with fishing), have increased, especially since 2019.

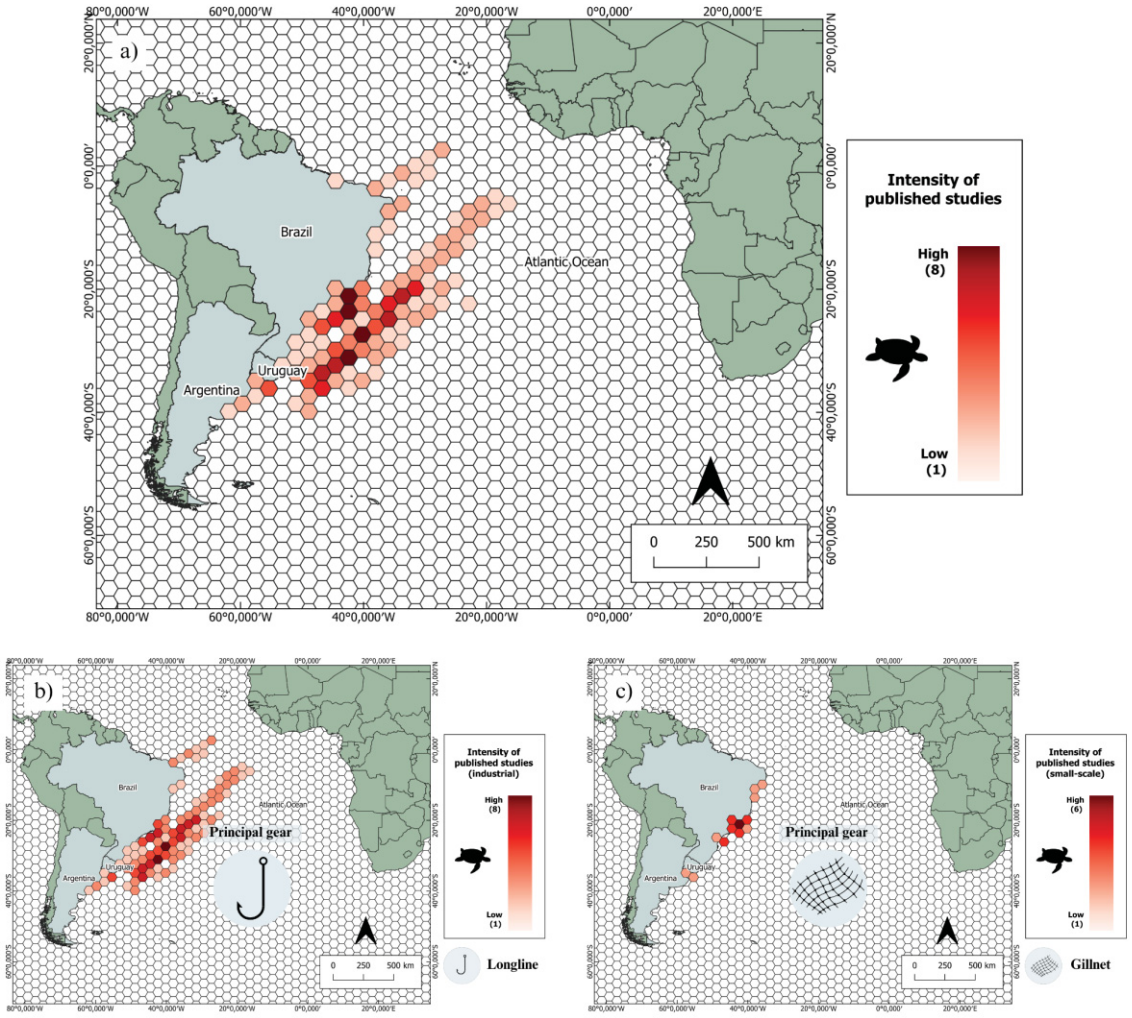
FIGURE 2 - Temporal trends (2004 to 2023) in publications describing the incidental capture/mortality of sea turtles by fishing in the southwest Atlantic Ocean including the (a) main theme of the publications; and (b) interaction characterization approaches addressed in publications. In (a), the dotted lines indicate the year of entry of countries into substantial actions for the investigation and protection of sea turtles against bycatch. The first dotted line highlights actions that occurred prior to 2004. CMS, Convention on Migratory Species; CITES, Convention on International Trade in Endangered Species of Wild Fauna and Flora; CBD, Convention on Biological Diversity; IAC, Inter-American Convention for the Protection and Conservation of Sea Turtles; PAN, National Action Plans; AR, Argentina; BR, Brazil; and UR, Uruguay.



3.2 SPATIOTEMPORAL DISTRIBUTION OF FISHING ACTIVITIES

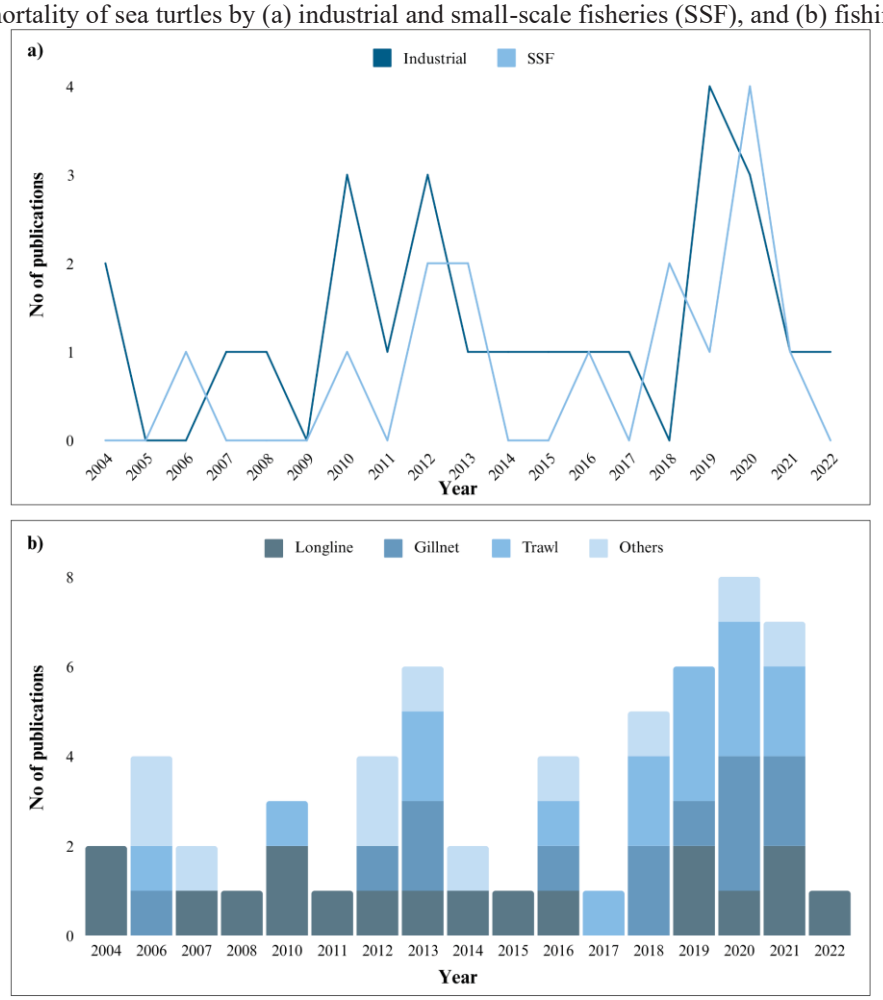
Regarding the geographical distribution of the studies, 78% (32) of articles referred only to Brazil, while 5% (2) each referred only to Argentina and Uruguay. Additionally, 12% (5) of the articles covered two SWAO member countries, and 7% (3) covered all three countries simultaneously. Therefore, most of the latitudes and longitudes studied were in Brazil's southern region, as well as the Río de la Plata estuary in Argentina and Uruguay (Fig. 3).

FIGURE 3 - Geographical coordinates of publications (a) across all gears, but with an emphasis on the most relevant affiliations; and describing (b) industrial or (c) small-scale fisheries. Data outside the southwest Atlantic Ocean were not represented.



Industrial and small-scale fisheries were addressed in 51% (21) and 27% (11) of the studies, respectively while 10% (4) focused on both categories, and 12% (5) did not specify the type of fisheries addressed. This effort is evident in the maps shown in Figure 3, where a higher concentration of studied areas was offshore where industrial fisheries are more prevalent. Further, industrial fisheries studies were the first to be retrieved in the search databases for this review, while small-scale fisheries started to see an increase in publications only after 2018 (Fig. 4a).

FIGURE 4 - Temporal trends (2004 to 2023) in numbers of publications describing the incidental capture/mortality of sea turtles by (a) industrial and small-scale fisheries (SSF), and (b) fishing gears.



Regardless of the region, many studies assessed more than one fishing gear, but longlines had the highest number, accounting for 32% (19) of the total. Trawls followed with 28% (17) of studies, and gillnets represented 21% (13), while the 'others' category accounted for 20% (12). Trawls and gillnets received limited attention in the early years. but have been increasingly investigated in the last decade, whereas studies on longlines have remained consistent (Fig. 4b).

Those studies addressing longlines predominantly focused on industrial fisheries, representing 82% (18) of the total. These publications primarily involved bycatch monitoring, often relying on on-board observers to gather data. Conversely, gillnets were predominantly associated with small-scale fisheries, comprising 78% (14) of the studies. Research involving this latter gear generally focused on ethnobiology, often utilizing indirect evidence of interactions and employing alternatives techniques alongside community-based approaches to assess impacts.

3.3 FISHING ACTIVITIES INTERACTING WITH SEA TURTLE SPECIES

All five sea-turtle species were recorded in the reviewed studies (Fig. 5). A total of 32% (10) of the studies focused on a single species. Another 22% (9) combined four species, while 20% (8) covered five. Additionally, 15% (6) addressed three species, and 7% (5) focused on two species. Among the species studied, *C. caretta* was the focus in 25% (28) of the studies followed by *D. coriacea* at 24% (27), and *C. mydas* at 23% (26)

Visually, despite variation in the number of studies, all five sea-turtle species were consistently represented over the years (Fig. 5). Nevertheless, *D. coriacea*, *C. caretta*, and *L. olivacea* were more frequently associated with industrial fisheries, particularly longlining and trawling, whereas *C. mydas* and *E. imbricata* were predominantly linked to small-scale fisheries, especially gillnets. These patterns are further supported by the spatial distribution illustrated in Figure 6. Most studies focusing on sea turtle–fishery interactions in the SWAO were concentrated in southern Brazil and the Rio de la Plata estuary, aligning with the southern portions of each species' RMUs. Furthermore, *D. coriacea* and *L. olivacea* appeared more frequently in the northeastern region compared to other species.

FIGURE 5 - Schematic diagram illustrating the relationships between sea-turtle species and the characteristics of the fisheries analyzed. The numbers indicate the frequency of studies where each data point appears, while the colored bars represent the proportional distribution of records for each species. The graph at the bottom left shows the proportion of sea-turtle species studied over time. SSF, small-scale fisheries; DC, *Dermocheys coriacea*; CC, *Caretta caretta*; CM, *Chelonia mydas*; LO, *Lepidochelys olivacea*; EI, *Eretmochelys imbricata*; and Unclear, did not specify the species and were not included.

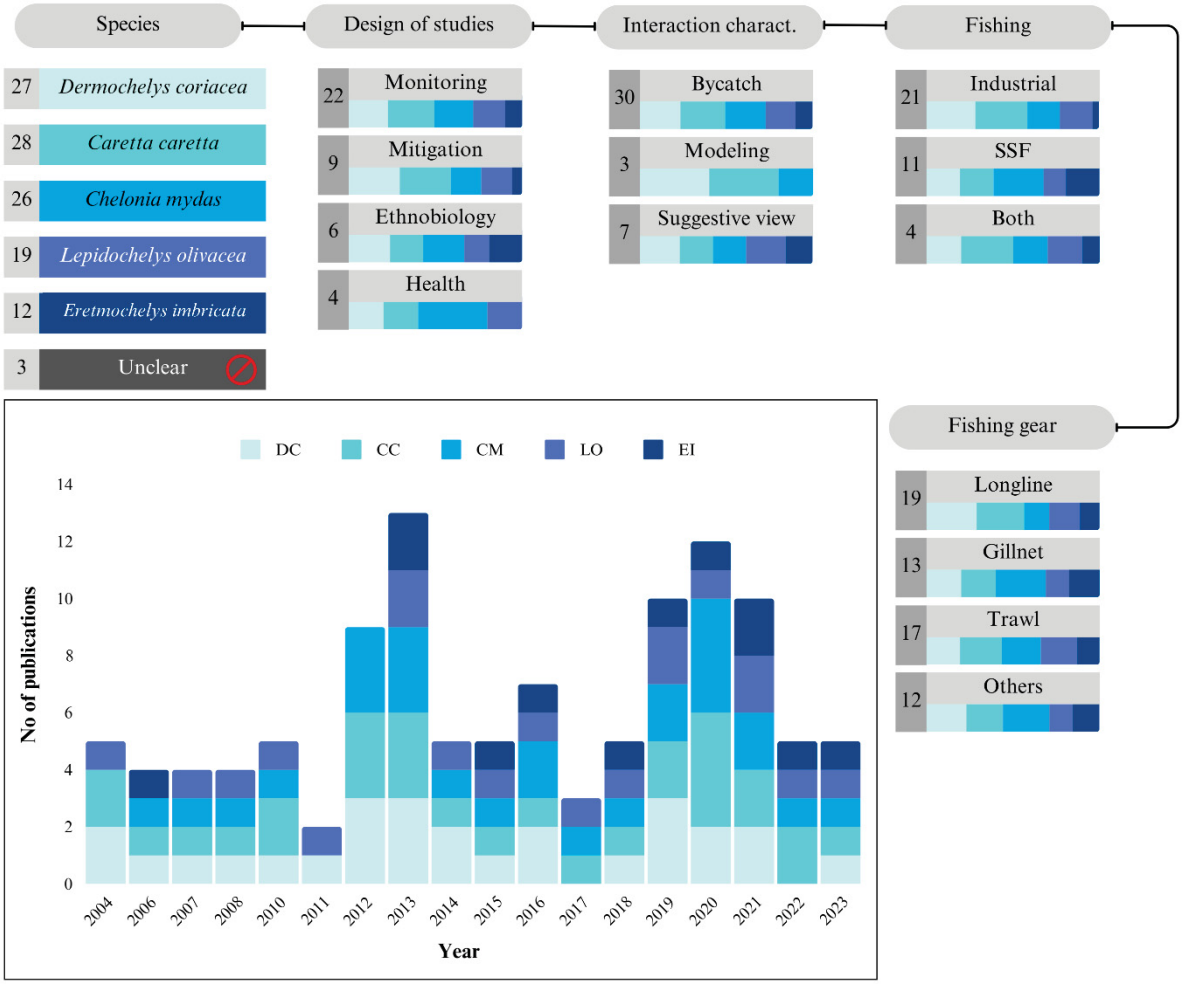
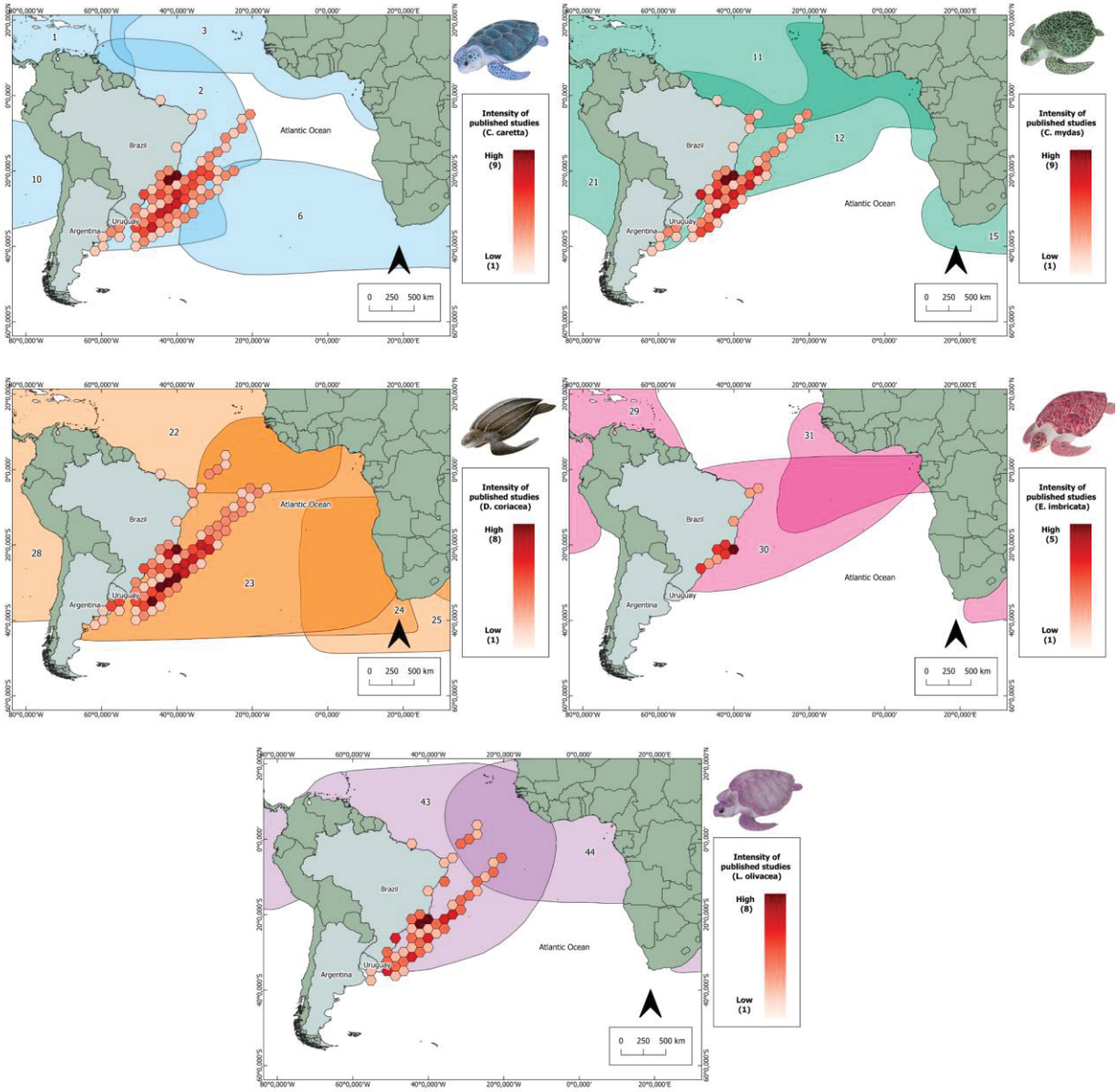


FIGURE 6 - The distribution of studies focusing on industrial and small-scale fisheries, emphasizing the regional management units (RMUs) associated with each species. Data outside the southwest Atlantic Ocean are not represented. The numbers within the RMUs indicate their corresponding identification according to Wallace et al. (2023).



3.4 MITIGATION APPROACHES IMPLEMENTED IN FISHING-ASSESSMENT STUDIES

Among only nine studies addressing mitigation methods, we categorized their methods as follows: (1) restriction: spatiotemporal closures; (2) modification: modified fishing gears; and (3) remediation: onboard release of live individuals. Three of the studies focused on modifying fishing gears, to include light-emitting diodes (LED), turtle excluder devices (TED), or the use of circular hooks (Table 1). Only one study focused on restricting fishing activities,

and via spatial and temporal alternation. of the remining two studies encompassed all categories, focusing on co-management in various aspects (Table 1).

TABLE 1 - Main information obtained from publications seeking to mitigate the incidental capture/mortality of sea turtles by fishing in the southwest Atlantic Ocean. LED, light emitting diode; TED, turtle excluder device; DC, *Dermocheys coriacea*; CC, *Caretta caretta*; CM, *Chelonia mydas*; LO, *Lepidochelys olivacea*; EI, *Eretmochelys imbricata*; and SSF, Small-scale fisheries.

Research	Country of research	Approach	Mitigation method	Specie	Fishing type	Fishing gear	Results
Afonso et al. 2021	Brazil	LED	Modification	NA	Industrial	Longline	Positive (to blue (peak wavelength at 465 nm) and white attractors
Domingo et al. 2012	Uruguay	Circle hook	Modification	DC, CC	Industrial	Longline	Inconclusive
Duarte et al. 2019	Brazil	TED	Modification	NA	Industrial	Trawl	Inconclusive
Gonzales-Carman et al. 2012	Argentina	Co-management	All categories	CM, DC, CC	SSF, industrial	Not specified (trawl, gillnet, longline, others)	Inconclusive
Pacheco et al. 2011	Brazil	Circle hook	Modification	DC, LO	Industrial	Longline	Positive
Rodrigues et al. 2022	Brazil	Time	Restriction	CC	Industrial	Longline	Positive
Sales et al. 2010	Brazil	Circle hook	Modification	CM, DC, LO, CC	Industrial	Longline	Positive
Schroeder et al.	Brazil	TED	Modification	NA	Industrial	Trawl	Inconclusive

2016							
Silva et al.	Brazil	Co-management	All categories	LO	SSF, industrial	Trawl	Inconclusive
2010							

As anticipated, mitigation efforts were more frequently associated with industrial longline fisheries, accounting for six of the studies, whereas small-scale fisheries and gillnets were rarely addressed. Consequently, mitigation studies were biased towards *D. coriacea* and *C. caretta*, with other species often being studied as secondary subjects in research primarily centered on these two species. The outcomes from this work were evenly distributed between positive and inconclusive, but with no negative impacts (i.e. in terms of target or bycatch species; Table 1).

4 DISCUSSION

This review highlights the historical distribution and characteristics of publications and authors related to sea-turtle bycatch in the SWAO-RMU. There has clearly been a growing trend in relevant publications in the last decade with notable increases in research focused on bycatch monitoring, mitigation strategies, and ethnobiology. Brazil has emerged as the primary contributor among authoring countries, reflecting a focus on local issues. Nevertheless, the Brazilian publications are primarily concentrated in the southern regions of the country and show greater integration with studies from Uruguay and northern Argentina than with research from the northern regions of Brazil.

Since the early years, research on sea turtles in northeastern Brazil has centered on land-based studies, particularly those focusing on adult females during the nesting season and on-nest monitoring (Seminoff & Shanker, 2008; Wildermann et al., 2018; Robinson et al., 2023). While such studies offer logistical advantages, they are limited in terms of assessing fishery impacts. Bycatch studies often report interactions involving juveniles or a mix of juveniles and adults, underscoring a high incidence of fishery-related impacts during critical developmental stages (Pinedo et al., 2004; Domingo et al., 2012; Ribeiro et al., 2014; López-Mendilaharsu et al., 2020; Nunes et al., 2023). As a result, the current research emphasis may hinder a more comprehensive understanding of the species' life cycle, particularly for the prolonged juvenile and immature phases spent predominantly in the marine environment (Wildermann et al., 2018).

Regardless of study focus, the observed increase in publications aligns with key environmental and policy milestones, considering the average delay in data publication. A notable turning point occurred in 2003 with the establishment of the 'ASO-Tortugas Network', which brought together research groups and individual scientists from Brazil, Uruguay, and Argentina. Given the shared habitat characteristics and anthropogenic threats in the SWAO, the network aimed to standardize scientific methodologies, strengthen regional collaboration, and coordinate conservation actions. Other publication peaks correspond with Brazil's ratification of the Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC) in 2001, the release of national sea turtle conservation action plans in 2011 and 2017, and the country's accession to the Convention on Migratory Species (CMS) in 2015.

Although Argentina and Uruguay participated in several of these key initiatives—some even preceding Brazil (Supplementary Table 2)—notable increases in publications from these countries only emerged around 2010. However, it is important to acknowledge that some relevant literature may have been missed, particularly older studies published in national journals or disseminated through grey literature. In addition to Caribbean and Latin American journals being underrepresented in international scientific database platforms (accounting for less than 3% of global production), Brazil still leads with the highest number of indexed journals, while Uruguayan articles do not appear in many (Crespo-Gascón et al., 2019; Barreto et al., 2021).

The differences in research output among the three countries may be at least partially explained by the influence of Brazil's environmental certification and licensing system. Under this framework, companies with significant environmental impacts are often required to fund research projects as part of their legal obligations, as established by Article 36 of Law No. 9,985 of July 18, 2000, and regulated by Articles 31 to 34 of Decree No. 4,340 of August 22, 2002 (https://www.planalto.gov.br/ccivil_03/leis/l9985.htm). This mechanism has the potential to foster studies on threatened species, including sea turtles, by recognizing research as a key component in the effective management of conservation units (Fonseca, 2015; Gaspar, 2023). In contrast, Argentina and Uruguay have less formalized structures and limited funding for conservation studies (González-Carman et al., 2012).

The role of structured legal mechanisms becomes even more evident when considering the evolution of regional bycatch research. Early studies emphasized the need to generate baseline data for monitoring bycatch and understanding broader ecological implications. In this context, initial research efforts relied heavily on *in situ* data collected primarily through onboard observations of industrial fleets. Brazilian policy makers, for example, took a substantial step

in this direction by establishing the National Observer Program for the Fishing Fleet (Programa Nacional de Observadores de Bordo da Frota Pesqueira – PROBORDO) in 2006 (Canton et al., 2023). This program mandated onboard observers on industrial vessels operating in the Brazilian EEZ, allowing for the systematic collection of detailed data on target species catches, bycatches and discards. However, despite its contributions to fisheries monitoring and conservation, PROBORDO was discontinued in 2012, leaving a deficit in long-term data collection efforts (Canton et al., 2023).

Similar in concept (albeit not at the same scale), in Patagonia, Argentina, since 2001, the Fisheries Secretariat of the Province of Chubut established the 'onboard observer program' (Programa de Observadores a Bordo da Provincia de Chubut - POBCh) for the double-rigged trawl fleet targeting Patagonian red shrimp (*Pleoticus muelleri*). Onboard observers collect biological data on target species and bycatch, contributing to enhancing knowledge about the ecosystem and biodiversity of the fishing areas (Góngora & Marin, 2016). Also, in Uruguay, the 'national onboard observer program' for the Uruguayan tuna fleet (Programa Nacional de Observadores a bordo de la Flota Atunera - PNOFA), established in 1998 and managed by the National Directorate of Aquatic Resources (Dirección Nacional de Recursos Acuáticos - DINARA), is crucial for monitoring fishing activities, particularly concerning tuna and other marine species catches (Passadore et al., 2012; Forselledo et al., 2019).

However, despite the potential of onboard observer programs to generate spatially and temporally comprehensive data, their continuity clearly has been hindered by substantial legal and logistical challenges (Canton et al., 2023). Additionally, these programs primarily monitor industrial fleets, likely due to the more structured legislation governing this sector, while small-scale fisheries remain largely unmonitored (Canton et al., 2023). Given the reliance on industrial fleets for data collection and the persistent legal and logistical constraints, alternative methods for studying interactions between sea turtles and fisheries have gained increasing prominence.

Since 2015, there has been an increasing use of ethnobiological approaches, which involve collecting data from local communities and fishers. These methods are not only more accessible and cost-effective than onboard observer programs but also facilitate data collection in regions where direct monitoring is challenging or prohibitively expensive (Silvano et al., 2023). Further, such initiatives foster collecting traditional ecological knowledge, enhancing the understanding of how human activities, including small-scale fisheries, impact natural resources and marine ecosystems (Molnár & Babai, 2021; Silvano et al., 2023).

The analyses of studies also revealed an increasing reliance on methodologies beyond *in situ* data collection to characterize interactions in publications since 2018. This trend may reflect the growing availability of data from systematic stranding records. In Brazil, such records are primarily generated through beach monitoring projects (Projetos de Monitoramento de Praias, or 'PMPs'), established as environmental requirements within licensing processes for hydrocarbon exploration and production activities. These projects are mandated by Article 36 of Law No. 9,985 (July 18, 2000) (https://comunicabaciadesantos.petrobras.com.br/projeto-de-monitoramento-de-praias-pmp-).

Most institutions involved in implementing PMPs are affiliated with universities or research non-governmental organizations, ensuring empirical rigor of data collection, analyses, and interpretation (https://comunicabaciadesantos.petrobras.com.br/projeto-de-monitoramento-de-praias-pmp-). These cost-effective, land-based monitoring programs generate valuable quantitative data, offering critical insights into the distribution, population structure, and mortality of marine turtle species, particularly in relation to anthropogenic impacts (Monteiro et al., 2016; Ten Doeschate et al., 2017; Tagliolatto et al., 2019b; Cantor et al., 2020; Fonseca et al., 2024; Oliveira et al., 2024).

This work has revealed distinct species-specific hotspots: studies on *D. coriacea*, *C. caretta*, and *L. olivacea* were primarily conducted in oceanic zones, whereas *C. mydas* and *E. imbricata* were more commonly associated with coastal areas. The spatial distribution of fisheries-related studies was uneven across RMUs in the SWAO, with certain units receiving disproportionately more attention. This pattern reflects both the ecological relevance of these areas and the focused allocation of research efforts, emphasizing the spatial overlap between fishing activities and critical habitats. Notably, Wallace et al. (2011) had already identified the Atlantic Ocean RMUs as particularly threatened by anthropogenic pressures, especially bycatch.

These management units are often defined based on groupings of the same species that share essential areas for different life-cycle phases, including reproduction, foraging, and juvenile development (Wallace et al., 2010b; Wallace et al., 2023). Although RMUs follow a regional approach, they can be effectively applied to areas that host multiple populations or stocks of various species (Wallace et al., 2010b; Wallace et al., 2023).

The SWAO-RMU is somewhat unique in that it comprises five species; all of which are impacted by fishing, albeit with some clear gear-specific differences reflecting life histories. Specifically, *D. coriacea*, *C. caretta*, and *L. olivacea* were more frequently associated with industrial fisheries whereas *C. mydas* and *E. imbricata* were impacted by small-scale fisheries.

The first three species exhibit generalist foraging strategies, moving widely between pelagic and neritic zones. *D. coriacea* primarily feeds on gelatinous zooplankton, while *C. caretta* and *L. olivacea* are generalist carnivores, consuming mollusks, crustaceans, and fish, with dietary shifts depending on habitat and life stage (James et al., 2006; Medeiros et al., 2019; Bezerra et al., 2024). Both *C. caretta* and *D. coriacea* have broad distributions in the south Atlantic Ocean, with several overlapping areas and known migratory corridors, particularly in the southern portion of Brazilian waters (Kotas et al., 2004; Pinedo & Polacheck, 2004; Fossette et al., 2014; Di Beneditto, Moura & Siciliano, 2015). *L. olivacea*, while present along nearly the entire Brazilian coast, is most concentrated in the north (Silva et al., 2011; Domingo et al., 2025).

All three species use both offshore and coastal waters year-round, reflecting complex spatial patterns. However, they predominantly occupy the upper 200 m of the water column, where interactions with industrial fisheries—especially semi-pelagic longlines—are likely to occur (Polovina et al., 2004; Barceló et al., 2013; Fossette et al., 2014; Domingo et al., 2025). These three species have been associated with incidental capture by the industrial pelagic longline fleet targeting swordfish (*Xiphias gladius*), tuna (*Thunnus* spp.), and various species of sharks off Brazil (Kotas et al., 2004; Pinedo & Polacheck, 2004; Sales et al., 2008; Pons et al., 2010).

Additionally, industrial double-rigged penaeid and single-rigged fish trawlers have also interacted with these species in the same regions off Brazil (Guimarães et al., 2017). Tagliolatto et al. (2019a) reported that *C. caretta* (52.2%) and *L. olivacea* (38.8%) were the most frequently captured species by pink shrimp (*Farfantepenaeus* spp.) and industrial fish trawlers operated at São Paulo and Rio de Janeiro states between 2015 and 2018. Similarly, Jones et al. (2024) identified these two species as being the most affected by demersal bottom trawling, from Bahía Blanca to Río de la Plata estuaries, Argentina. Notably, *C. caretta*, *D. coriacea*, and *C. mydas* are the three most commonly occurring sea turtle species in the waters off Argentina and Uruguay, which also explains the higher levels of interaction between the first two species and industrial fleets (Lezama (2009; Gonzáles-Carman et al., 2011).

Unlike *C. caretta* and *D. coriacea*, juvenile and adult *C. mydas* are commonly described as herbivorous but can also be classified as generalist and opportunistic consumers (Santos et al., 2015; Gama et al., 2021). Depending on their geographical location and life stage, their diet may comprise macroalgae, seagrass, and/or invertebrates (Gama et al., 2016; Seminoff et al., 2021). Similarly, *E. imbricata* is generally considered an omnivore, often favoring sponges, but it also consumes tunicates, algae, and mangrove material (Martínez-Estévez et al.,

2021; Reynolds et al., 2023). Among juveniles and subadults, which exhibit more coastal behavior, this dynamic increases the likelihood of overlapping with small-scale fishing practices operating in neritic areas, and stranding on proximal shores (Gallo et al., 2006).

Several studies, particularly ethnobiological, have highlighted interactions between juveniles of *C. mydas* and *E. imbricata* and artisanal gillnet fleets off Brazil (Gallo et al. (2006), López-Barrera, Longo, and Monteiro-Filho (2012), Guebert et al. (2013), and Nogueira and Romeu (2016)0 reported. Similarly, Gonzales-Carman et al. (2011) and Lezama (2009) documented small-scale gillnet fisheries interacting with *C. mydas* off Argentina and Uruguay. Nevertheless, the absence of legal frameworks for regulation, management, and monitoring precludes accurate estimation of the broader impacts (González-Cárman et al., 2012). This deficit not only obscures the true extent of bycatch and collateral mortalities but also leads to underestimating both the sector's socioeconomic contributions and its environmental impacts (Castro et al., 2021).

For instance, an initiative to monitor small-scale fisheries along the southern coast of Brazil began in 2016 with the Santos Basin Fisheries Monitoring Project (Projeto de Monitoramento da Atividade Pesqueira da Bacia de Santos - PMAP-BS). Although originally designed to systematically monitor fish catches and assess the region's socioeconomic and structural fishing characteristics, data collection has relied on monitoring landed catches. Consequently, there are no onboard observers, and incidental catch data are not recorded, limiting bycatch assessments (https://comunicabaciadesantos.petrobras.com.br/projeto-de-monitoramento-da-atividade-pesqueira-pmap-).

The same pattern is also reflected in the results obtained for publications addressing mitigation efforts. This work was more frequently associated with industrial fisheries, whereas small-scale fisheries and gillnets were rarely considered. Consequently, mitigation studies have been predominantly focused on *D. coriacea* and *C. caretta*, with other species only peripherally examined. The main mitigation approach identified involved modifications to fishing gears, notably the testing of TEDs in trawls and circle hooks on longlines (Table 2).

Most publications have focused on Brazilian fishing fleets and, as in other contexts, suggest that research efforts may be shaped by national legislation and regional market or certification pressures. The first TED initiatives in Brazil began in 1994, largely driven by economic pressure from the United States regarding penaeid imports (Renaud et al., 1992; Duarte et al., 2018). Ordinance No. 36 (April 7, 1994) mandated TED use in penaeid shrimp trawl vessels ≥11 m targeting *Penaeus paulensis*. Later, Ordinance No. 5 (1997) extended this requirement to all ≥11 m vessels authorized for penaeid - fishing along the coast, regardless of

target species. However, over the following three decades, TED adoption has remained limited, and enforcement is largely absent (Duarte et al., 2018).

In addition to penaeid trawling, previous studies documented interactions between longline fisheries and sea turtles off Brazil (Domingo et al., 2006; Giffoni et al., 2014), although the mandatory implementation of circle hooks (designed to reduce turtle catches but especially hook ingestion and therefore death) only occurred in 2017 through Interministerial Ordinance No. 74. This regulation required the use of circle hooks by both national and leased foreign vessels operating in Brazilian territorial waters, specifically those using the pelagic longlines (https://www.icmbio.gov.br/).

In contrast, no similar regulations were found for Uruguay and Argentina. Although interactions with the above types of fisheries have been reported in these countries (Domingo et al., 2006; Laporta et al., 2006; González-Carman et al., 2012; Domingo et al., 2012; Laporta et al., 2013; Jones et al., 2024), bycatch rates remain poorly understood, highlighting a deficit in monitoring and management (González-Carman et al., 2012). The delays between scientific findings and regulatory actions suggest that strong evidence alone may not be sufficient to evoke immediate policy changes, emphasizing the influence of broader policy frameworks, and better comprehension of industry dynamics, and enforcement challenges in fisheries management.

One important, often limiting factor to adopting mitigation methods is perceived negative impacts to established fishing practices. For example, while modified fishing gears may offer high cost-effectiveness and efficiency in reducing sea turtle bycatch, their effectiveness may vary among different taxonomic groups, including those commercially retained for sale (Castro et al., 2021). For instance, TEDs are widely used in overseas industrial trawl fisheries and are effective for all species of turtles (depending on bar spacings). The biggest challenge is getting fishers in some areas to use the devices, and often because they reduce catches of fish and other commercially important species (Duarte et al., 2019). Similarly, the use of circle hooks in longline fisheries has been shown to reduce bycatches and mortalities of *D. coriacea* and *C. caretta* while simultaneously increasing the capture of other species, particularly sharks (Sales et al., 2010; Santos et al., 2013).

Thus, although existing techniques are legally supported and provide significant benefits, their variable effectiveness among catches of different taxa and species underscores the need for continuous monitoring, adaptation, enforcement and the development of complementary regional strategies. A more integrative approach that considers the ecological roles and vulnerabilities of different species is essential to improving conservation outcomes

and ensuring the sustainability of fisheries. Moreover, integrating traditional and scientific knowledge is important to increase effectiveness of any mitigation approach, particularly for small-scale fisheries.

4.1 BRIDGING GAPS, SETTING PRIORITIES FOR CONSERVATION AND GOVERNANCE AND CONCLUSIONS

The review of available studies revealed substantial knowledge gaps regarding sea-turtle bycatch and mortality in the SWAO, particularly regarding the geographical distribution of research, the species and life stages studied, and data collection methods. In Brazil, most bycatch studies have been concentrated in the southern regions. In contrast, the northern region from Rio de Janeiro to Rio Grande do Norte are home to critical nesting and foraging areas for all five sea turtle species in the SWAO but have received comparatively little attention (Marcovaldi & Marcovaldi, 1999). These latter areas play a crucial role in sea-turtle life cycles (Marcovaldi & Marcovaldi, 1999; Moura et al., 2012; Lopez et al., 2015; Siqueira et al., 2021; Pereira et al., 2023) while also supporting extensive fishing activities, particularly small-scale fisheries, leading to frequent interactions with sea turtles (Silva et al., 2010; Santos et al., 2021). The lack of studies quantifying these interactions hampers the understanding of bycatch impacts on reproductive populations, thereby limiting the effectiveness of conservation and management strategies.

Another deficit is the underrepresentation of male and juvenile sea turtles in research, with existing studies primarily focusing on adult females during the nesting season due to the logistical and financial feasibility of land-based sampling (Seminoff & Shanker, 2008; Wildermann et al., 2018). This lack of information is particularly concerning since fisheries bycatch frequently affects juveniles (López-Barrera; Longo; Monteiro-Filho, 2012; López-Mendilaharsu et al., 2019), which, due to their late sexual maturity, constitute most of the regional population (Wildermann et al., 2018). Neglecting quantifying the impacts to this life stage may lead to biased conservation assessments and ineffective management decisions. Additionally, The lack of systematic in situ monitoring of small-scale fisheries leads to underestimating the overall bycatch impact, particularly in coastal regions where these fisheries are predominant (Castro et al., 2021). Greater efforts at quantifying the bycatch of inshore fleets are therefore warranted.

Further, while ethnobiological approaches have proven valuable for gathering data in areas where direct monitoring is unfeasible, particularly in small-scale fisheries, they rely on interviews with fishers and local communities, which can introduce biases (Moore et al., 2010;

Nogueira & Alves, 2016; González-Carman & Carman, 2018; Awabdi et al., 2021). The reliability of such data varies depending on the collection methodology and the willingness of fishers to report bycatch incidents. Additionally, the lack of standardization in ethnobiological methods hinders comparability between studies and regions (Moore et al., 2010).

The challenges faced in small-scale fisheries also extend to bycatch mitigation strategies in the SWAO. While various mitigation methods are well-documented overseas and legislated (albeit with variable participation) among some industrial fleets in the SWAO, there is a dearth of research regarding applicability of solutions among small-scale fisheries. It remains unclear whether techniques developed for industrial fisheries or overseas more broadly can be effectively adapted to small-scale use and, which socioeconomic factors may hinder adoption. Efforts to address this lack of work are urgently required.

Although Brazil has made progress in implementing conservation policies, such as ratifying the IAC and adopting National Action Plans, a gap remains between scientific knowledge production and the implementation of evidence-based conservation measures. In countries such as Argentina and Uruguay, the lack of robust legal frameworks and insufficient research funding pose additional challenges for developing effective policies. Uruguay still lacks an official threatened species list, underscoring the need for advances in marine biodiversity protection (Supplementary Table 2).

Based on the analyses of available data, substantial gaps have been identified that need to be prioritized to improve the conservation and management of sea turtles in the SWAO. Despite the various methodologies developed over the years, we recommend implementing long-term onboard observer programs with qualified researchers and/or technicians, and/or a monitoring program with cameras and GPS tags on the boats, particularly for small-scale fisheries. Such programs, combined with ethnobiological approaches and quantitative methods, can enhance data quality and deepen knowledge on the incidental capture of sea turtles in these fisheries. For industrial fisheries, the government should insert more effort in monitoring fleets by satellite equipment, including developing algorithms and analytical strategies to confirm fishing activities and promote more efficient enforcement. Moreover, it is essential to expand such programs and research in general to the north of Brazil, where the interaction between sea turtles and small-scale fisheries is significant but still poorly documented.

Enhancing national action plans, improving the implementation of legislation, and creating participatory spaces for fishers and communities are essential strategies for ensuring the effective implementation of mitigation measures. Finally, it is imperative to reduce biases in the evaluation of mitigation strategies, ensuring that both successes and failures are

transparently reported. In the long term, the integration of research, policy formulation, and systematic monitoring will be crucial to minimizing the impacts of incidental capture of sea turtles in the SWAO and ensuring their effective conservation more broadly.

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6 SUPPLEMENTARY MATERIALS

SUPPLEMENTARY TABLE 1 - Main information obtained from publications describing the incidental capture/mortality of sea turtles by fishing in the southwest Atlantic Ocean. (†) refers to publications that did not specify the species and where regional management units (RMUs) could not be inferred. DC, *Dermocheys coriacea*; CC, *Caretta caretta*; CM, *Chelonia mydas*; LO, *Lepidochelys olivacea*; EI, *Eretmochelys imbricata*; and SSF, Small-scale fisheries.

Research	Country of research	RMU	Design of study	Specie	Fishing type	Fishing gear	Interaction characterization
Afonso et al. 2021	Brazil	NA†	mitigation	NA	industrial	longline	bycatch
Awabdi et al. 2018 2021	Brazil	2, 12, 23, 30, 43	etnobio	CM, DC, LO, EI, CC	SSF	gillnet, trawl, line	bycatch
Barreto et al. 2022	Brazil	2, 12, 30, 43	monitoring	CM, LO, EI, CC	NA	NA	suggestive impressions
Bugoni et al. 2007	Brazil	2, 12, 30, 43	monitoring	CM, DC, LO, CC	industrial	longline, trawl, others	bycatch
Domingo et al. 2012	Uruguay	2, 23	mitigation	DC, CC	industrial	longline	bycatch
Duarte et al. 2019	Brazil	NA†	mitigation, etnobio	NA	industrial	trawl	bycatch
Fiedler et al. 2020 2012	Brazil	2, 12, 23, 30, 43	monitoring	CM, DC, LO, EI, CC	SSF, industrial	gillnet, others	bycatch
Fossette et al. 2014	Brazil, Argentina, and Uruguay (all Atlantic ocean)		monitoring	DC	industrial	longline	modeling
Gallo et al. 2006	Brazil	2, 12, 23, 30	monitoring	CM, DC, EI, CC	SSF	trawl, gillnet, others	bycatch
Gonzales-Carman et al.	Argentina	2, 12, 23	etnobio, mitigation	CM, DC, CC	SSF, industrial		bycatch

2012 2018						not specified (trawl, gillnet, longline, others)	
Guebert et al. 2013	Brazil	2, 12, 23, 30	etnobio	CM, DC, EI, CC	SSF	gillnet	bycatch
Guimarães et al. 2017	Brazil	2, 12, 23	monitoring	CM, LO, CC	industrial	trawl	bycatch
Huang 2015	Brazil, Argentina, and Uruguay (all Atlantic ocean)		monitoring	CM, DC, LO, EI, CC	industrial	longline	bycatch
Jerdy et al. 2004	Brazil	12	health	CM	SSF	gillnet	bycatch
Kotas et al. 2004	Brazil	2, 23	monitoring	DC, CC	industrial	longline	bycatch
Laporta et al. 2013	Brazil	2, 12, 30, 43	monitoring	CM, DC, LO, CC	industrial	trawl	bycatch
Lima et al. 2021 2012 2019 2020	Brazil	2, 12, 23, 30. 43	monitoring	CM, DC, LO, EI, CC	NA	gillnet, longline, others	suggestive view
López-Barrera et al. 2012	Brazil	12	monitoring	CM	SSF	gillnet	bycatch
López-Mendilaharsu et al. 2019 2020	Brazil, Uruguay, and Argentina	2, 23	monitoring	DC, CC	SSF, industrial	trawl, longline	bycatch, modeling
Miguel et al.	Brazil	12	health	CM	SSF	gillnet, others	bycatch

2020							
Nogueira and Alves 2016	Brazil	12, 23	etnobio	CM, DC	SSF	trawl, gillnet, longline, others	bycatch
Nunes et al. 2023	Brazil	2, 12, 23, 30, 43	monitoring	CM, DC, LO, EI, CC	NA	NA	suggestive view
Oliveira and Schiavetti 2013	Brazil	2, 12, 23, 30, 43	etnobio	CM, DC, LO, EI, CC	SSF	trawl, gillnet, longline, others	bycatch
Pacheco et al. 2011	Brazil	23, 43	mitigation	DC, LO	industrial	longline	bycatch
Pinedo and Polachek 2004	Brazil	2, 23, 43	monitoring	DC, LO, CC	industrial	longline	bycatch
Pons et al. 2010	Brazil and Uruguay	2	monitoring	CC	industrial	longline	bycatch
Praga et al. 2020	Brazil	2, 43	health	LO, CC	industrial	trawl	bycatch
Prosdocimi et al. 2020	Argentina and Uruguay	2, 12, 23	monitoring	CM, DC, CC	industrial	trawl	modeling
Ribeiro et al. 2014	Brazil	2, 12, 30, 43	monitoring	CM, DC, LO, CC	NA	others	suggestive view
Rodrigues et al. 2022	Brazil	2	mitigation	CC	industrial	longline	bycatch
Sales et al. 2008 2010	Brazil	2, 12, 30, 43	monitoring, mitigation	CM, DC, LO, CC	industrial	longline	bycatch
Santos-Costa et al. 2020	Brazil	23	health	DC	NA	NA	suggestive view
Schroeder et al.	Brazil		mitigation		industrial	trawl	bycatch

2016		2, 12, 23, 30, 43		CM, DC, LO, EI, CC			
Silva et al. 2010	Brazil	43	monitoring, mitigation	LO	SSF, industrial	trawl	suggestive view
Tagliolatto et al. 2019	Brazil	2, 12, 23, 30, 43	monitoring	CM, DC, LO, EI, CC	SSF, industrial	trawl, gillnet, longline	bycatch, suggestive view
2019							

SUPPLEMENTARY TABLE 2 - Important turning points in sea turtle conservation over the years.

Turning point	Year	Country	Starting year	Scale
Convention of Migratory Species (CMS)	1979	Argentina	1992	International
		Brazil	2015	
		Uruguay	1990	
Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)	1975	Argentina	1981	International
		Brazil	1975	
		Uruguay	1975	
Convention of Biological Diversity (CBD)	1992	Argentina	1995	International
		Brazil	1994	
		Uruguay	1994	
Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC)	2001	Argentina	2011	Central and South America
		Brazil	1997	
		Uruguay	1998	
National Action Plans	-	Argentina	2014	Local (each country)
		Brazil	2010/2017/2023	
		Uruguay	Non-existent	

SUPPLEMENTARY TABLE 3 - Global and regional threat levels of sea turtles occurring in the Southwestern Atlantic Ocean (SWAO). Regional threat levels for each country were reported based on endangered national species lists. (*) Indicates species that do not occur regionally in the SWAO. (-) Indicates either the species' absence from the national threatened species list (Brazil) or the lack of an official endangered species list for the region (Uruguay). IUCN, International Union for Conservation of Nature; VU, Vulnerable; EN, Endangered; CR, Critically Endangered.

Specie	**Threat category**			
	Global (IUCN)	Argentina	Brazil	Uruguay
Dermochelys coriacea	VU	CR	CR	-
Caretta Caretta	VU	EN	VU	-
Chelonia mydas	EN	EN	-	-
Lepidochelys olivacea	VU	*	VU	*
Eretmochelys imbricata	CR	*	EN	*

CAPÍTULO 2

Distribuição espaço-temporal de tartarugas-verde (*Chelonia mydas*) encalhadas com sinais de interação com pesca ao longo da costa sul do Brasil

Spatio-temporal distribution of green turtles (*Chelonia mydas*) stranded with fisheries interaction along the southern coast of Brazil

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Spatio-temporal distribution of stranded green turtles (*Chelonia mydas*) in southern Brazil

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HIGHLIGHTS

1. A total of 42,333 *Chelonia mydas* strandings were recorded by PMP-BS between 2016 and 2023 along 1,400 km of coastline from Rio de Janeiro to Santa Catarina.
2. The majority were juveniles (39.3 ± 7.3 cm CCL) and females (4:1 sex ratio), with an overall mortality rate of 90%.
3. Paraná exhibited the highest stranding rates, with peaks in winter and spring.
4. The main anthropogenic impacts were related to fisheries (37.2% of strandings with assessable evidence), and entanglement (36.0%) and ingestion of marine debris (41.6%).
5. The high and potentially unsustainable juvenile mortality underscores the urgent need to review coastal fisheries management.

RESUMO

Foram analisados oito anos (2016 a 2023) de dados diários sobre encalhes de *Chelonia mydas* ao longo de quatro estados do sul e sudeste do Brasil (do Rio de Janeiro a Santa Catarina; ~1400 km de costa), com o objetivo de identificar padrões espaço-temporais de mortalidade, sexo, estágio de vida e impactos antrópicos. No total, foram registrados 42.333 indivíduos (com 90% de mortalidade), a maioria juvenis (média do comprimento curvilíneo da carapaça ± DP de 39,3 ± 7,3 cm) e com razão sexual enviesada para fêmeas (4:1). O Paraná apresentou as maiores taxas semanais de encalhes por 100 km de costa, mais que o dobro das registradas nos demais estados, especialmente entre junho e dezembro (inverno e primavera austral). A maioria dos indivíduos apresentava decomposição avançada (70%). Entre os animais que puderam ser analisados (11,885), interações antrópicas relacionadas à pesca foram documentadas em 4.418 indivíduos (37,2% dos avaliáveis). Essas interações também variaram no tempo e no espaço, mas com maiores probabilidades (log odds) de ocorrência no verão e início do outono, especialmente no Paraná. A interação (estrangulamento) com resíduos sólidos marinhos (4.955 casos ou 41,6%) também variou espaço-temporalmente, com maiores probabilidades de ocorrência durante o inverno no Rio de Janeiro, São Paulo e Paraná, e probabilidades muito menores ao longo do ano em Santa Catarina. Outras interações registradas mantiveram certa estabilidade temporal, mas variaram entre os estados, incluindo ingestão de resíduos sólidos (4.279 casos ou 36,0%, mais frequente no Paraná e em São Paulo), colisões com embarcações (1.233 casos ou 10,4%, concentradas no Rio de Janeiro), agressões (760 casos ou 6,4%, com menor ocorrência em Santa Catarina) e dragagem (36 casos; <1%). O esforço pesqueiro sazonal, aliado ao comportamento migratório e às exigências energéticas de *C. mydas,* pode explicar os padrões regionais de encalhes observados. De forma geral, os resultados sugerem níveis de mortalidade altos e potencialmente insustentáveis para juvenis de múltiplos estoques que se agregam na região. O encalhe não reflete o número total de mortalidade, fato que reforça a necessidade urgente de revisão das estratégias de gestão da pesca, principalmente a costeira e de pequena escala, bem como inserção da perda de juvenis nos critérios de classificação de risco de extinção da espécie, considerando os impactos populacionais da ampla retirada do estágio de desenvolvimento da população de *C. mydas* do oceano Atlântico Sul ocidental.

Palavras-chave: tartaruga-marinha, captura incidental, declínio populacional, encalhe, gestão de pesca

ABSTRACT

Eight years (2016–2023) of data describing daily *Chelonia mydas* strandings across four southern Brazilian states (Rio de Janeiro to Santa Catarina; ~1400 km of coastline) were analyzed to inform spatio-temporal trends in mortality, sex, life stage and anthropogenic impacts. In total, 42,333 *C. mydas* were recorded (90.0% mortality); most of which were juveniles (mean ± SD curved carapace length of 39.3 ± 7.3 cm) with a sex ratio biased towards females (4:1). Paraná had the greatest weekly stranding rates per 100 km of coastline—more than double those in other states, particularly between June and December (austral winter and spring). Most individuals had an advanced decomposition stage (70%). Anthropogenic interactions related to fishing activities were documented in 4,418 individuals (i.e. 37,2% of those that could be assessed) and biased towards individuals in early decomposition. While such interactions also varied across space and time, they generally had greater log odds of occurrence during summer and early autumn, especially in Paraná. Marine debris entanglement (4,955 cases or 41.6%) also varied spatio-temporally but with greater log odds during winter in Rio de Janeiro, São Paulo and Paraná, and much lower log odds year-round in Santa Catarina. Other recorded interactions remained temporally consistent, but varied across states, including marine debris ingestion (4,279 or 36.0% and greatest in Paraná and São Paulo), boat collisions (n = 1,233 or 10.4% biased to Rio de Janeiro), aggression (n = 760 or 6.4% and lowest in Santa Catarina), and dredging (n = 36; <1%). Seasonal fishing effort, combined with the migratory behavior and energetic requirements of *C. mydas*, may explain the observed regional stranding patterns. Overall, our findings suggest great and potentially unsustainable mortality levels for regional juvenile *C. mydas* and, considering the impact on this vulnerable life stage, underscore the need for revised fisheries management strategies, particularly for coastal and small-scale fisheries, as well as further assessments of the species' extinction-risk classification in the region. The high level of juvenile mortality across multiple genetic stocks may contribute to the decline of the Atlantic Southwestern *C. mydas* population.

Keywords: sea turtle, bycatch, population decline, strandings, fishery management

1 INTRODUCTION

Chelonioid sea turtles (Hirayama, 1994) are widely recognized as environmental sentinels (Domiciano et al., 2017), having played key ecological roles in marine ecosystems since the Late Cretaceous epoch by facilitating energy transfer across trophic levels (Roche et al., 2021). In addition to their ecological importance, sea turtles have had deep cultural, traditional, and spiritual significance in human societies for millennia, and this longstanding relationship has led to their frequent use as flagship species in marine-conservation campaigns (Campbell, 2002; Godley et al., 2020).

Over the past ~150 years, increasing anthropogenic pressures have exposed sea turtles to complex and growing threats, including overfishing, habitat loss and degradation, various forms of pollution, hunting and poaching, invasive species, diseases, and climate change (Seminoff et al., 2004; Seminoff & Shanker, 2008; Domiciano et al., 2017; Fuentes et al., 2020; Castro et al., 2021). While all threats contribute to cumulative impacts and widespread population declines, fisheries 'bycatch' is regarded as a primary cause of mortality affecting all sea-turtle species (Marcovaldi et al., 2006; Wallace et al., 2010; Lewison et al., 2014; Wallace et al., 2023).

Currently, seven species of sea turtles are recognized globally; five of which occur within the Southwestern Atlantic Ocean Regional Management Unit (SWAO-RMU): the green turtle (*Chelonia mydas*), loggerhead turtle (*Caretta caretta*), leatherback turtle (*Dermochelys coriacea*), hawksbill turtle (*Eretmochelys imbricata*), and olive ridley turtle (*Lepidochelys olivacea*) (Marcovaldi & Marcovaldi, 1999). These species share similar life-history traits such as delayed sexual maturity, trans-oceanic migrations, and reliance on diverse habitats and food resources throughout their ontogeny (Lewison et al., 2014). Such life-history traits make sea turtles adaptive for long-term survival, but they also increase vulnerability to cumulative and synergistic anthropogenic impacts (Castro et al., 2021).

In the SWAO-RMU, interactions between the five sea-turtle species and various fishing practices, such as longlining, trawling, and gillnetting, are well documented (Gallo et al., 2006; Sales et al., 2008; López-Barrera et al., 2012; Fiedler et al., 2020; Maruyama et al., 2023). Spatial overlap between sea-turtle foraging areas and fishing grounds substantially increases the risk of bycatch and mortality, contributing to some of the highest sea-turtle stranding rates reported globally—particularly for the *C. mydas* subpopulation in southern Brazil where up to >5000 are stranded on beaches each year (Monteiro et al., 2016; Tagliolatto et al., 2019b; Cantor et al., 2020; Fuentes et al., 2020; Maruyama et al., 2023; Prado et al., 2023; Fonseca et al., 2024). This region supports large-, medium-, and small-scale fisheries, with just

over 16,000 vessels operating in the area (MPA, 2023). However, bycatch in small-scale gillnet fisheries is considered the primary anthropogenic threat to this *C. mydas* subpopulation. Nonetheless, critical knowledge gaps remain regarding the structure of small-scale fisheries and the spatio-temporal dynamics of bycatch within the SWAO-RMU (López-Barrera et al., 2012; Castro et al., 2021).

Within this context, standardized beach monitoring has emerged as a useful tool for detecting and documenting sea-turtle strandings and interactions with fisheries, especially when necropsies are performed on recovered individuals. Since 2015, the 'Santos Basin Beach Monitoring Project' (Projeto de Monitoramento de Praias da Bacia de Santos – PMP-BS) has conducted systematic surveys along the coast of Rio de Janeiro, São Paulo, Paraná, and Santa Catarina, recording all stranded turtles and making these data publicly available via the 'Marine Biota Monitoring Information System' (SIMBA; Fig. 1). Daily monitoring of ~1,400 km of coastline has generated a robust dataset on sea-turtle biology and mortality. Recently, this dataset was used to identify stranding trends (Cantor et al. 2020) and propose management strategies, particularly for *C. caretta* (Fonseca et al., 2024). Nevertheless, long-term and integrated evaluations of *C. mydas* strandings and their associations with human activities—particularly fisheries—remain limited.

Given the prioritization of bycatch reduction in national and international conservation agendas, this study aimed to assess the spatial and temporal patterns of *C. mydas* strandings, mortality, and fisheries interactions in southern Brazil. The specific objectives were to (a) analyze the subpopulation structure of stranded *C. mydas* individuals with and without signs of fisheries interactions and identify those fishing gears most likely to spatio-temporally overlap and then (b) evaluate risks and knowledge gaps associated with any regional interactions. Ultimately, satisfying these objectives informs conservation strategies for helping to address anthropogenic threats to *C. mydas* in the SWAO-RMU.

2 METHODS

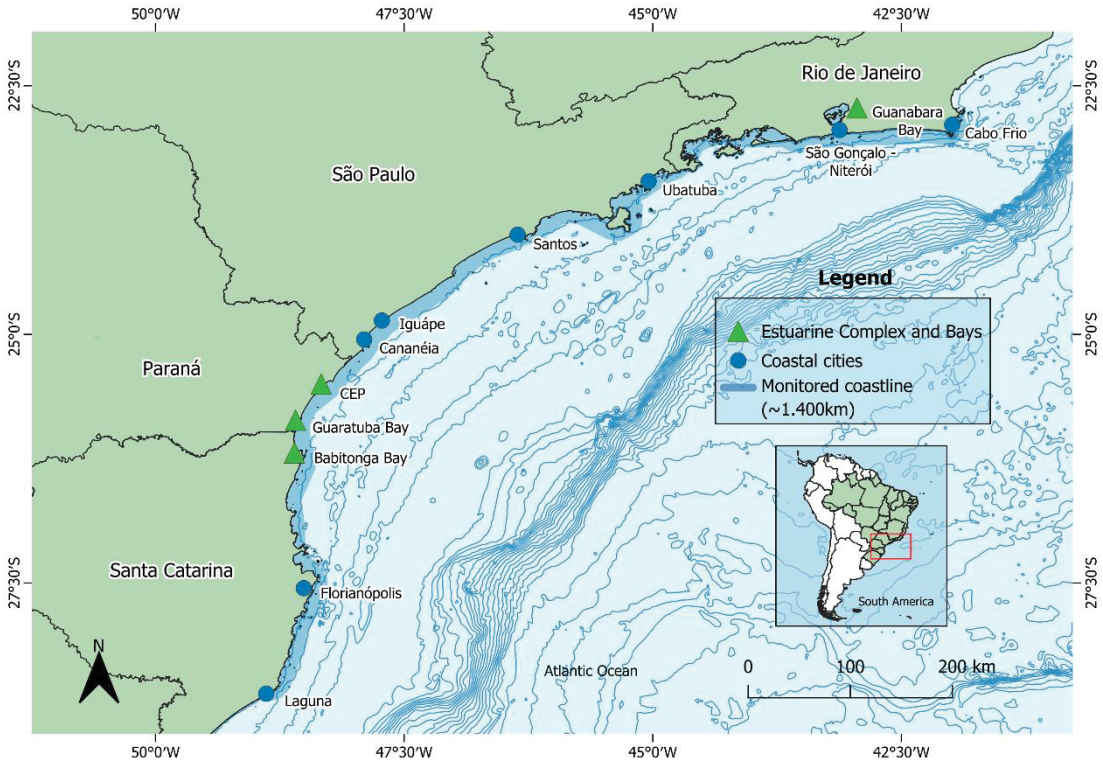
2.1 STUDY AREA

The Santos Basin extends across the southern Brazilian continental margin, between the states of Rio de Janeiro and Santa Catarina. It is bounded to the north by the Cabo Frio Arch, which separates it from the Campos Basin, and to the south by the Pelotas Basin at the Florianópolis Platform (Fig. 1). To the west, the Serra do Mar physiographic formation marks its boundary with the oceanic domain (PCR-BS, 2022).

Off the Santos Basin, the continental shelf supports high production and autotrophic biomass. Nutrient enrichment occurs from coastal upwellings, such as off Cabo Frio where the maximum primary productivity ranges from 9.77 mgC/m³/h at the surface to 14.98 mgC/m³/h at the base of the mixed layer (Gonzalez-Rodriguez et al., 2017). Other significant continental inputs include estuarine discharge, such as that from the Paranaguá estuarine complex, Cananéia-Iguape estuarine-lagoon system, and eutrophic bays, such as Santos, Guanabara and Babitonga bays (Fig. 1). In contrast to continental areas, oceanic portions are predominantly oligotrophic (Barrera-Alba et al., 2009; Villac & Tenenbaum, 2010).

Fishing activities are described below by fleet origin, with emphasis on the study area. Given the high productivity and wide distribution of resources, fleets from neighboring states—such as Espírito Santo and Rio Grande do Sul—also operate in the region (Sales et al., 2008; López-Mendilaharsu et al., 2020).

FIGURE 1 – Coastal area monitored by the Santos Basin Beach Monitoring Project (PMP-BS) along the southern Brazilian coastline. CEP, Paranaguá estuarine complex.



2.2 FISHING ACTIVITIES

2.2.1 Rio de Janeiro state

Rio de Janeiro comprises about 8% of the Brazilian coastline and contributes nearly 10% of national fishery production (Fig. 1; Di Beneditto, 2001; PMAP-RJ, 2020). Annual landings are ~45,000 tonnes (t) across 44 fishing sites in 15 municipalities, with industrial

fisheries accounting for ~70% of this total. São Gonçalo, Niterói, Cabo Frio, and Angra dos Reis represent around 90% of the state's production (PMAP-RJ, 2020). Industrial fisheries land ~130 species, but 20 account for >90%, and especially *Cetengraulis edentulus*, *Opisthonema oglinum*, *Lycengraulis grossidens*, *Scomber colias*, and *Sardinella brasiliensis*. The main fishing gears include purse seines, pair trawls, pole-and-line fishing for fish and double-rigged benthic trawls for penaeids (Perez et al., 2003; Tagliolatto et al., 2019).

Small-scale fisheries land some 204 categories of species, with the top 20 making up 81% of total landings (PMAP-RJ, 2020). Key species include *C. edentulus*, *O. oglinum, L. grossidens*, *S. brasiliensis*, and *Mugil liza*, along with crustaceans like *Xiphopenaeus kroyeri*, *Farfantepenaeus brasiliensis*, and *Ucides cordatus*. Small-scale fisheries primarily use purse seines, gillnets, double-rigged penaeid trawls and handlines (Di Beneditto, 2001; PMAP-RJ, 2020). All industrial and small-scale fisheries operate throughout the year, although for the decade prior to 2023, penaeid trawling was prohibited along the entire southern Brazilian coast from March 1 to May 31 to coincide with stock recruitments (established by Portaria SAP/MAPA No. 656/2022). Nevertheless, the highest production in all fisheries occurs during the first half of the year (PMAP-RJ, 2020).

2.2.2 São Paulo state

The coastal region of São Paulo predominantly comprises a small-scale fisheries fleet (~99%) (Fig. 1; PMAP-SP, 2020). Among 15 coastal municipalities, there are over 250 fish-landing sites (PMAP-SP, 2020). The average annual fishery catch exceeds 15,000 t. Although small-scale fisheries dominate, industrial fisheries contribute 60–80% of the landed volume (Mendonça et al., 2008). In the industrial sector, the municipalities of Santos and Guarujá handle over 80% of the state's total fish landings, however, Cananéia in the southern area is also an important landing area (PMAP-SP, 2020). The most caught species are *Micropogonias furnieri, M. liza*, and *Balistes capriscus*. The primary fishing techniques in this sector include those used in Rio de Janeiro (Mendonça et al., 2008).

Small-scale fisheries occur in all coastal municipalities, with the greatest catches landed at Santos and Guarujá, followed by Iguape and Ubatuba (Gallo et al., 2006; Bochini et al., 2019). The most representative species in this sector is *X. kroyeri*, accounting for nearly 37% of the total catch (Bochini et al., 2019; PMAP-SP, 2020). Other important species include *Anchoviella lepidentostole*, *M. furnieri*, *M. liza*, and *Trachurus trachurus* (Mendonça & Katsuragawa, 2008). The main fishing gears used in small-scale fisheries include double-rigged penaeid trawls, gillnets, and purse seines (PMAP-SP, 2020). Both industrial and small-scale

fisheries in São Paulo have higher production levels during the second half of the year (PMAP-SP, 2020).

2.2.3 Paraná state

The coastline of Paraná extends ~107 km, representing about 1% of the Brazilian coast (Fig. 1). Fishers are distributed across roughly 60 communities, both rural and urban, and small-scale fisheries are dominant (Adriguetto-Filho et al., 2006; Brandini, 2013). In the municipality of Guaratuba, part of the penaeid-trawl fleet is equipped with storage holds, cabins, and >150 Kw engines, increasing their fishing capacity compared to the rest of the state's small-scale fleet (Adriguetto-Filho et al., 2006). Annually, around 2,500 t are landed, with Guaratuba accounting for nearly 50% (PMAP-PR, 2020).

The dominant catch is *X. kroyeri* (Adriguetto-Filho et al., 2006; Brandini, 2013). Other important species in small-scale fisheries include *Anomalocardia brasiliana*, *Scomberomorus brasiliensis*, *M. liza*, and *Pleoticus muelleri* (PMAP-PR, 2020). The primary gear in terms of landed volume is double-rigged penaeid trawling, accounting for nearly 99% of larger vessel fisheries landings and around 50% of small-scale fisheries landings. Gillnets also play an important role in small-scale fisheries year-round, contributing slightly over 21.7% of the total landings (PMAP-PR, 2020). As observed in other states, fisheries in Paraná show higher production levels during the second half of the year, influenced in part by the closed season for penaeid trawling (Portaria SAP/MAPA No. 656/2022).

2.2.4 Santa Catarina state

Santa Catarina has 35 coastal municipalities, with industrial fisheries accounting for about 60% of landings, exceeding 100,000 t annually (Fig. 1; PMAP-SC, 2020). The sector is one of the most productive in Brazil, integrating industrial and small-scale fisheries with diverse techniques and target species (Pio et al., 2016). Itajaí and Navegantes contribute around 95% of the state's industrial production (Perez et al., 2007; Alvarez & Pezzuto, 2018; PMAP-SC, 2020). Industrial fisheries encompass ~130 species/groups with *S. brasiliensis*, *O. oglinum*, *M. furnieri*, and *Katsuwonus pelamis* the main species (Perez et al., 2007; PMAP-SC, 2020). Purse seining accounts for >40% of total production, followed by gillnetting, pair trawling, live-bait, pole-and-line for fish and benthic double-rigged penaeid trawling (Pio et al., 2012; Alvarez & Pezzuto, 2018).

Small-scale fisheries are concentrated in Florianópolis, Laguna, and Governador Celso Ramos, representing ~37% of the state's production. This fleet targets 148 species/groups

annually, with *M. furnieri*, *X. kroyeri*, and *M. liza* being dominant (PMAP-SC, 2020; Freitas et al., 2024). Gillnets account for ~50% of artisanal production, followed by double-rigged penaeid trawls, purse seines, and fyke nets (Martins & Alvarez, 2008; Rodrigues-Filho et al., 2016; PMAP-SC, 2020; Freitas et al., 2024). As in other states, fisheries in Santa Catarina show higher production levels during the second half of the year, also influenced by the closed season for shrimp trawling (Portaria SAP/MAPA No. 656/2022).

2.3 STRANDING DATA

The data analyzed in this study describe *C. mydas* strandings recorded by the PMP-BS throughout the above states between 1 January 2016, and 15 November, 2023, and are publicly available at the online SIMBA database (https://simba.petrobras.com.br/simba/web/). This standardized monitoring program covered an area from Saquarema, Rio de Janeiro (22°93'S, 42°36'W) to Laguna, Santa Catarina (28°29'S, 48°45'W), totaling over 1,400 km of surveyed beaches (Fig. 1). Most of the coastline (81.5%) was monitored daily at low tide by foot or using vehicles (cars, boats, or bicycles) by researchers from 14 institutions; all of whom were trained to follow a standardized methodological protocol, conducted the monitoring and responded promptly to public reports of strandings.

When a stranded *C. mydas* was encountered, it was confirmed as such via a morphological assessment and then assigned a number, followed by its stranding date and geographical coordinates. The condition of each individual was then categorized according to Geraci and Lounsbury (2005) as code 1, when alive, or when dead: code 2 – freshly deceased; code 3 – early decomposition; code 4 – advanced decomposition; and code 5 – mummified.

All individuals were collected and transported to laboratories for either rehabilitation (if alive) or necropsy (if deceased). During these procedures, biological data and samples were collected according to protocols specific to the decomposition stages. Biometric measurements were obtained, including curved carapace length (CCL, cm) to the nearest 1 mm. Sex was determined through gonadal inspection during necropsy or histological evaluation (Wibbels, 2003). Development stage (hatchling, juvenile, or adult) was determined by gonadal analysis when possible; otherwise, individuals with a CCL>20cm and <90 cm (the minimum reported size of nesting females in the SWAO-RMU; Almeida et al., 2011) were classified as juveniles.

During stranding assessments, rehabilitation, and necropsy procedures, all individuals were examined for evidence of any interactions with oil, boat collisions, dredging activities, aggression, marine debris (including entanglements, external attachments, or ingestion) and fisheries (e.g., presence of netting, hooks, or bycatch-related injuries) following Fonseca et al.

(2024). Finally, where possible for all necropsied *C. mydas*, veterinarians submitted a report on encountered pathologies, and associated scores on body condition (great, good, cachectic, or bad) (similar to Thomson et al. 2009) and possible the cause of death. In all cases, if definitive binary outcomes could not be determined (i.e. ‘yes’ or ‘no'), the specimen was labeled ‘unknown’ for that variable.

2.4 STATISTICAL ANALYSES

2.4.1 Stranding patterns

Data were analyzed using various generalized linear mixed models (GLMMs); all with fixed effects (predictors) including ‘month’ (January to December), regional ‘state’ (Rio de Janeiro, São Paulo, Paraná and Santa Catarina) and their interaction. The spatial scales (Brazilian states) were chosen to promote integrated governance results, accounting for state legislation. The random-bocking structure incorporated ‘week’ nested within ‘month’, within ‘year’, as well as ‘year’ as a separate factor, to capture variability both within and between surveyed years (Fonseca et al., 2024).

First, we undertook a negative binomial GLMM with the response variable comprising the stranding data for *C. mydas* (≥0) from the daily beach surveys within each week of the year, in each regional state, to evaluate general spatio-temporal stranding patterns. An offset was applied to standardize the variable sampling effort (i.e., beach monitoring) across states and throughout the months.

Next, using only those data for all stranded *C. mydas* (≥1), separate binomial GLMMs were constructed to analyze monthly and regional variability among intrinsic and extrinsic factors. These models included as response variables the dichotomous sex (male or female) and interactions with fishing, marine debris, boat collisions, oil, dredging, aggression and marine debris ingestion (all yes or no). The binomial fishing-interaction GLMM included *C. mydas* decomposition code (fresh or advanced) as a fixed effect to help elucidate the proximity of impacts to stranding. We assessed model fits by inspecting residuals and comparing Akaike Information Criterion values (AIC), followed by multicollinearity evaluation through variance inflation factor values (VIF).

For all models, the significance of modeled fixed effects was assessed using Wald tests. Mean (±SE) stranding rates and log odds for binomial responses (recalculated by suppressing model intercepts) were plotted. All models were developed in R environment (R Core Team, 2017).). Maps were plotted using Heatmap tool in QGIS (version 3.10.10, 2020), with standard influence radius of 1.5 mm (Cantor et al., 2020).

3 RESULTS

For the survey period (2,875 days) the PMP-BS team covered ~2.5 million km. A total of 42,333 stranded *C. mydas* were recovered; 4,243 of which were alive (10.0%) (Table 1, Fig. 2). Of the remaining deceased specimens that could be assessed ~20% were recently deceased (code 2: n = 2,095; and code 3: n = 6,221), while 70% had advanced decomposition (code 4: n = 25,346; and code 5: n = 4,428) (Table 1). On average, 5,000 *C. mydas* individuals were stranded annually, with 2017 (n > 8,000) and 2018 (n > 7,500) recording more than twice the number of strandings observed in 2021, which had the lowest yearly rate (~3,000) (Fig. 3). Spatially, the greatest absolute numbers were observed in São Paulo state (Fig. 2).

Sex determination was possible for 11,133 individuals (79.4% females) and ~95% of strandings comprised juveniles (Table 1). The mean CCL among all specimens was 39.3 ± 7.3 cm (mean ± SD), with a median of 37.7 cm.

TABLE 1 - Biological data describing green turtles (*Chelonia mydas)* stranded along the southern Brazilian coast between 1 January 2016 and 15 November 2023, stratified by decomposition codes.

		Number of strandings			
		Alive (code 1)	Early decomposition (codes 2 and 3)	Advanced decomposition (codes 4 and 5)	Total
Sex	Female	2655	5021	1163	8839
	Male	704	1280	310	2294
	Unknown	884	2015	28301	31200
Development stages	Adults	7	15	80	102
	Juveniles	4207	8239	27616	40062
	Hatchlings	13	7	43	63
	Unknown	16	55	2035	2106
Body condition	Great or good	429	3127	947	4503
	Bad or cachectic	2895	3537	701	7133
	Unknown	919	1652	28126	30697
Cause of death	Euthanasia	-	0	0	314
	Anthropogenic	-	1575	371	2542
	Natural – Drowning	-	1101	29	1655
	Natural – Others	-	1329	65	3146
	Unknown	-	4310	29308	33618
	All†	1666	3765	4794	6628

Evidence of anthropogenic interactions	Fishing	805	2312	1301	4418
	Boat collision	316	366	551	1233
	Aggression	69	183	508	760
	Marine-debris entanglement	1331	2503	1021	4855
	Marine-debris ingestion	1277	2408	594	4279
	Dredging	3	4	29	36
	Oil	3	7	6	16
	None	1618	2795	844	5257
	Unknown	959	1756	27733	30448

(†) Refers to the total number of individuals with at least one type of anthropogenic interaction. Note that a single individual may exhibit more than one interaction type; therefore, the sum of all categories exceeds the number in "All". –, not relevant.

Owing to the condition of many *C. mydas* (especially those in advanced decomposition), it was not possible to definitively determine evidence (or otherwise) of anthropogenic interactions in 30,448 specimens (Table 1). Of the 11,885 *C. mydas* that could be assessed, 4,418 (or 37.2%) had evidence of fisheries interactions and the stranding patterns were consistent with total strandings (Table 1; Fig. 2b). The main injuries associated with fisheries interaction were classified into three categories: (a) skin marks and impressions, usually resulting from the entanglement of limbs and/or appendages in nets or lines (Supplementary Fig. 3); (b) the presence of fishing gear attached to the animal's body, such as lines, hooks, nets, or ropes (Supplementary Fig. 4); and (c) internal injuries, including signs of drowning or decompression sickness.

In addition to bycatch, marine debris ingestion was also notable, with 4,279 recorded cases (36.0% of assessable specimens), while marine debris entanglement was observed in 4,955 instances (41.6%; Table 1). Other anthropogenic interactions included boat collisions (n = 1,233; or 10.4%) and aggression (n = 760; 6.4%), with fewer records of impacts related to dredging (n = 36; 0.3%) or oil contamination (n = 16; 0.01%) (Table 1).

The GLMM assessing spatio-temporal variability in total stranding rates revealed significant effects of the month and regional states and their interaction, with the latter precluding any discussion of main effects in isolation ($P < 0.001$; Table 2). The interaction appeared to be driven by an increase in strandings from May to December across all states, but

especially in Paraná (Fig. 4). Between June and October, stranding rates in Paraná (concentrated at the adjacent areas of PEC; Fig. 2) doubled or tripled those of the other regions—São Paulo and Rio de Janeiro had rates ranging from 0.4 to 1.3 and from 0.4 to 1.1 strandings month^{-1} 100 km^{-1}, respectively (Figs 2 and 3).

Among all stranded *C. mydas* sex, fisheries interactions and marine debris entanglement and ingestion also exhibited significant spatio-temporal interactions (GLMM, $P < 0.05$, Table 2). Specifically, while the log odds consistently favored females during all months in all states, these were lowest during April and November in Paraná and October in Santa Catarina (Table 2, Fig. 5; Supplementary Table 1).

For fisheries interactions, the greatest log odds occurred in Rio de Janeiro and São Paulo during February, and in Paraná (also the highest overall) between February and May (Fig. 6). In comparison, the log odds of interactions fluctuated in Santa Catarina between January and August, after which they lowered (Fig. 5). Additionally, carcass decomposition stage had a significant effect on detecting fisheries interactions: fresh carcasses had a log odds of 2.2, indicating that the likelihood of detecting such interactions was over 9 times higher in early decomposed individuals than in those at advanced decomposition stages ($p < 0.001$; Table 2; Supplementary Table 1).

For marine debris entanglement and ingestion, the greatest log odds were generally during February to July for all states and especially the former for São Paulo (Figs 7 and 8). The binomial GLMM for boat collision returned significant main effects of state and month, with a higher rate in Rio de Janeiro and Paraná across all months and, regardless of state, most during February to April ($P < 0.001$; Table 2, Supplementary Table 1).

TABLE 2 - Summary of significant fixed effects from GLMMs assessing the importance of the main effects of "month" (January to December), regional "state" (Rio de Janeiro, São Paulo, Paraná, and Santa Catarina), and their interaction on: (i) the overall stranding rates of green turtle (*Chelonia mydas*) on beaches along the southern Brazilian coast over nearly eight years (from 1 January 2016 to 15 November,2023); and then (where there were sufficient data or applicable), these factors and "carcass decomposition" (fresh and advanced) and appropriate interactions on (ii) intrinsic and extrinsic characteristics among stranded specimens.

Response Variable	Month (M)	State (S)	M × S	Carcass decomposition (D)
Number of strandings	***	***	***	NA
Sex	Ns	Ns	*	NA
Fisheries interaction	***	***	***	***
Marine debris entanglement	Ns	***	**	NA
Oil	Ns	Ns	Ns	NA

Boat collision	***	***	Ns	NA
Dredging	Ns	Ns	Ns	NA
Aggression	Ns	Ns	Ns	NA
Marine debris ingestion	Ns	***	***	NA

Random blocking effects for all models included “week,” within “month,” and within “year” and “year” $^{*}P < 0.05$; $^{**}P < 0.01$; and $^{***}P < 0.001$. Ns: not significant and Na: not applicable.

FIGURE 2 - Spatial distribution of green turtles (*Chelonia mydas*) stranded along the southern Brazilian coast between 1 January 2016 and 15 November 2023: (a) all strandings; (b) strandings with signs of fisheries interactions.

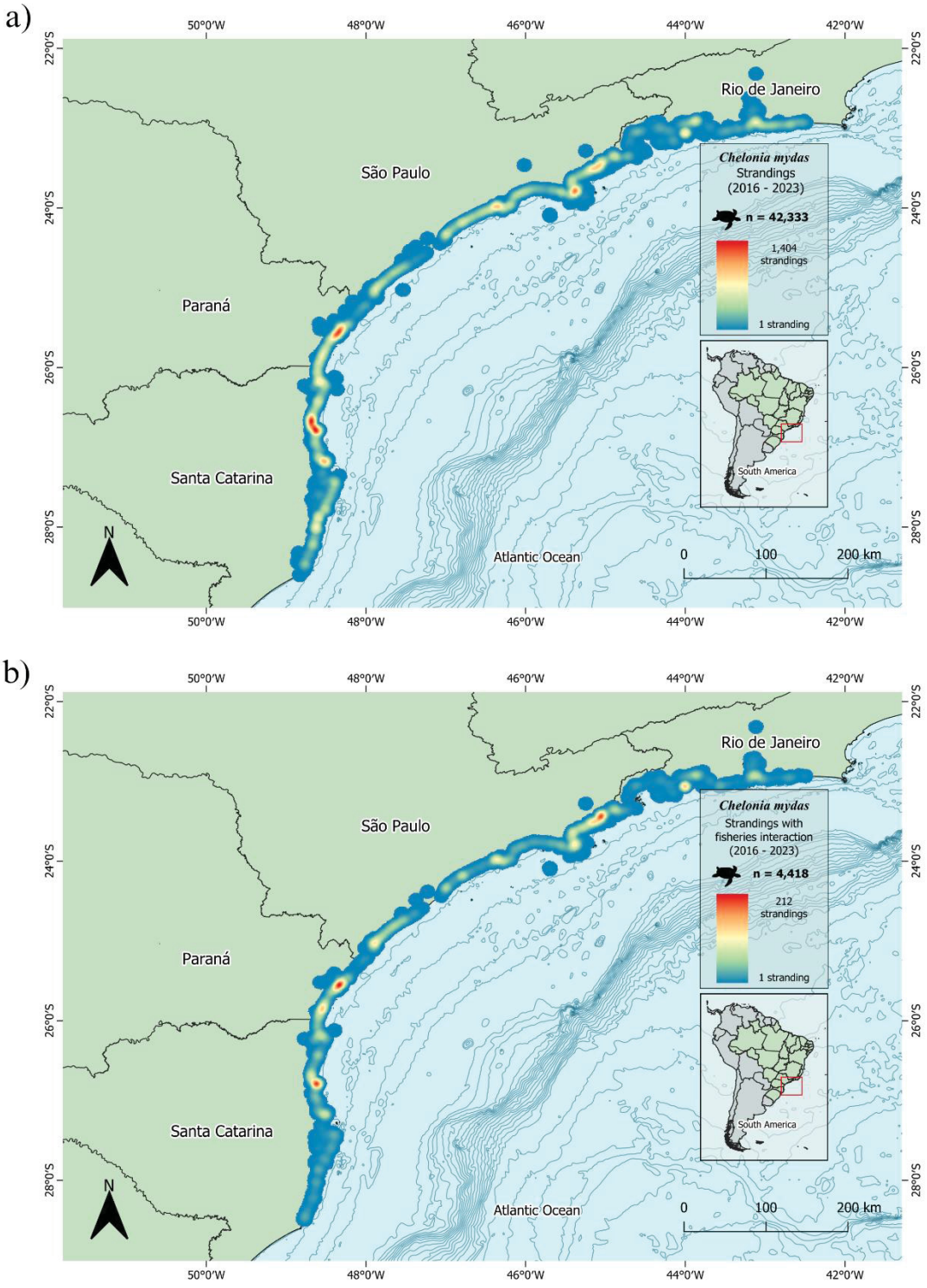


FIGURE 3 - Temporal distribution of green turtles (*Chelonia mydas*) stranded along the southern Brazilian coast between 1 January 2016 and 15 November 2023.

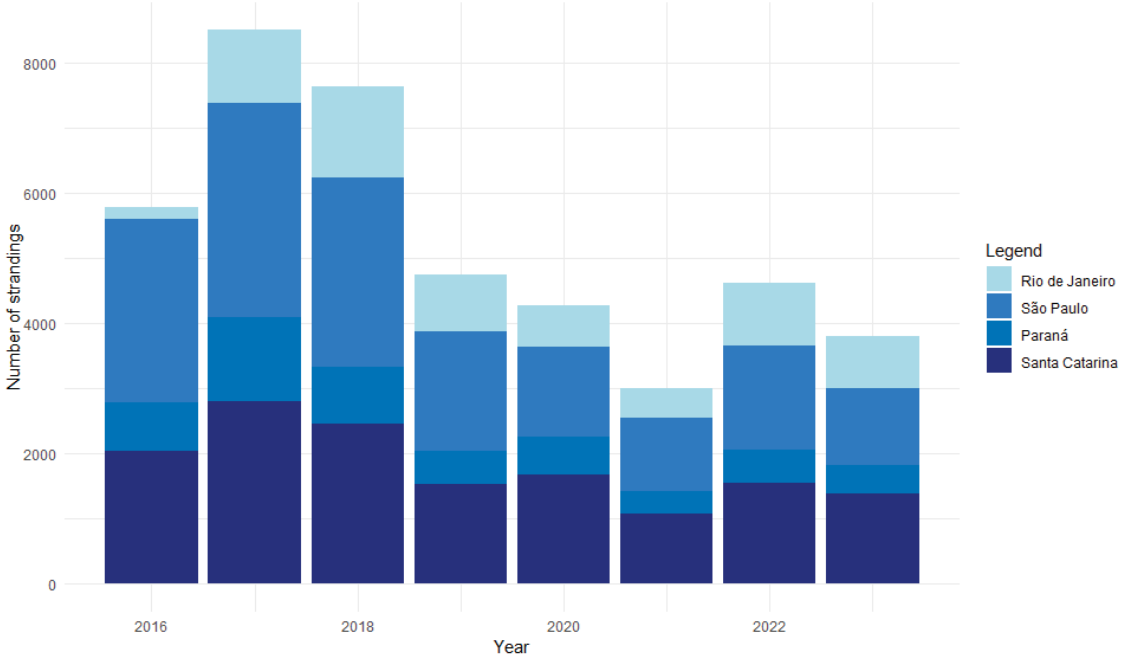


FIGURE 4 - Differences in mean (±SE) weekly stranded rates (100 km^{-1} of beaches) for green turtles (*Chelonia mydas*) stranded along the southern Brazilian coast between 1 January 2016 and 15 November 2023.

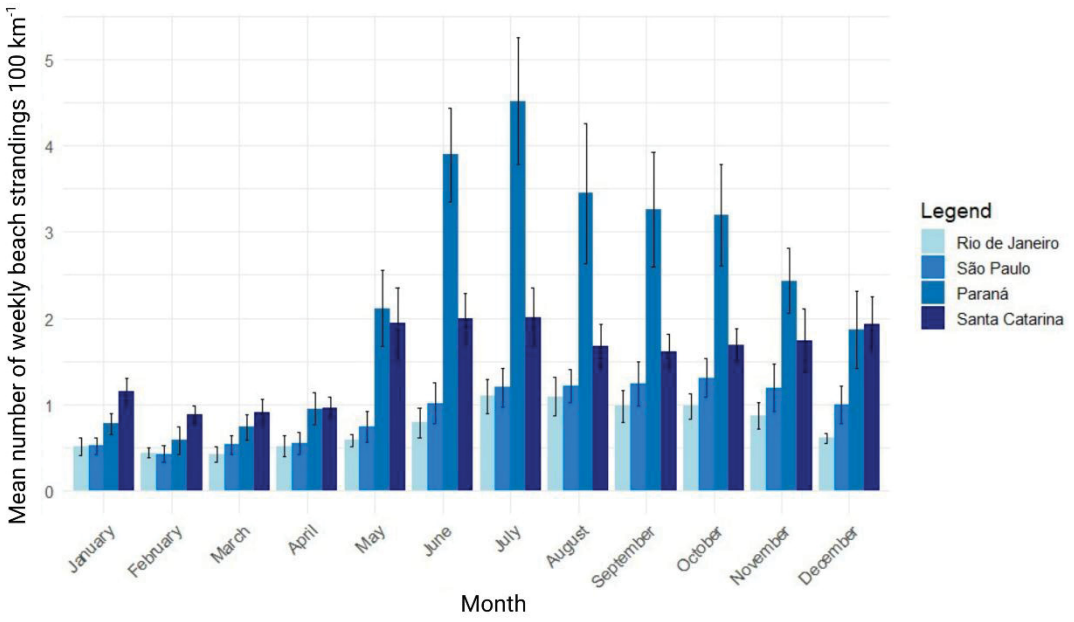


FIGURE 5 - Monthly log odds (±SE) from logistic models for the sex ratio (females) of green turtles (*Chelonia mydas*) stranded along the coasts of four southern Brazilian states between 1 January 2016 and 15 November 2023.

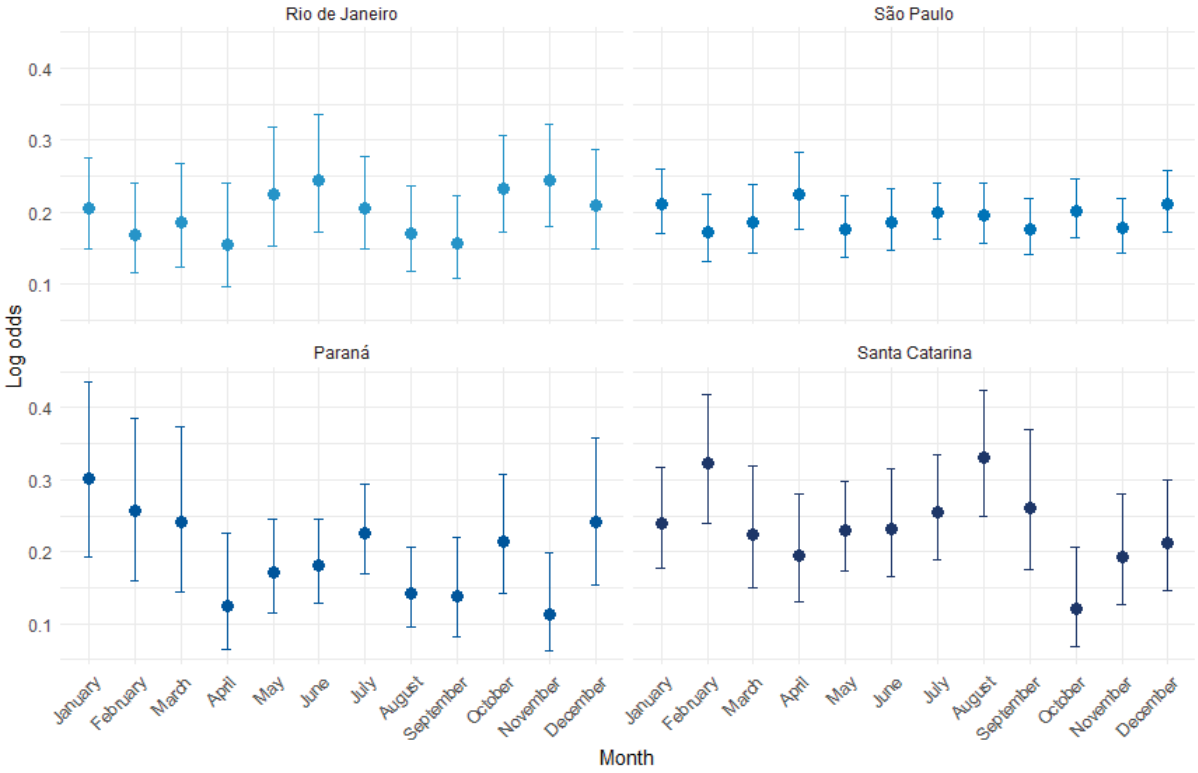


FIGURE 6 - Monthly log odds (±SE) from logistic models for evidence **of fisheries interactions** among green turtles (*Chelonia mydas*) stranded along the coasts of four southern Brazilian states between 1 January 2016 and 15 November 2023.

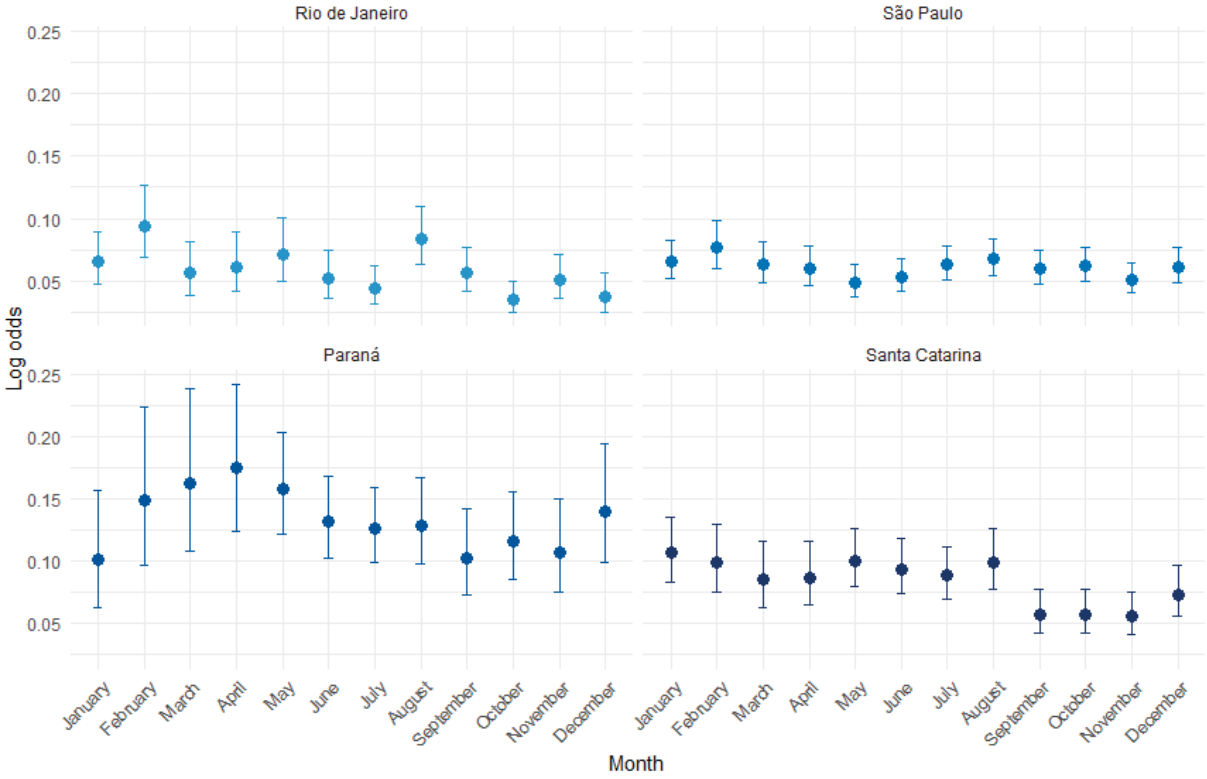


FIGURE 7 - Monthly log odds (±SE) from logistic models for evidence **of marine-debris entanglement** among green turtles (*Chelonia mydas*) stranded along the coasts of four southern Brazilian states between 1 January 2016 and 15 November 2023.

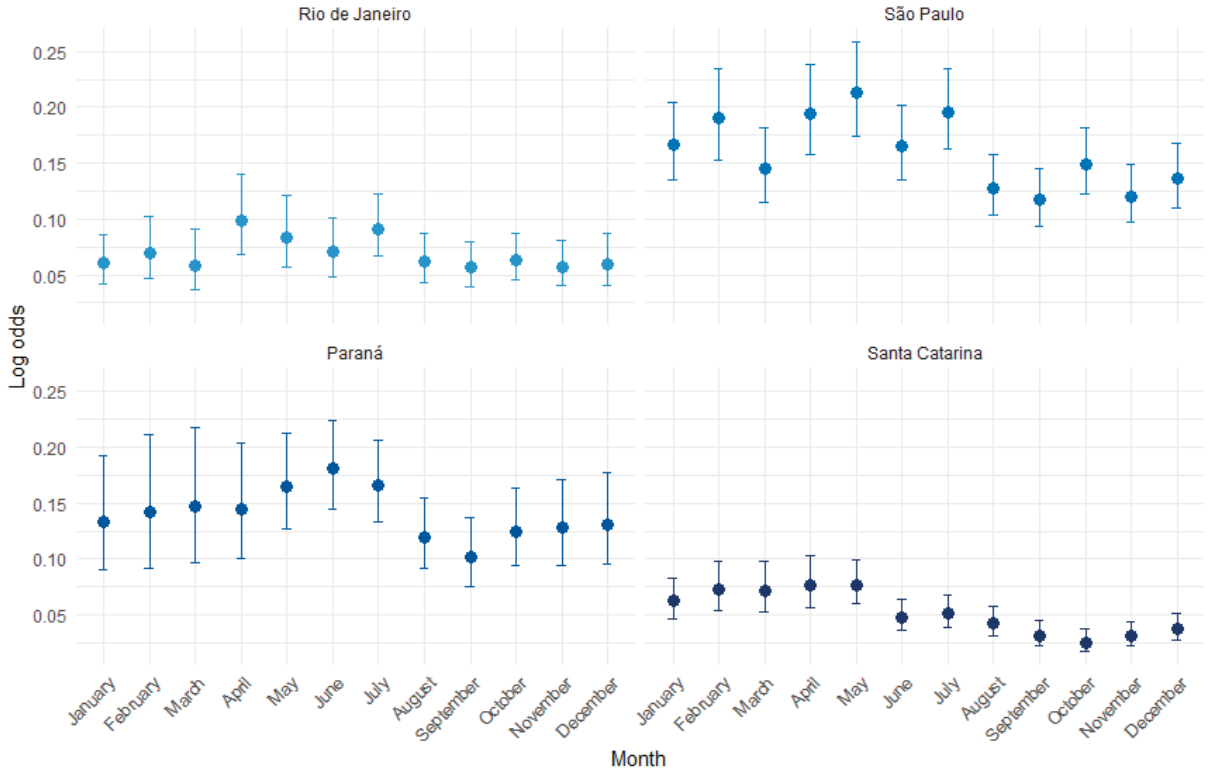


FIGURE 8 - Monthly log odds (±SE) from logistic models for evidence **of marine-debris ingestion** among green turtles (*Chelonia mydas*) stranded along the coasts of four southern Brazilian states between 1 January 2016 and 15 November 2023.

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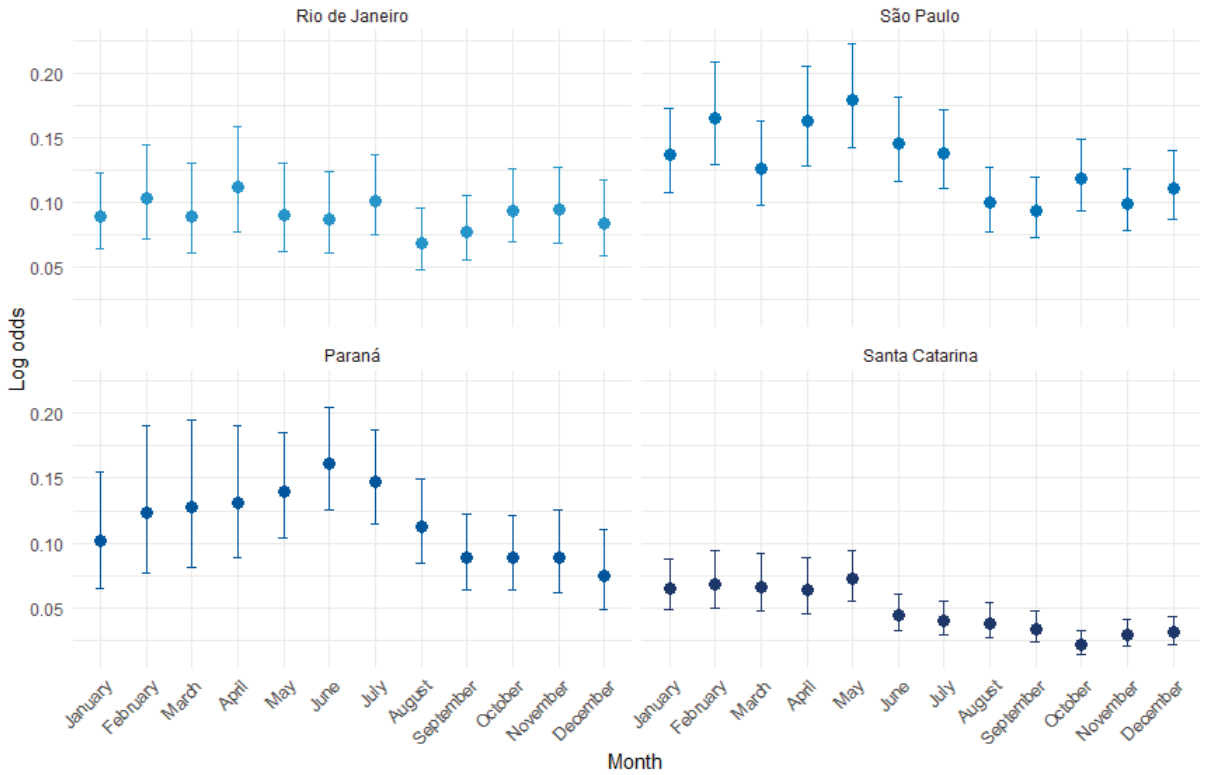

4 DISCUSSION

This study represents one of the most comprehensive and long-term beach-monitoring efforts for *C. mydas* strandings worldwide (Velez-Rubio et al., 2013; Nicolau et al., 2016; Dimitriadis et al., 2022). The observed ~3000 to 8200 *C. mydas* stranded year^{-1} recorded during of the eight surveyed years (for a total exceeding 42,000 individuals) reiterates previous, regionally reported sea-turtle strandings over shorter periods (Monteiro et al., 2016; Tagliolatto et al., 2019; Cantor et al., 2020). Most of the stranded *C. mydas* died and while already substantial, the total deaths are likely to be considerably underestimated, because fewer than 20% of carcasses are assumed to wash ashore (Epperly et al., 1996; Hart et al., 2006; Peltier et al., 2012; Koch et al., 2013). Such sustained high mortalities require urgent, mitigation efforts off southern Brazil to prevent impacts to the SWAO-RMU subpopulation (Wallace et al. 2010). Some clarity for future resolution can be facilitated by first considering the spatio-temporal variability among apparent intrinsic and extrinsic factors associated with strandings, particularly for small and coastal species for which the carcasses' drifting is not expected to be long-distance (Peltier et al., 2021; Maruyama et al., 2023).

The data revealed a high incidence of juvenile strandings and a strong female-biased sex ratio; both consistent with the demographic profile of *C. mydas* in the SWAO-RMU. This subpopulation predominantly comprises individuals with CCLs ranging from 30 to 60 cm, corresponding to 2–8-year-old juveniles originating from at least 12 distinct rookeries, with Ascension Island, the Caribbean, and West Africa identified as the most likely source areas (Naro-Maciel et al., 2006; Prosdocimi et al., 2012; Andrade et al., 2016; Jordão et al., 2015; Savada et al., 2021). However, the observed sex ratio reflects the pattern typical of species with temperature-dependent sex determination, such as all sea turtles (Hawkes et al., 2009; Hays et al., 2022).

Resident and transient *C. mydas* juveniles benefit from the favorable foraging and growth conditions off southern Brazil, which supports high primary production and substantial autotrophic biomass (Barrera-Alba et al., 2009; Villac & Tenenbaum, 2010). During winter, juveniles from more southern regions, such as Uruguay and Argentina, migrate to northern waters (southern Brazil) in search of thermal refuge and increased food availability (González-Carman et al., 2012). Some of these individuals remain in southern Brazil year-round and exhibit high site fidelity, staying within a single island or bay throughout their juvenile phase (Nunes, 2021). Others demonstrate greater mobility (Fuentes et al., 2020; Nunes, 2021).

Spatial concentration patterns were consistent across all strandings here, with key areas identified along southern Rio de Janeiro, northern São Paulo, the vicinity of the PEC in Paraná,

and Babitonga Bay in Santa Catarina. In particular, Paraná exhibited the highest stranding rate (>4.5 weekly strandings 100 km^{-1}). The environmental conditions of southern Brazilian support the development of multiple trophic levels, including *C. mydas*, and their food sources, as well as various commercially important crustaceans and fish (Mendonça et al., 2017). Such high productivity leads to a spatial overlap between *C. mydas* foraging grounds and areas of intense fishing activity, increasing the risk of interactions, particularly with small-scale fishing practices, which dominate the region (López-Barrera et al., 2012; Guebert etal., 2013; Tagliolatto et al., 2019; Fiedler et al., 2020; Fuentes et al., 2020; Castro et al., 2021).

The risk to *C. mydas* is supported by long-term stranding records along the southern and southwestern Brazil (Guebert-Bartholo et al., 2011; Guebert et al., 2013; Reis et al., 2009; Monteiro et al., 2016; Cantor et al., 2020), as well as by the concentration of strandings in several hotspots where small-scale gillnet and trawl fisheries are active—particularly in areas adjacent to Sepetiba Bay (RJ), Ubatuba (SP), and the Paraná coast (PEC) (Gallo et al., 2006; Tagliolatto et al., 2019; Guebert et al., 2013; López-Barrera et al., 2012). This association is further supported by ethnographic interviews with fishing communities in Rio de Janeiro, Paraná, and Santa Catarina, which reveal high bycatch rates of *C. mydas* (Guebert et al., 2013; Awabdi et al., 2021).

Over the eight years of data analyzed, a pronounced seasonal pattern was observed, with a higher likelihood of strandings occurring between May and December. This period corresponds to the coldest and driest months of the year (winter and spring in Brazil) and aligns with the seasonal migration of juvenile *C. mydas* from colder southern waters in search of more favorable thermal conditions and increased food availability (González-Carman et al., 2011; González-Carman et al., 2012). Additionally, this period coincides with the recruitment of oceanic *C. mydas* juveniles into coastal areas, where they spend a substantial portion of their life cycle (Gallo et al., 2006).

However, these months are also associated with reduced food availability in coastal zones, including algae and seagrass (Guebert-Bartholo et al., 2011; Gama et al., 2021; 2024). Such scarcity can lead to nutritional stress, driving individuals to expand their foraging ranges into areas with higher anthropogenic risks—particularly regions subject to intense small-scale fishing activity. This interplay between ecological pressures and seasonal peaks in fishing effort not only increases the likelihood of fisheries-related interactions but might also suggest that the region functions as an ecological trap: a scenario in which individuals make maladaptive habitat choices by selecting environments that seem suitable but ultimately reduce survival or reproductive success due to hidden anthropogenic threats (Battin, 2004).

Regardless of classification, the seasonal dynamics of fishing effort, combined with the migratory behavior and energetic requirements of *C. mydas*, appear to be key determinants of the stranding patterns observed in the region, although evidence of fisheries interactions did not align with the overall stranding peaks observed from May to December. Nevertheless, this anomaly may simply reflect the propensity or otherwise of particular fishing gears to leave physical evidence of interactions, and variability in their effort. More specifically, owing to their capture mechanism, hooks and gillnets are more likely to evoke visible damage to sea turtles than trawling, although all methods can cause drowning. Further, the propensity for greater interactions detected among freshly deceased specimens implies inshore fisheries (or at least rapid drift), although some confounding effects of decomposition stage on detectability cannot be ruled out (discussed below).

Small-scale inshore fisheries in southern Brazil primarily involve gillnets and double-rigged trawl nets (Adriguetto-Filho et al., 2006; Mendonça et al., 2017). While gillnets are fished continuously throughout the year (albeit with some peaks in summer), trawling follows a seasonal pattern (Adriguetto-Filho et al., 2006; Mendonça et al., 2017; Bochini et al., 2019; Freitas et al., 2024).

Until 2022, trawling occurred intensively along the entire coastline, especially off the coast of Paraná during the second half of the year, following the seasonal closure in autumn. With the implementation of a new regulation in 2023 (Portaria SAP/MAPA No. 656, March 30, 2022), trawling became more restricted in the first semester and is now largely concentrated after April 30. Trawling is widely recognized as a significant source of *C. mydas* bycatch and mortality (Laporta et al., 2013; Duarte et al., 2018; Jones et al., 2024). Despite its impact, the adoption of turtle excluder devices (TEDs) in Brazil remains minimal and is only mandatory for industrial fleets (Duarte et al., 2018; Canton et al., 2023; González-Cárman et al., 2012). Industrial trawl operations frequently exceed two hours—surpassing the breath-hold tolerance of most sea turtles under stress—which can lead to drowning without leaving visible external injuries (Poiner et al., 1990).

Nevertheless, even trawls may contribute to *C. mydas* mortalities, the extensive and year-round use of gillnets increases the risk of incidental capture, particularly for juvenile *C. mydas*, and has therefore been more thoroughly investigated (López-Barrera et al., 2012; Cantor et al., 2020; Fiedler et al., 2020; Fuentes et al., 2020). In Paraná, for example, anchored gillnets are deployed year-round, with peak usage between June and October, coinciding with the flatfish (*Paralichthys* spp.) fishing season (Andriguetto-Filho et al., 2006). Additionally, other types of nets are widely used from May to July to target migrating schools of mullet (*Mugil*

spp.) (Andriguetto-Filho et al., 2009). Between January and May, in the absence of a dominant target species, fisheries typically diversify their gear including using hooks, leading to the potential for greater evidence of impacts observed here (Andriguetto-Filho et al., 2006).

Notwithstanding the strong overall evidence of fishery impacts (i.e. 37% of those assessable), attributing causality presents several challenges, particularly in the case of internal injuries, which require necropsy for confirmation. This process is often hindered by the condition of the carcass and the availability of infrastructure for detailed analyses (Archibald & James, 2018; Phillot & Godfrey, 2018). Advanced decomposition degrades evidence indicative of fishing interaction (Geraci & Lounsbury, 2005; Pugliares et al., 2007; Phillot & Godfrey, 2018). Such deterioration may lead to an underestimation of mortality rates associated with these activities.

Beyond fisheries interactions, marine debris has been identified as a significant factor contributing to the stranding and mortality of *C. mydas* in the study area (Guebert-Bartholo et al., 2011; Nunes et al., 2021). Strandings related to entanglement exhibited a distinct seasonal pattern, with more between March and August, coinciding with high precipitation and land-based runoff, which increases regional marine-debris loads (Krelling et al., 2017). Both entanglement in, and ingestion of, marine debris can impair animal mobility and development, potentially increasing susceptibility to capture by fishing gear (Gama et al., 2016; Gama et al., 2021). Interactions with marine debris depend on availability in the environment, which can vary according to physical and oceanographic conditions (Krelling et al., 2017), as well as the feeding preferences of *C. mydas* individuals, particularly in cases of ingestion (Schuyler et al., 2012; Schuyler et al., 2013; Colferai et al., 2017; Nunes et al., 2021).

The ingestion of marine debris is particularly concerning for juvenile *C. mydas*, because high concentrations in the digestive tract can severely impact individual health by reducing nutrient absorption, promoting fecaloma formation, triggering inflammatory responses, and facilitating the bioaccumulation of chemical contaminants (Feitosa et al., 2024). These effects collectively weaken the immune system, increasing susceptibility to diseases and other anthropogenic threats (Iurk et al., 2024). Consequently, debilitated individuals may become more prone to interactions with fishing gear, further elevating the risks of incidental capture and mortality (Guebert-Bartholo et al., 2011; Gama et al., 2016).

4.1 CLARITY FOR FUTURE RESOLUTION

This study provides valuable insights into the subpopulation structure and threats faced by *C. mydas* off southern Brazil and the SWAO-RMU. Regional stocks are currently classified as 'Least Concern' by the IUCN (Seminoff et al., 2015), but assessment is based on population size and for sea turtles exclusively on female reproductive rates and does not incorporate mortalities among juveniles or other life-cycle stages (Seminoff & Shanker, 2008; Wildermann et al., 2018). Considering the data here, the factor of the IUCN criteria for categorizing species risks of extinction can be inferred or suspected, and that causes of potential population reduction are not ceased, we highlight the importance of systematic stranding monitoring as a fundamental tool for assessing risks to *C. mydas* populations, in the medium and long-term.

Although applied to a specific portion of the SWAO-RMU and a subset of *C. mydas* individuals, the systematic stranding monitoring program—combined with analytical advancements for detecting fishery interactions and estimating carcass drift origins (e.g., through the use of drift models, as in Peltier et al., 2021)—represents a replicable framework that could be expanded to other marine megafauna. Such an approach would enhance understanding of fishery interactions and bycatch dynamics, while providing more accurate estimates of mortality rates (Monteiro et al., 2016; Ten Doeschate et al., 2017; Tagliolatto et al., 2019b; Cantor et al., 2020; Fonseca et al., 2024; Oliveira et al., 2024).

Despite its advantages, stranding records are estimated to represent only 5–20% of actual mortality (Epperly et al., 1996; Hart et al., 2006; Peltier et al., 2012; Koch et al., 2013). Additionally, advanced decomposition often obscures critical information on threats and causes of death, limiting the accuracy of mortality assessments (Archibald & James, 2018; Phillot & Godfrey, 2018). Therefore, it is reasonable to infer that the removal of *C. mydas* in the SWAO-RMU occurs at a significantly higher rate and more rapidly than stranding data alone suggests and might be faster than the natural subpopulation dynamics can support. Nevertheless, integrating stranding monitoring with other approaches, such as telemetry, spatial modeling, and fisheries observer programs, maybe required to provide more accurate estimates of mortality rates and better assess the impacts of human activities on *C. mydas*. This combination of methods would enable the identification of critical risk areas, a better understanding of environmental and anthropogenic factors influencing species distribution and survival, and improved mitigation strategies and participatory management approaches.

Another challenge for *C. mydas* conservation in Brazil is the disparity in fisheries regulations. While industrial fishing has a more structured legal framework (Pacheco et al., 2010; Duarte et al., 2018), small-scale fisheries lack sufficient regulatory support, making

enforcement, impact assessment, and mitigation measures more challenging (González-Cárman et al., 2012). This issue is particularly concerning for juvenile *C. mydas*, which rely on coastal areas for their development and are highly vulnerable to small-scale fishing practices (Castro et al., 2021). In this context, fisheries monitoring conducted by onboard researchers, or monitoring by cameras associated with GPS tags remains essential for understanding and sustainably managing small-scale fisheries. Furthermore, the government should promote bottom-up co-management approaches that include environmental, social, and economic factors to develop and test more effective regional mitigation strategies (Guebert et al., 2013; Castro et al., 2021). Crucially, it also relies on effective governmental fisheries monitoring to assess current practices and guide impact mitigation strategies.

Considering the above, the conservation of *C. mydas* in the SWAO-RMU requires integrated approaches that consider habitat connectivity and enforce the regulation and monitoring of fishing and other anthropogenic activities that interact with this species (e.g. dredging and boat traffic). The success of these strategies depends on a collaborative effort among governments, researchers, and society at large. Only through coordinated action and evidence-based policies can we ensure the long-term survival of both juvenile and adult *C. mydas*, the quality of ecosystems they inhabit and a sustainable fishing operation.

5 CONCLUSIONS

Since 2016, the PMP-BS has been consolidating a comprehensive database on sea-turtle strandings along the Brazilian coast, representing a strategic tool for advancing scientific knowledge and improving public policies for species conservation and coastal and ocean management. Based on this dataset, the present study provides relevant insights into the: (1) structure of the juvenile *C. mydas* subpopulation in the SWAO-RMU; (2) role of human activities, particularly bycatch, in the mortality of the species; (3) identification of stranding hotspots, with emphasis on the coast of Paraná and the seasonal peak observed between June and December; (4) identification of anthropogenic activities with a higher potential for interaction with *C. mydas* along the year; and (5) need to reassess the conservation status currently assigned to this subpopulation, given the magnitude of the current threats identified.

Moreover, this study highlights the relevance of stranding data as a key resource for guiding management and conservation strategies, especially in regions where direct observation / interactions are logistically challenging. Further investigations focusing on drift patterns and the influence of environmental variables will be essential to improve understanding of the ecological and stranding dynamics of *C. mydas* and to fully assess mortality areas and rates.

Finally, the stranding rates observed in this study suggest a possible underestimation of the conservation risks faced by *C. mydas* in the SWAO-RMU. The pressures identified, which affect individuals during a critical stage of their life cycle, may have long-term consequences for the viability of this subpopulation. Therefore, we advocate for integrated and coordinated efforts among researchers, policymakers, civil society, and decision-makers, not only to reassess the species' conservation status but also to design and implement effective, collaborative conservation measures aimed at ensuring the recovery and long-term persistence of *C. mydas* in the region.

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7 SUPPLEMENTARY MATERIALS

SUPPLEMENTARY TABLE 1 - Estimated coefficients (log odds for binomial GLMMs), standard errors, z-values, and p-values from mixed-effects log-odds models assessing the effects of 'months' (January to December) and, where appropriate, regional 'states' (Rio de Janeiro, São Paulo, Paraná, and Santa Catarina) and their interactions on key variables describing green turtle (*Chelonia mydas*) strandings off southern Brazil from 2016 to 2023. All coefficients are relative to January and/or Rio de Janeiro and where relevant the decomposition state was referenced to 'advanced'.

Model	Variables	Parameter estimate	Standart error	z-value	p-value	Significance
All *C. mydas* strandings	(Intercept)	-5.66777	0.18318	-30.941	<2e-16	***
	February	-0.187	0.18946	-0.987	0.323645	
	March	-0.21057	0.19149	-1.1	0.271476	
	April	-0.23402	0.18702	-1.251	0.210832	
	May	0.19774	0.18499	1.069	0.285106	
	June	0.35539	0.18186	1.954	0.050673	.
	July	0.51834	0.17612	2.943	0.003250	**
	August	0.73873	0.17805	4.149	3.34e-05	***
	September	0.64548	0.17782	3.63	0.000283	***
	October	0.71504	0.17792	4.019	5.85e-05	***
	November	0.52512	0.17927	2.929	0.003398	**
	December	-0.26419	0.18289	-1.444	0.148601	
	São Paulo	0.05278	0.13334	0.396	0.692253	
	Paraná	0.49701	0.15169	3.276	0.001051	**
	Santa Catarina	0.86697	0.12775	6.786	1.15e-11	***
	February:São Paulo	-0.02871	0.19246	-0.149	0.881407	
	March:São Paulo	0.19306	0.19172	1.007	0.313950	
	April:São Paulo	0.03351	0.18852	0.178	0.858928	
	May:São Paulo	0.1309	0.18442	0.71	0.477833	
	June:São Paulo	0.25745	0.17986	1.431	0.152313	
	July:São Paulo	0.06956	0.17395	0.4	0.689228	
	August:São Paulo	0.15255	0.17511	0.871	0.383665	
	September:São Paulo	0.04562	0.17508	0.261	0.794439	
	October:São Paulo	0.17486	0.17433	1.003	0.315839	
	November:São Paulo	0.18951	0.17623	1.075	0.282228	
	December:São Paulo	0.30754	0.18164	1.693	0.090435	.
	February:Paraná	-0.10262	0.22389	-0.458	0.646688	
	March:Paraná	0.15553	0.21946	0.709	0.478530	
	April:Paraná	0.27023	0.21321	1.267	0.205002	
	May:Paraná	0.7612	0.20123	3.783	0.000155	***
	June:Paraná	1.19162	0.19443	6.129	8.86e-10	***
	July:Paraná	0.99604	0.18902	5.269	1.37e-07	***
	August:Paraná	0.74782	0.19217	3.892	9.96e-05	***
	September:Paraná	0.38996	0.19294	2.021	0.043271	*
	October:Paraná	0.47033	0.19278	2.44	0.014702	*
	November:Paraná	0.3569	0.19584	1.822	0.068390	.
	December:Paraná	0.49947	0.20197	2.473	0.013397	*
	February:Santa Catarina	-0.07187	0.1843	-0.39	0.696580	

	March:Santa Catarina	-0.02733	0.18642	-0.147	0.883450	
	April:Santa Catarina	-0.14057	0.18301	-0.768	0.442415	
	May:Santa Catarina	0.27026	0.17712	1.526	0.127043	
	June:Santa Catarina	0.16728	0.17334	0.965	0.334531	
	July:Santa Catarina	-0.21495	0.16827	-1.277	0.201451	
	August:Santa Catarina	-0.35725	0.16982	-2.104	0.035406	*
	September:Santa Catarina	-0.44591	0.17038	-2.617	0.008867	**
	October:Santa Catarina	-0.31421	0.16995	-1.849	0.064481	.
	November:Santa Catarina	-0.24854	0.17117	-1.452	0.146507	
	December:Santa Catarina	0.17138	0.17534	0.977	0.328341	
Sex ratio	(Intercept)	-1.35038	0.197522	-6.837	8.11e-12	***
	São Paulo	0.034949	0.207002	0.169	0.86593	
	Paraná	0.507699	0.334212	1.519	0.12874	
	Santa Catarina	0.197971	0.248392	0.797	0.42545	
	February	-0.24359	0.273173	-0.892	0.37256	
	March	-0.13139	0.28678	-0.458	0.64685	
	April	-0.34672	0.316514	-1.095	0.27332	
	May	0.114473	0.286857	0.399	0.68985	
	June	0.22482	0.274435	0.819	0.41266	
	July	-0.00318	0.252032	-0.013	0.98994	
	August	-0.2385	0.264417	-0.902	0.36706	
	September	-0.33081	0.268745	-1.231	0.21835	
	October	0.154075	0.247074	0.624	0.53289	
	November	0.219778	0.251346	0.874	0.38190	
	December	0.022621	0.262519	0.086	0.93133	
	São Paulo:February	-0.00568	0.324672	-0.017	0.98604	
	Paraná:February	0.022839	0.489384	0.047	0.96278	
	Santa Catarina:February	0.653539	0.374248	1.746	0.08076	.
	São Paulo:March	-0.03007	0.33526	-0.09	0.92854	
	Paraná:March	-0.17388	0.506374	-0.343	0.73131	
	Santa Catarina:March	0.041077	0.407332	0.101	0.91967	
	São Paulo:April	0.424305	0.357693	1.186	0.23553	
	Paraná:April	-0.76054	0.551083	-1.38	0.16756	
	Santa Catarina:April	0.075341	0.426304	0.177	0.85972	
	São Paulo:May	-0.34395	0.330016	-1.042	0.29731	
	Paraná:May	-0.85347	0.455982	-1.872	0.06124	.
	Santa Catarina:May	-0.17217	0.369028	-0.467	0.64082	
	São Paulo:June	-0.38891	0.31613	-1.23	0.21862	
	Paraná:June	-0.89445	0.43248	-2.068	0.03862	*
	Santa Catarina:June	-0.26706	0.378594	-0.705	0.48055	
	São Paulo:July	-0.0732	0.288323	-0.254	0.79959	
	Paraná:July	-0.38679	0.411211	-0.941	0.34691	

	Santa Catarina:July	0.081517	0.352981	0.231	0.81736	
	São Paulo:August	0.140124	0.303195	0.462	0.64397	
	Paraná:August	-0.71297	0.439775	-1.621	0.10497	
	Santa Catarina:August	0.683732	0.365444	1.871	0.06135	.
	São Paulo:September	0.109837	0.307531	0.357	0.72097	
	Paraná:September	-0.66159	0.478898	-1.381	0.16713	
	Santa Catarina:September	0.437366	0.401092	1.09	0.27552	
	São Paulo:October	-0.21051	0.28528	-0.738	0.46057	
	Paraná:October	-0.61671	0.44334	-1.391	0.16421	
	Santa Catarina:October	-0.98195	0.429287	-2.287	0.02217	*
	São Paulo:November	-0.4286	0.289794	-1.479	0.13915	
	Paraná:November	-1.42859	0.494675	-2.888	0.00388	**
	Santa Catarina:November	-0.50081	0.383565	-1.306	0.19166	
	São Paulo:December	-0.02523	0.29958	-0.084	0.93289	
	Paraná:December	-0.32521	0.471361	-0.69	0.49024	
	Santa Catarina:December	-0.17976	0.382198	-0.47	0.63812	
Fisheries interaction	(Intercept)	-3.31138	0.164548	-20.124	<2e-16	***
	São Paulo	-0.00861	0.159904	-0.054	0.95708	
	Paraná	0.467692	0.261077	1.791	0.07323	.
	Santa Catarina	0.532732	0.169545	3.142	0.00168	**
	February	0.390031	0.204535	1.907	0.05653	.
	March	-0.16943	0.232151	-0.73	0.46550	
	April	-0.07817	0.236242	-0.331	0.74074	
	May	0.084921	0.225852	0.376	0.70691	
	June	-0.24907	0.227141	-1.097	0.27285	
	July	-0.41283	0.211093	-1.956	0.05050	.
	August	0.263295	0.19061	1.381	0.16718	
	September	-0.16216	0.202243	-0.802	0.42267	
	October	-0.66313	0.21985	-3.016	0.00256	**
	November	-0.2668	0.213693	-1.249	0.21184	
	December	-0.58031	0.239924	-2.419	0.01558	*
	Fresh decomposition	2.211569	0.039845	55.504	<2e-16	***
	São Paulo:February	-0.20504	0.23565	-0.87	0.38423	
	Paraná:February	0.057368	0.374174	0.153	0.87815	
	Santa Catarina:February	-0.47713	0.253761	-1.88	0.06008	.
	São Paulo:March	0.131586	0.261411	0.503	0.61470	
	Paraná:March	0.719574	0.384734	1.87	0.06144	.
	Santa Catarina:March	-0.07352	0.284177	-0.259	0.79586	
	São Paulo:April	-0.0091	0.265568	-0.034	0.97267	
	Paraná:April	0.715215	0.367387	1.947	0.05156	.
	Santa Catarina:April	-0.14947	0.283567	-0.527	0.59812	

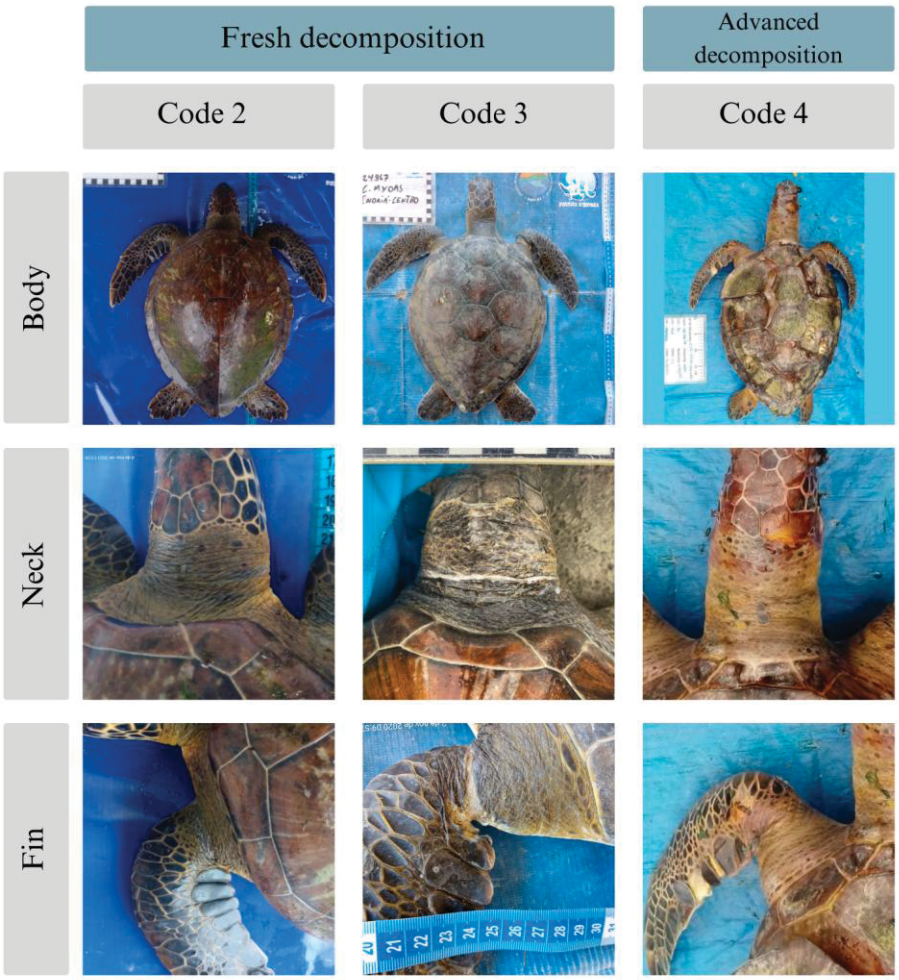
	São Paulo:May	-0.38382	0.25703	-1.493	0.13536	
	Paraná:May	0.428705	0.335749	1.277	0.20165	
	Santa Catarina:May	-0.15277	0.257465	-0.593	0.55295	
	São Paulo:June	0.042939	0.251245	0.171	0.86430	
	Paraná:June	0.552983	0.3306	1.673	0.09439	.
	Santa Catarina:June	0.10181	0.259608	0.392	0.69493	
	São Paulo:July	0.38501	0.231129	1.666	0.09576	.
	Paraná:July	0.661954	0.31882	2.076	0.03787	*
	Santa Catarina:July	0.203482	0.246038	0.827	0.40822	
	São Paulo:August	-0.22768	0.215443	-1.057	0.29060	
	Paraná:August	0.009097	0.31266	0.029	0.97679	
	Santa Catarina:August	-0.34352	0.232536	-1.477	0.13960	
	São Paulo:September	0.066976	0.226065	0.296	0.76702	
	Paraná:September	0.181329	0.337884	0.537	0.59150	
	Santa Catarina:September	-0.51409	0.25975	-1.979	0.04780	*
	São Paulo:October	0.610845	0.24043	2.541	0.01107	*
	Paraná:October	0.822868	0.338298	2.432	0.01500	*
	Santa Catarina:October	-0.01012	0.271133	-0.037	0.97022	
	São Paulo:November	0.011473	0.235978	0.049	0.96122	
	Paraná:November	0.334548	0.347207	0.964	0.33528	
	Santa Catarina:November	-0.43481	0.262752	-1.655	0.09796	.
	São Paulo:December	0.519661	0.260276	1.997	0.04587	*
	Paraná:December	0.952056	0.364304	2.613	0.00897	**
	Santa Catarina:December	0.167145	0.280427	0.596	0.55115	
Marine debris entanglement	(Intercept)	-2.73765	0.188724	-14.506	<2e-16	***
	February	0.145418	0.251941	0.577	0.56381	
	March	-0.04343	0.272314	-0.159	0.873288	
	April	0.524314	0.23944	2.19	0.028542	*
	May	0.343164	0.242768	1.414	0.157495	
	June	0.157213	0.238183	0.66	0.509222	
	July	0.440526	0.210439	2.093	0.036316	*
	August	0.020726	0.228723	0.091	0.927796	
	September	-0.07591	0.224803	-0.338	0.735625	
	October	0.043656	0.219061	0.199	0.842038	
	November	-0.05855	0.230079	-0.254	0.799113	
	December	-0.01685	0.242541	-0.069	0.944609	
	São Paulo	1.127343	0.176765	6.378	1.8e-10	***
	Paraná	0.865982	0.248699	3.482	0.000498	***
	Santa Catarina	0.034432	0.194882	0.177	0.85976	
	February:São Paulo	0.018639	0.273785	0.068	0.945722	
	March:São Paulo	-0.11849	0.294377	-0.403	0.687297	
	April:São Paulo	-0.33302	0.260635	-1.278	0.20135	
	May:São Paulo	-0.03643	0.262179	-0.139	0.889477	

	June:São Paulo	-0.16643	0.255832	-0.651	0.51535	
	July:São Paulo	-0.24228	0.226929	-1.068	0.28569	
	August:São Paulo	-0.32799	0.248796	-1.318	0.187404	
	September:São Paulo	-0.33494	0.24389	-1.373	0.169651	
	October:São Paulo	-0.17143	0.236138	-0.726	0.467858	
	November:São Paulo	-0.31835	0.247372	-1.287	0.198114	
	February:São Paulo	-0.21567	0.259598	-0.831	0.406092	
	February:Paraná	-0.07352	0.380947	-0.193	0.846957	
	March:Paraná	0.160968	0.393449	0.409	0.682451	
	April:Paraná	-0.43197	0.354825	-1.217	0.223441	
	May:Paraná	-0.09303	0.327064	-0.284	0.776078	
	June:Paraná	0.203638	0.315003	0.646	0.517979	
	July:Paraná	-0.18023	0.294248	-0.613	0.540199	
	August:Paraná	-0.14217	0.315733	-0.45	0.652511	
	September:Paraná	-0.22704	0.320551	-0.708	0.478775	
	October:Paraná	-0.11765	0.311441	-0.378	0.705611	
	November:Paraná	0.009849	0.325993	0.03	0.975898	
	February:Paraná	-0.00432	0.339772	-0.013	0.989866	
	February:Santa Catarina	0.013647	0.302406	0.045	0.964004	
	March:Santa Catarina	0.188862	0.320094	0.59	0.555177	
	April:Santa Catarina	-0.31291	0.291209	-1.075	0.282589	
	May:Santa Catarina	-0.1207	0.278178	-0.434	0.664378	
	June:Santa Catarina	-0.43695	0.282227	-1.548	0.121568	
	July:Santa Catarina	-0.64649	0.257951	-2.506	0.012202	*
	August:Santa Catarina	-0.44017	0.283251	-1.554	0.12019	
	September:Santa Catarina	-0.63955	0.289588	-2.208	0.02721	*
	October:Santa Catarina	-0.98467	0.293251	-3.358	0.000786	***
	November:Santa Catarina	-0.6575	0.288069	-2.282	0.022463	*
	February:Santa Catarina	-0.52114	0.29375	-1.774	0.07605	.
Marine debris ingestion	(Intercept)	-2.32197	0.179036	-12.969	< 2e-16	***
	February	0.1564	0.215914	0.724	0.468843	
	March	0.002289	0.230169	0.01	0.992065	
	April	0.249776	0.221223	1.129	0.258869	
	May	0.016092	0.228824	0.07	0.943936	
	June	-0.02181	0.214261	-0.102	0.918909	
	July	0.140302	0.192835	0.728	0.466875	
	August	-0.29191	0.209437	-1.394	0.163388	
	September	-0.16378	0.198063	-0.827	0.408302	
	October	0.055564	0.189346	0.293	0.769175	
	November	0.060037	0.194704	0.308	0.757814	
	December	-0.06597	0.208671	-0.316	0.751893	
	São Paulo	0.482804	0.159573	3.026	0.002481	**

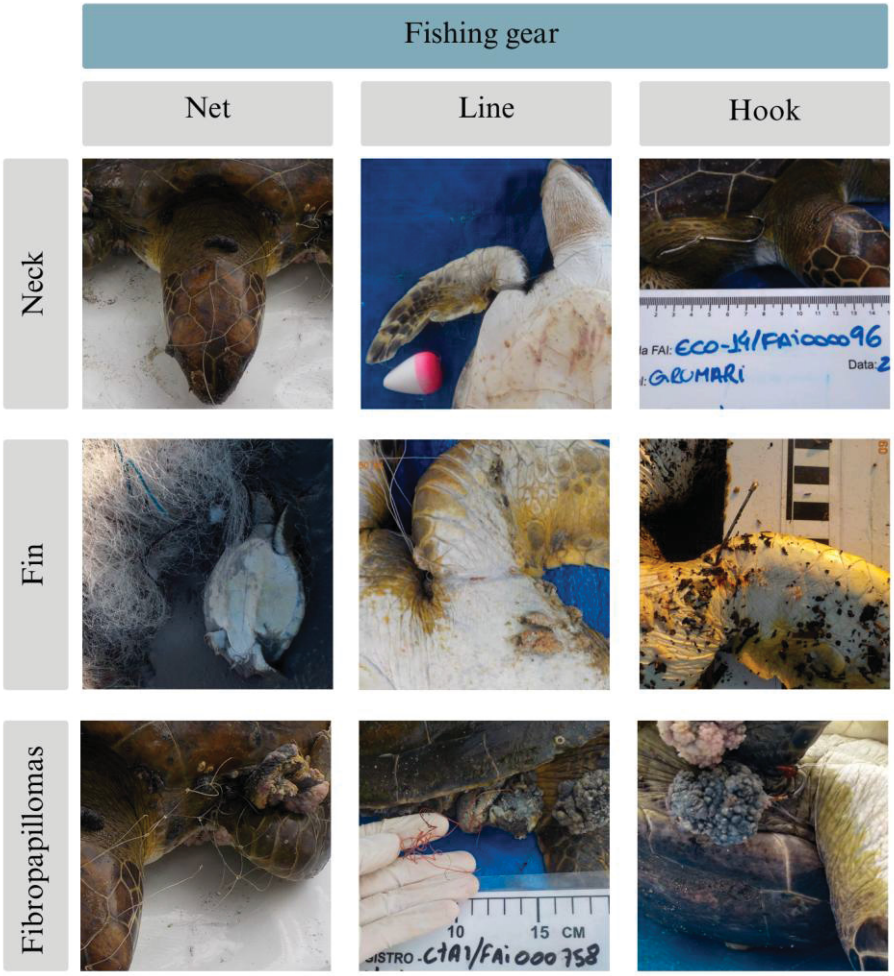
	Paraná	0.138954	0.245935	0.565	0.572072	
	Santa Catarina	-0.34061	0.178073	-1.913	0.055782	.
	February:São Paulo	0.06006	0.243971	0.246	0.805547	
	March:São Paulo	-0.0949	0.25854	-0.367	0.713576	
	April:São Paulo	-0.04736	0.247235	-0.192	0.848100	
	May:São Paulo	0.298481	0.251966	1.185	0.236173	
	June:São Paulo	0.092414	0.236119	0.391	0.695511	
	July:São Paulo	-0.1306	0.214421	-0.609	0.542484	
	August:São Paulo	-0.06841	0.235021	-0.291	0.770976	
	September:São Paulo	-0.26386	0.22323	-1.182	0.237197	
	October:São Paulo	-0.21994	0.212301	-1.036	0.300211	
	November:São Paulo	-0.42558	0.218355	-1.949	0.051295	.
	December:São Paulo	-0.17692	0.230828	-0.766	0.443398	
	February:Paraná	0.06154	0.375434	0.164	0.869796	
	March:Paraná	0.256372	0.376184	0.682	0.495551	
	April:Paraná	0.041741	0.353349	0.118	0.905964	
	May:Paraná	0.346449	0.329212	1.052	0.292635	
	June:Paraná	0.553292	0.306184	1.807	0.070753	.
	July:Paraná	0.289178	0.290743	0.995	0.319922	
	August:Paraná	0.413838	0.310104	1.335	0.182036	
	September:Paraná	0.02318	0.312983	0.074	0.940962	
	October:Paraná	-0.20661	0.307845	-0.671	0.502121	
	November:Paraná	-0.20543	0.31923	-0.644	0.519891	
	December:Paraná	-0.27481	0.343818	-0.799	0.424118	
	February:Santa Catarina	-0.10647	0.274636	-0.388	0.698261	
	March:Santa Catarina	0.014017	0.288085	0.049	0.961193	
	April:Santa Catarina	-0.27447	0.281726	-0.974	0.329939	
	May:Santa Catarina	0.098758	0.267993	0.369	0.712493	
	June:Santa Catarina	-0.38888	0.265231	-1.466	0.142596	
	July:Santa Catarina	-0.6565	0.250695	-2.619	0.008826	**
	August:Santa Catarina	-0.2707	0.271938	-0.995	0.319514	
	September:Santa Catarina	-0.53214	0.268583	-1.981	0.047559	*
	October:Santa Catarina	-1.23046	0.281103	-4.377	1.2e-05	***
	November:Santa Catarina	-0.91467	0.264852	-3.453	0.000553	***
	December:Santa Catarina	-0.72398	0.27279	-2.654	0.007955	**
Boat collision	(Intercept)	-2.28278	0.180336	-12.658	<2e-16	
	February	-0.35597	0.242187	-1.47	0.141610	
	March	-0.34433	0.256333	-1.343	0.179179	
	April	-0.89634	0.308975	-2.901	0.003720	**
	May	-0.64646	0.272547	-2.372	0.017697	*
	June	-0.7393	0.260135	-2.842	0.004483	**
	July	-1.49865	0.292074	-5.131	2.88e-07	***

August	-0.81691	0.236987	-3.447	0.000567	***
September	-1.20351	0.258803	-4.65	3.31e-06	***
October	-0.8691	0.241483	-3.599	0.000319	***
November	-0.81026	0.248359	-3.262	0.001104	**
December	-0.70877	0.260929	-2.716	0.006601	**
São Paulo	-0.12261	0.178786	-0.686	0.492859	
Paraná	-0.97633	0.385945	-2.53	0.011416	*
Santa Catarina	-1.96812	0.285921	-6.883	5.84e-12	***
February:São Paulo	-0.00917	0.300138	-0.031	0.975624	
March:São Paulo	0.047676	0.30681	0.155	0.876511	
April:São Paulo	0.351238	0.36009	0.975	0.329353	
May:São Paulo	-0.21579	0.33599	-0.642	0.520702	
June:São Paulo	-0.11691	0.312228	-0.374	0.708070	
July:São Paulo	0.669789	0.330063	2.029	0.042430	*
August:São Paulo	0.101164	0.285161	0.355	0.722768	
September:São Paulo	0.402903	0.30334	1.328	0.184106	
October:São Paulo	0.064757	0.287302	0.225	0.821671	
November:São Paulo	0.187014	0.289491	0.646	0.518273	
December:São Paulo	0.10083	0.302281	0.334	0.738709	
February:Paraná	-0.30885	0.705149	-0.438	0.661390	
March:Paraná	-0.32313	0.713167	-0.453	0.650483	
April:Paraná	0.906527	0.585476	1.548	0.121536	
May:Paraná	0.149921	0.543469	0.276	0.782656	
June:Paraná	-0.99496	0.617023	-1.613	0.106848	
July:Paraná	0.269082	0.555126	0.485	0.627874	
August:Paraná	-0.12426	0.529135	-0.235	0.814334	
September:Paraná	0.256302	0.578246	0.443	0.657592	
October:Paraná	-0.67577	0.653186	-1.035	0.300865	
November:Paraná	0.640418	0.518235	1.236	0.216546	
December:Paraná	0.062716	0.59549	0.105	0.916124	
February:Santa Catarina	0.734049	0.418278	1.755	0.079271	.
March:Santa Catarina	0.052071	0.495232	0.105	0.916261	
April:Santa Catarina	0.698791	0.510498	1.369	0.171049	
May:Santa Catarina	0.034966	0.469746	0.074	0.940664	
June:Santa Catarina	0.279551	0.441245	0.634	0.526374	
July:Santa Catarina	0.578127	0.499306	1.158	0.246921	
August:Santa Catarina	-0.2844	0.523956	-0.543	0.587275	
September:Santa Catarina	-0.03586	0.566514	-0.063	0.949535	
October:Santa Catarina	0.275742	0.460712	0.599	0.549499	
November:Santa Catarina	-0.1992	0.505967	-0.394	0.693805	
December:Santa Catarina	0.006706	0.484844	0.014	0.988964	

SUPPLEMENTARY FIGURE 3 - Main lesions and entanglement marks observed in juveniles of *C. mydas* recorded stranded in southern Brazil, along with the progressive loss of information due to decomposition.



SUPPLEMENTARY FIGURE 4 - Main fishing gears associated with fisheries interactions, highlighting the presence of hooks, nets, and lines attached to various parts of the animal's body recorded in juveniles of *C. mydas* stranded in southern Brazil.



2 CONCLUSÃO GERAL

Este estudo ressalta a importância crítica das unidades de manejo regional do Atlântico sul ocidental (ASO-RMU) para a conservação das tartarugas marinhas, destacando os padrões espaciais e temporais de captura incidental e encalhes, bem como as vulnerabilidades específicas de cada espécie frente às diferentes práticas pesqueiras. A revisão da literatura científica revelou um aumento significativo nas publicações na última década, com o Brasil se consolidando como principal polo de produção, embora persistam lacunas geográficas e temáticas — especialmente quanto à pesca em pequena escala. Complementarmente, as análises baseadas nos dados do PMP-BS evidenciaram a elevada incidência de encalhes de *Chelonia mydas*, a influência de fatores sazonais e espaciais, e o papel expressivo da captura incidental, sobretudo por redes de emalhe e arrasto costeiros, na mortalidade de juvenis. Conjuntamente, esses achados demonstram o valor da integração entre dados sistemáticos de encalhe e o conhecimento científico já existente como estratégia para preencher lacunas críticas e orientar medidas de conservação mais eficazes. As altas taxas de mortalidade de juvenis de *C. mydas*, aliadas às evidências mais amplas de seletividade na captura incidental, sugerem uma possível subestimação dos riscos de conservação na ASO-RMU. Assim, este estudo defende ações urgentes, colaborativas e transnacionais voltadas ao aprimoramento do monitoramento, ao fortalecimento da regulamentação pesqueira, à reavaliação dos status de conservação das espécies e à implementação de estratégias mais eficazes de mitigação da captura incidental. Tais esforços são essenciais para garantir a viabilidade a longo prazo das populações de tartarugas marinhas no ASO, especialmente diante do aumento das pressões antrópicas na região.

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