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Ingestão plástica em aves marinhas necropsiadas pelo Projeto de Monitoramento de Praias da Bacia de Santos (PMP-BS)

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Dissertação apresentada ao Programa de Pós-Graduação em Ecologia e Recursos Naturais da Universidade Federal de São Carlos para obtenção do título de mestre em Ecologia e Recursos Naturais.

Área de Concentração: Ecologia e Recursos Naturais.

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A transexualidade se constrói conforme se conhece e se permite conhecer do seu eu e do que cerca - por fora e por dentro do corpo transexual. Se constrói não apenas no campo teórico-conceitual, com a criação de termos e nomenclaturas, mas também com afeto. Se aprende a ser, se aprende a amar a si e ao outro (e a si de novo). É um mergulho diário em minha própria existência, um mergulho cego, um salto de confiança, pois não se cai no raso. A transexualidade é profunda, porque mexe em seus pilares mais básicos, nos seus valores mais primitivos. É negar um roteiro e viver no improviso. É atentar contra o sagrado, e descobrir que o pecado é, na verdade, se negligenciar. É mais cruel do que qualquer pessoa cisgênero poderia vivenciar, mas é mais bonita do que qualquer produção cisgênera poderia explorar - daí surge o grito de urgência pela necessidade de mais pessoas transexuais e travestis se levantarem, ocuparem os espaços que são nossos por direito.

(Gabriela Naomi, 2019)

Resumo

A poluição por plástico é um problema que afeta os oceanos do mundo e está aumentando ao longo do tempo, sendo reconhecida como uma nova crise ambiental. Sabe-se que aves marinhas são um grupo de aves extremamente ameaçado e são impactadas por um conjunto de fatores ambientais e antrópicos. Um destes, é a ingestão plástica, comportamento abrangente entre as espécies, sofrendo impactos diretos e indiretos. Por permitirem a avaliação da poluição plástica em oceano aberto, abordagens de monitoramento vêm sendo implementadas no mundo, possibilitando que a poluição seja examinada ao longo do tempo para embasar e avaliar políticas de combate. No Brasil, no entanto, há um atraso para se tratar do tema, sendo considerado um dos principais poluidores do Atlântico Sul. A partir disso, o presente estudo utilizou um banco de dados de monitoramento diário e ininterrupto do Projeto de Monitoramento de Praias da Bacia de Santos (PMP-BS) de aves marinhas encalhadas na costa Sul e Sudeste brasileira e registros de necropsia para entender como as espécies que ocorrem no Brasil estão relacionadas à poluição plástica e como são impactadas juntamente com outros distúrbios antrópicos, para posteriormente designar espécies potenciais bioindicadoras. É fornecido um novo diagnóstico de espécies marinhas ingerindo plástico, com oito novos registos (três aves marinhas e cinco aves aquáticas). Foi identificado um aumento na interação aves marinhas-plástico entre 2017 e 2020 e foram diagnosticadas as principais causas de morte, impactos antrópicos (pesca, ingestão de plástico e óleo) e espécies vulneráveis. O plástico potencialmente influencia as causas de morte relacionadas à síndrome de caquexia/inanição, um efeito secundário da ingestão de plástico quando não é uma causa direta. A partir disso, discute-se espécies de aves marinhas a serem consideradas bioindicadoras no Brasil.

Palavras-chave: aves marinhas, ingestão plástica, poluição plástica, monitoramento, impactos antrópicos, emaranhamento em pesca, efeitos subletais.

Abstract

Plastic pollution is a problem that affects the world's oceans and is increasing over time, being recognized as a new environmental crisis. It is known that seabirds are an extremely threatened group of birds by many natural and anthropogenic threats, and they ingest plastic in a comprehensive way between species, suffering direct and indirect impacts. These species allow the assessment of plastic pollution in the open ocean. Monitoring approaches based on this have been implemented around the world, providing robust data to evaluate pollution over time and to inform policies to tackle plastic pollution. On the other hand, in Brazil, there is a delay in dealing with the issue, being considered one of the main polluters of the South Atlantic. From this, the present study used a database from the daily and uninterrupted monitoring of seabirds stranded on the South and the Southeast Brazilian coast and necropsy records by the Projeto de Monitoramento de Praias da Bacia de Santos (Beach Monitoring Program of Santos Basin, PMP-BS) to understand how the species that occur in Brazil are related to plastic pollution and being impacted along with other anthropic disturbances, to ultimately designate potential bioindicator species. A new diagnosis of marine species ingesting plastic is provided, with 8 new records (3 seabirds and 5 shorebirds). An increase in reports of plastic ingested by birds was identified between 2017 and 2020 and the main causes of death and anthropic impact (fishing, plastic ingestion, and oiling) and vulnerable species were diagnosed. Plastic is also seen to potentially influence causes of death related to starvation, a secondary effect of plastic ingestion when not a direct cause. From this, we discussed species of seabirds to be considered as bioindicators in Brazil.

Keywords: bycatch-fisheries, plastic ingestion, plastic pollution, monitoring, human impacts, sublethal effects, seabirds.

Declaração de publicação e coautoria

Os capítulos 1 e 2 foram produzidos em forma de artigo, sendo o primeiro capítulo já submetido e o segundo em estágio final de preparação do manuscrito. As seguinte pessoas e instituições contribuíram para a publicação de tais trabalhos como parte desta tese:

Laura Baes Caetano[1] (Baes, L.) – Programa de Pós-graduação em Ecologia e Recursos Naturais – PPGERN/UFSCar; Laboratório de Ecologia de Interações, Departamento de Ecologia e Biologia Evolutiva/UFSCar – candidata pela dissertação e responsável pelo trabalho (primeira autora).

Cristini Diniz Santiago (Santiago, C. D.) – Departamento de Ciências Ambientais/UFSCar – coautora.

Priscilla Carla dos Santos Costa (Santos-Costas, P. C.) – Laboratório de Patologia Comparada de Animais Silvestres FMVZ/USP, Instituto de Pesquisas Cananéia e Instituto BIOPESCA – coautora.

Lauren Roman (Roman, L.) - Commonwealth Scientific and Industrial Research Organisation (CSIRO, Austrália) – coautora.

Carolina Reigada Montoya (Reigada, C.) – Laboratório de Ecologia de Interações, Departamento de Ecologia e Biologia Evolutiva/UFSCar – coautora.

Érica Pugliesi (Pugliesi, E.) – Departamento de Ciências Ambientais/UFSCar – coautora.

[1] Nome social da autora.

Detalhes da autora e atribuições

A candidata foi responsável pelo estudo dentro do Programa de Pós-graduação em Ecologia e Recursos Naturais, nível mestrado, da Universidade Federal de São Carlos. Atribuições: desenvolvimento do projeto, metodologia e coleta de dados (incluindo contato com instituições parceiras que realizaram coleta e necropsia de aves marinhas encalhadas), recepção e organização do banco de dados, análises estatísticas, interpretação dos resultados e preparação dos artigos a seguir.

Artigo 1 Baes, L.; Santiago, C. D.; Roman, L.; Santos-Costa, P. C; Reigada, C.; Pugliesi, E. (2022) Beached seabirds as plastic biomonitors in Brazil suggest that exposure to plastic in the nearshore South Atlantic is increasing through time. Em preparação para submissão.

Contribuições: LB, CDS, PCSC, LR e EP conceberam a ideia do estudo. CR e LR supervisionaram o estudo. LB organizou e preparou o banco de dados de aves marinhas necropsiadas. LB desenvolveu a diagnose de ingestão de lixo marinho a partir do banco de dados do PMP-BS. LB, CR e LR analisaram os dados. LB, CDS, LR, CR e PCSC contribuíram na escrita e edição do manuscrito.

Artigo 2 Baes, L.; Santos-Costa, P. C; Roman, L. Reigada, C. (2022) Human activity impacted on half of seabirds beach-cast in Brazil. Em preparação para submissão.

Contribuições: LB, LR e PCSC conceberam a ideia do estudo. CR e LR supervisionaram o estudo. LB organizou e preparou o banco de dados de aves marinhas necropsiadas. LB e PCSC determinaram a causa de morte e principais processos patológicos de aves marinhas necropsiadas. LB quantificou o plástico ingerido. LB e LR analisaram os dados. LB, LR, PCSC e CR contribuíram na escrita e edição do manuscrito.

Declaração de conduta ética

As amostras usadas neste estudo foram coletadas em total conformidade com uma autorização federal específica emitida pelo Ministério do Meio Ambiente aprovado pelo Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA (ABIO 640/2015), além de aprovação pelo Uso de Dados para Trabalhos Técnico-Científicos no âmbito do Projeto de Monitoramento de Praias da Bacia de Santos (PMP-BS) através da instituição executora Instituto de Pesquisas Cananéia (IPeC) e coordenação técnica Mineral – Engenharia e Meio Ambiente. Como este estudo envolveu aves mortas, não houve exigência de aprovação ética oficial ou institucional.

Sumário

1. Introdução geral

Aves marinhas são consideradas o grupo taxonômico mais ameaçado dentre as aves (CROXALL et al., 2012). A captura acidental em artefato pesqueiro, invasão de espécies exóticas em sítios reprodutivos (ratos, gatos etc.) e mudanças climáticas são listadas como os principais riscos para a conservação destes animais (DIAS et al., 2019). Entretanto, tais fatores isolados não explicam o intenso declínio populacional das espécies (PALECZNY et al., 2015). Neste cenário, há uma variabilidade de outros distúrbios ainda pouco conhecidos, principalmente em espécies pelágicas que habitam o oceano aberto, onde o impacto de ameaças antrópicas é menos perceptível, como é o caso da poluição plástica.

Estima-se que até 2014, 311 milhões de toneladas de plástico tenham sido produzidas no mundo (WERNER, 2018), havendo pelo menos 5 trilhões de partículas plásticas com um peso excedendo 250 mil toneladas em todo o oceano (ERIKSEN et al., 2014). Mais de 690 espécies da fauna marinha já foram relacionadas à ingestão plástica (BERGMANN; GUTOW; KLAGES, 2015; GALL; THOMPSON, 2015). O plástico pode ser ingerido quando um organismo confunde o item flutuante como seu alimento ou quando o próprio alimento já está impregnado por plástico (ROBARDS; PIATT; WOHL, 1995). Os Procellariiformes são as aves marinhas com maior risco e registro de ocorrência na ingestão de resíduos plásticos (PROVENCHER; BOND; MALLORY, 2014; ROMAN et al., 2016), além de serem um dos grupos de aves mais diversos no hemisfério sul.

Ao passo que a ingestão plástica já está bem documentada na literatura (WILCOX; VAN SEBILLE; HARDESTY, 2015; O'HANLON et al., 2017; PROVENCHER et al., 2017), estudos prioritários para a conservação têm buscado entender seus efeitos na mortalidade individual (VEGTER et al., 2014; ROMAN et al.; 2019a). A ingestão plástica tem sido associada também com diversos fatores ecológicos, como a estratégia de forrageamento das aves e seu habitat (costeiro, oceânico etc.), explorando a relação com o tipo de material ingerido (ROMAN et al., 2016; TAVARES et al., 2017; ROMAN et al., 2019b) e principais causas de morte (ROMAN et al., 2020a).

Além de avaliar os impactos diretamente relacionados às aves em si, a abordagem também permite o monitoramento da poluição plástica no oceano de modo geral. Ao serem ingeridos por certas espécies com características morfológicas e fisiológicas específicas, como uma constrição entre o pro-ventrículo e ventrículo (estômago), itens plásticos se acumulam no estômago de forma que integram os níveis encontrados em sua área de forrageamento (VAN

FRANEKER; KÜHN, 2019). O Mar do Norte europeu é a única região onde a ingestão plástica é constantemente monitorada de forma sistemática a partir de um bioindicador vertebrado, o que permite que a poluição seja examinada ao longo do tempo para embasar e avaliar políticas de combate (PROVENCHER et al., 2017).

Desde 2002, países europeus discutem a poluição plástica em seu sistema de 'Objetivos de Qualidade Ecológica' (EcoQOs) a partir da OSPAR - Convenção para a Proteção do Meio Marinho do Atlântico Nordeste (NORTH SEA MINISTERIAL CONFERENCE, 2002). Essa abordagem de monitoramento utiliza uma espécie alvo de ave marinha, a pardela-branca (Procellaridae: *Fulmarus glacialis*), com amostragem incidental do conteúdo gastrointestinal a partir de necropsia de indivíduos encalhados na costa, sendo então aprimorada para implementação internacional pela OSPAR como um de seus EcoQOs (OSPAR, 2008, 2009, 2010; VAN FRANEKER et al., 2011). A última modelagem de tendências temporais realizada indica que as melhorias observadas são lentas, com diminuição da carga plástica ingerida, sendo possível que a meta definida para alcançar a sua qualidade ecológica possa ser alcançada em 2054 (VAN FRANEKER et al., 2021).

Diante disso, o principal entrave que impossibilita comparações espaço-temporais no mundo é a falta de métodos padronizados no reporte de dados. Menos de 25% das publicações mundiais até 2016, relacionadas à megafauna marinha, utilizam protocolos para reportar resíduos plástico ingerido no oceano (PROVENCHER et al., 2017). Atualmente, indica-se que, no mínimo, estudos devem reportar a (i) localização, (ii) tempo e (iii) método de amostragem, (iv) tamanho amostral, (v) frequência de ocorrência de plásticos ingeridos (prevalência), (vi) média (com desvio e erro padrão), (vii) mediana e (viii) intervalo de quantidade e massa de plásticos ingeridos por indivíduo incluindo todos amostrados (PROVENCHER et al., 2017).

No hemisfério norte, o reporte de resíduos plásticos ingeridos por aves marinhas já está bem consolidado neste sentido e vem sendo analisado em diversas espécies para investigar os níveis de poluição nos oceanos (BAAK; PROVENCHER; MALLORY, 2020). Por outro lado, no Brasil, os reportes existentes sobre aves marinhas não utilizam métodos padronizados por estes serem recentes e muitos dos estudos apresentam pequeno tamanho amostral (BARBIERI, 2009; COLABUONO et al., 2009; PETERSEN et al., 2010; TOURINHO; DO SUL; FILLMANN, 2010). A incoerência dos dados entre a maioria dos estudos dificulta análises comparativas, bem como a compreensão da distribuição da poluição plástica nos oceanos. A falta de padronização também dificulta o embasamento científico e a consistência como premissa para tomada de decisão política.

A poluição marinha por plásticos, em si, constitui uma preocupação global crescente, o que é reiterado pela Conferência das Nações Unidas sobre os Oceanos (2017), sendo reconhecida como uma crise ambiental desafiadora (VINCE; STOETT, 2018). No cenário brasileiro, entretanto, há um atraso histórico ao se referir à gestão de resíduos sólidos e à poluição plástica, uma vez que a própria Política Nacional de Resíduos Sólidos (PNRS), Lei 12.305/2010, surgiu na última década e está distante de sua implementação integral (SANTIAGO, 2016). A principal fonte de poluição marinha é de origem continental e o combate aos resíduos inicia-se no local de geração, isto é, nos municípios, prevenindo que cheguem aos oceanos pelas mais diversas vias (JAMBECK et al., 2015).

Como o panorama brasileiro no combate aos resíduos sólidos e à poluição marinha é recente, os plásticos apresentam-se como um grande impacto antrópico acumulativo no Atlântico Sul desde sua produção e consumo acelerado a partir de 1950. Já há evidências de que a frequência da ingestão plástica em petréis (Procellariiformes: Procellariidae) nas águas brasileiras tem aumentado nas últimas décadas (PETRY; BENEMANN, 2017), denotando a necessidade de novos estudos que vão além do reporte de resíduos.

Não existe uma diagnose atualizada e consistente de aves marinhas relacionadas com a poluição plástica no Brasil. Faz-se necessária a produção de dados que integrem a tendência científica mundial frente à problemática e expressem uma situação de partida para discussão e avaliação temporal a partir de bioindicadores (p. ex. aves marinhas) para as recentes políticas públicas brasileiras que estão sendo implementadas (p. ex. Plano de Combate ao Lixo no Mar Brasileiro, 2019; e o Plano Estratégico de Monitoramento e Avaliação do Lixo no Mar do Estado de São Paulo PEMALM, 2021).

Além disso, pouco se sabe sobre como a poluição plástica impacta os indivíduos no Atlântico Sul, principalmente através de efeitos subletais/secundários. Relacionar os dados de ingestão plástica com processos patológicos e de morbidade é um tópico emergente na ciência, contribuindo significativamente para a conservação no entendimento dos efeitos e riscos para as espécies (ROMAN et al., 2020; DAOUST et al., 2021). Destaca-se a importância de análises anátomo e histopatológicas a partir de necropsia como abordagem promissora para entender os efeitos diretos e indiretos da ingestão plástica em aves marinhas (PUSKIC, LAVERS; BOND, 2020).

Diante disso, o presente trabalho utilizou-se de um banco de dados construído a partir de um monitoramento diário e ininterrupto de aves marinhas encalhadas na costa brasileira e registros de necropsia do Projeto de Monitoramento de Praias da Bacia de Santos (PMP-BS) para entender como as espécies que ocorrem no Brasil estão se relacionando com a poluição plástica e como estão sendo impactadas.

2. Objetivos

O objetivo geral desta dissertação foi de entender quais espécies de aves marinhas estão vulneráveis à poluição plástica e, assim, estabelecer possíveis espécies bioindicadoras como alvo de monitoramento. Dessa forma, o trabalho foi dividido em 2 capítulos para responder tais perguntas:

<u>Capítulo 1 – Quais são as espécies afetadas no Brasil? Como a ingestão plástica está se comportando ao longo do tempo?</u>

Objetivos específicos: (1) acessar a frequência de interações aves marinhas-plástico no Brasil; (2) determinar se as interações plásticas têm mudado ao longo do tempo e em diferentes regiões costeiras brasileiras; e (3) identificar potenciais espécies bioindicadoras para monitorar a poluição plástica.

<u>Capítulo 2 – O plástico é um fator contributivo na mortalidade de aves marinhas? Quais espécies são afetadas por esta poluição?</u>

Objetivos específicos: (1) diagnosticar as principais causas de morte e processos patológicos em aves marinhas necropsiadas no Sudeste Brasileiro; (2) quantificar resíduos plástico ingerido; (3) relacionar o plástico às principais causa de morte e processos patológicos para identificar espécies vulneráveis.

3. Capítulo 1

Title: Beached seabirds as plastic biomonitors in Brazil suggest that exposure to plastic in the nearshore South Atlantic is increasing through time.

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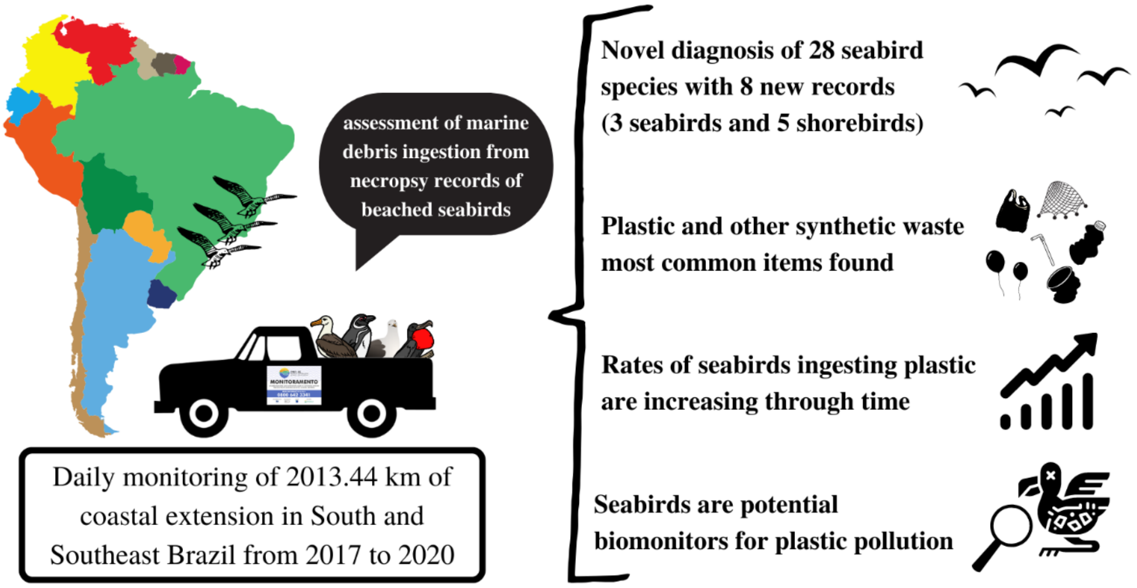
Highlights

- Twenty-eight seabird species are ingesting marine debris prior to death.
- We found eight new records including three seabirds and five shorebirds.
- Plastic and other synthetic waste represented 88% of diagnosed items ingested.
- Rates of seabird-plastic interactions are increasing in the South Atlantic.
- Four species have potential to track changes in plastic pollution through time.

Graphical abstract

Beached seabirds as plastic biomonitors in Brazil suggest that exposure to plastic in the nearshore South Atlantic is increasing through time.



Abstract

Plastic pollution is an emerging environmental challenge, as production and consumption of plastic and other products is rapidly expanding globally. To counteract this environmental challenge, many countries are responding by enacting policies to reduce plastic losses to the environment. Across most of the world, and especially outside of high-income countries, there is little information about the trends of plastic leakage to environment and interaction with marine species, posing a concern for marine animal conservation. Bioindicator species, especially seabirds, are useful to monitor wildlife exposure to plastic pollution, and the response of this plastic-wildlife interface to human plastic use and disposal, plastic leakage, and policy interventions. Here, we aimed to explore marine debris ingestion in seabird species across four years of monitoring in the South and Southeast Brazil, investigating the biomonitoring potential of different species. Using the necropsy stranding database of the Beach Monitoring Project of the Santos Basin (PMP-BS), a consolidated initiative that can pioneer as a monitoring program, we analyzed the frequency of debris ingestion through time and among four Brazilian states that integrate the PMP-BS. Specifically, we evaluated i) the frequency of seabird-plastic pollution interactions in Brazil; ii) whether plastic interactions have changed through time and in different coastal regions across the course of this study; and iii) potential bioindicator seabirds for monitoring the exposure of seabirds to plastic in the nearshore South Atlantic Ocean. We found that many individuals of 28 species had ingested plastic prior to death, including eight new records (three seabirds and five new shorebird). Importantly, we found that the rates of seabird interaction with plastic are increasing through time in Brazil. We discuss the PMP-BS approach and its potentiality for monitoring marine pollution with bioindicators in the South Atlantic Ocean, suggesting four potential biomonitor species to track plastic pollution through time.

Keywords: bioindicators, marine debris, monitoring, plastic pollution, plastic ingestion.

Introduction

Marine debris are defined as any solid material manufactured or processed by human-activity that had its final destination into the marine environment (Galgani et al., 2010; Sheveal y et al., 2012). There are numerous negative impacts of litter in marine environments, including posing a threat to marine species (Roman et al., 2021a). To date, more than 1400 species are recorded to interact with marine litter through entanglement and ingestion (Claro et al., 2019). Plastics typically comprise the majority of items littering marine environments (Galgani et al., 2015). The increase through time in marine plastic pollution (Ostle et al., 2019; Borrelle et al. 2020), caused by leakage of items from both land and sea-based sources to the ocean (Borrelle et al. 2020), is being recognized as an emerging risk for the conservation of marine species (Roman et al, 2021a). There are numerous policy actions being undertaken worldwide to reduce leakage of waste to the oceans through addressing solid waste management (The Honolulu Strategy, Shevealy et al., 2012; The UN Environment Assembly, Carlini and Kleine, 2018; Haward, 2018).

Given that plastic pollution is a transboundary environmental challenge, there is a need for a worldwide effort to address this issue. One of the major challenges is establishing programs that monitor the presence and impacts of plastic in the environment; enabling the quantification of changes through time, in response to plastic policy change, and ultimately evaluating whether the current approaches are adequate to reach plastic pollution reduction goals. Globally, there are numerous isolated monitoring programs and published datasets on plastic pollution, but due to variable methodologies and lack of harmonization, it is challenging to analyze these data across broad geographies in an integrated way (Claro et al., 2019). Even though there are theoretical models to estimate the amount of plastic in the ocean in a determined time (e.g., Eriksen et al., 2014; Jambeck et al., 2015), ground-truthing these models using robust methods and empirical data to monitor plastic loads and impacts in the ocean is missing across most jurisdictions.

One monitoring strategy that has been contemplated in the recent decades is the usage of bioindicators, a biotic component, such as animal species, that can be collected as a passive means to sample presence, wildlife encounter or impact of plastic in the environment (Backer, 2008; Connor et. al., 2011; Schlacke et al., 2011; Rapport and Hildén, 2013; Acampora et. al., 2016; Matiddi et al., 2017; Fossi et. al., 2018; Macali and Bergami, 2020). Since bioindicator approaches are allied to the conservation of species by considering the response of the organisms impacted when they encounter plastic in their environment, this approach further informs adequate and realistic mitigating actions for plastic-wildlife conservation interface.

To date, the only jurisdiction that applies a consolidated federal monitoring program using a megafauna bioindicator to track plastic pollution through time is The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) in the North Sea, followed in all European marine areas (European Commission, 2014). In Europe, plastic pollution was recognized as a conservation issue in 2002, when member countries tasked OSPAR with including marine litter in their system of Ecological Quality Objectives (EcoQOs) (Ministerial Declaration of the Fifth International Conference on the Protection of the North Sea, 2002). The OSPAR biomonitoring program was initially developed out of an existing national monitoring program undertaken in the Netherlands, where plastic monitoring was carried out through necropsy sampling of plastic debris found in the stomach of a target species of seabird, the northern fulmar (Procellariidae: *Fulmarus glacialis*). The approach of beached seabird necropsy to quantify ingested plastic was developed for international implementation by OSPAR as one of its EcoQOs (OSPAR, 2008, 2009, 2010; Van Franeker et al., 2011).

In Brazil, the Beach Monitoring Project of the Santos basin (Projeto de Monitoramento de Praias da Bacia de Santos, PMP-BS) is a pioneering monitoring program that daily covers an extensive coastal region in the South and Southeast Brazil in search for the stranded marine megafauna (seabirds, sea turtles and marine mammals) to perform veterinary care (PETROBRAS, 2019), including necropsy. The PMP-BS allows the assessment of ingested marine debris, presenting a valuable opportunity for a plastic bioindicator monitoring program because it provides occurrence, ecological and pathological data of stranded animals in a vast and daily updated database. Therefore, our main goal was to diagnose the quantity of stranded birds along the entire coast monitored by the PMP-BS across 4 years to understand which marine species that are collected through this program have interacted with plastic pollution and have potential use as a plastic bioindicator for the South Atlantic. This study aims to i) assess the frequency of seabird-plastic pollution interactions in Brazil using the PMP-BS database, ii) determine whether plastic interactions have changed through time and in different coastal regions across the course of this study, and iii) identify potential bioindicator seabirds for plastic monitoring.

Methods

Beach Monitoring Project of the Santos basin (PMP-BS)

The PMP-BS is developed as a condition of the federal environmental licensing of PETROBRAS' activities for production and flow of oil and natural gas in the Santos Basin Pre-Salt Pole, conducted by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). Its main objective is to evaluate the possible impacts of the activities on the target marine megafauna (seabirds, sea turtles and marine mammals) by monitoring the coastal extension of the South and Southeast Brazil to perform veterinary care, including necropsy and rehabilitation (PETROBRAS, 2019). All data collected by the PMP-BS is publicly available at the Aquatic Biota Monitoring Information System (SIMBA, n.d.) from where we extracted the data for this study.

The monitoring program is undertaken across 4 States from the South (Santa Catarina, SC; and Paraná, PR) and Southeast (São Paulo, SP; and Rio de Janeiro, RJ) of Brazil and covers the municipalities of Laguna – SC (28°29'43.1"S 48°45'38.5"W) to Saquarema – RJ (22°56'08.1"S 42°29'43.9"W) along 2013.44 km of coastal extension (Figure 1) (PETROBRAS, 2019). Monitoring is carried out along the coastal extension with active search on a daily and weekly frequency, embarked actions, partnerships with other institutions and notification of occurrences of beached animals by the community. Due to the extension monitored, the program is divided into 15 sections, each one with at least one Executive Institution responsible, and 3 Coordinations (SC and PR; SP; and RJ). Beach monitoring is done preferably in the early hours of the day, with the main objective of finding stranded marine megafauna (seabirds, sea turtles and marine mammals).

Animals are taken to the facilities of a Veterinary Care Network of the Executive Institutions, composed by Stabilization Units, Marine Mammal Necropsy Units, and Rehabilitation and Depetrolization Centers; where rehabilitation, release, and destination of recovered animals are performed, as well as necropsies of animals found dead or that eventually die in care. They are classified according to their condition of decomposition: code 1 (live animal), code 2 (carcass in good condition; fresh), code 3 (carcass in fair condition; decomposed, but organs intact), code 4 (carcass in poor condition; advanced decomposition), and code 5 (mummified or skeletal remains) (Table S1).

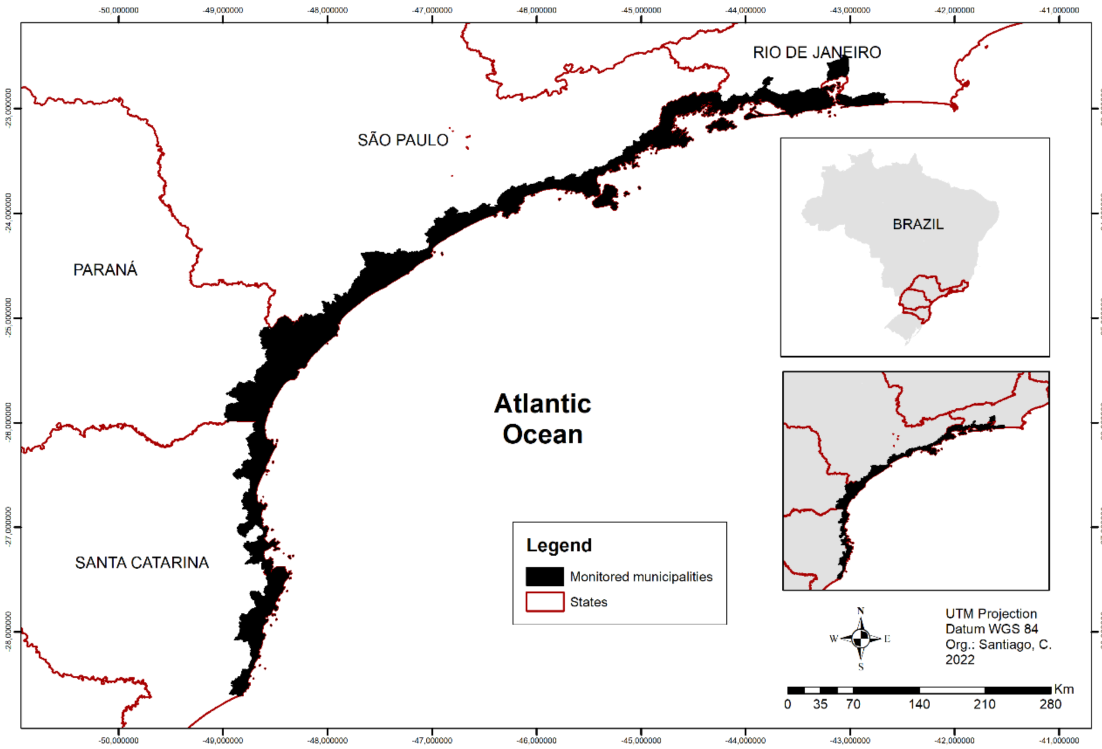


Figure 1. Coastal extension monitored by PMP-BS

Necropsies are performed only for code 2 and 3 animals, with exceptions (PETROBRAS, 2019), and several information is collected, providing data for taxonomic level, biometry, sex, development stage, body score, external exams, macroscopic pathological findings, histopathological analysis, and other laboratory exams (biomolecular, antibiogram, parasitological, etc.). During this process, the gastrointestinal tract of the animal is dissected, and its content is sorted in a sequence of granulometric sieves (2 mm, 1 mm, 0.5 mm) according to the PMP-BS protocol. Marine debris, when present, are processed and stored in a biological collection according to each Executive Institution. All logistics and protocols applied are present in the Integrated Executive Project of the PMP-BS (PETROBRAS, 2019).

<u>Accessing marine debris ingestion</u>

Monitoring plastic pollution is not one of the goals of the PMP-BS. However, it is possible to diagnose marine debris ingestion from SIMBA. We selected only birds for this study because they are the most numerous and diverse within the marine megafauna (Croxal et al., 2012), as well as having the largest scientific record regarding plastic ingestion (Provencher et al., 2017; Kühn and Van Franeker, 2020). In this way, beached bird occurrence and necropsy data from 2017 to 2020 were downloaded from SIMBA.

In the necropsy dataset, there is information regarding the presence of marine debris in the gastrointestinal tract (“presence of solid waste”) and assignment for any anthropogenic interaction, including “interaction with solid waste (litter)”. The last one is classified according to the level of evidence that the veterinary pathologist has about it: 1) low, when there is suspicion, but no evidence or injuries that prove the act; 2) medium, when there is no direct evidence, but injuries and strongly indicative factors; 3) high, when there is direct evidence. We considered that animal had ingested debris with the assignments for the “presence of solid waste” and the “interaction with solid waste (litter) level 3”. The ones assigned with “interaction with solid waste (litter) level 1 and 2” were manually checked on their respective necropsy records for photos of marine debris or description in the veterinary diagnosis.

The Executive Institutions can also assign further information for the “description of the gastrointestinal tract contents” with “reason for not collecting its content” (if they do not collect it), which may also contain information on ingested debris. They were also checked to seek for all marine debris ingestion cases that weren’t properly assigned for the “presence of solid waste” nor “interaction with solid waste (litter) level 3”. It was done by filtering the information with keywords chosen by the marine debris classifications used by Provencher et al. (2017) and Roman et al. (2019a): pellets, hard plastic, flexible plastic, nylon, foamed synthetic, balloon, rubber, microplastic, hook, metal, and glass (Table S2). Accordingly, we could access the main types of ingested debris, though this information wasn’t available for all individuals.

We did not consider code 4 and 5 birds, individuals that had their carcasses related to scavenger animals (e.g., vultures), and the ones that their taxonomic level could not be identified due to carcass autolysis because gastrointestinal contents may not have been explored. The identification of necrophagy behavior (scavenging) was sorted from the anatomopathological description of the organs that comprise the gastrointestinal tract (esophagus, stomach, and intestines), by filtering the information of “reason for not collecting the organ” in the dataset with the keywords: predation, predated, necrophagy, scavengers and absent. Such birds were assigned as non-analyzed (NA).

To sum up, the categorization of marine debris ingestion was identified checking several information in a vast necropsy dataset with the records of presence of solid waste, interaction with solid waste (litter) level 3, search by keywords referring marine debris categories and manual checking on necropsy records (Figure 2). More information about the methodological assessment and the PMP-BS is presented in supplementary material.

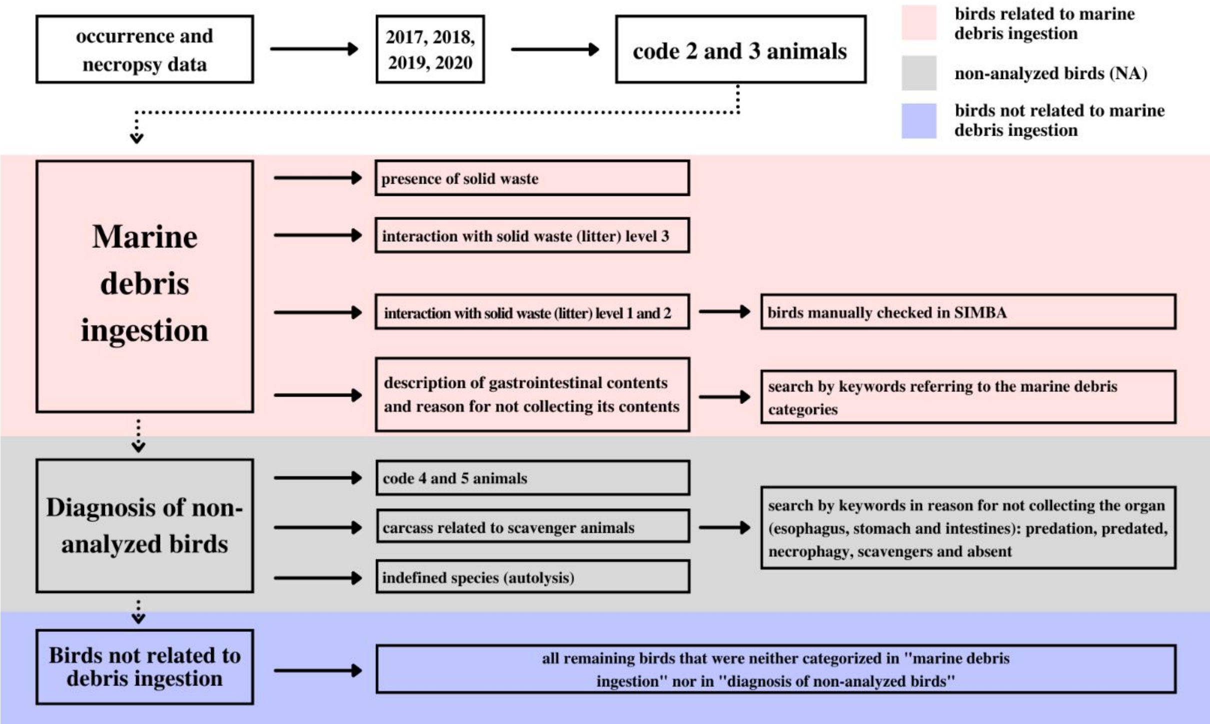


Figure 2. Methodological design to access marine debris ingestion from SIMBA.

Data analysis

We used data regarding taxonomic level (order, family, and species), occurrence date, local of occurrence (State), and marine debris ingestion (Fig. 2). All analyses were performed with R statistical software (The R foundation for Statistical Computing; http://www.R-project.org). Frequency of occurrence (FO) in percent of ingested marine debris was calculated for all species disregarding NA individuals. For the analysis, we considered only seabird species (characterized by Gaston, 2004) related to marine debris ingestion. The variation of debris ingestion by all individuals (FO) over the years (2017 to 2020) in different states (PR, RJ, SC and SP) was analyzed by fitting a generalized linear model (GLM), assuming Binomial error. The occurrence of overdispersion was corrected by using the quasibinomial distribution. The best statistical model applied in the analysis was chosen by comparisons between the fits of the full models and models with variable reduction using the maximum likelihood testing to compare the changes in deviances before and after the removal of variables. Interactions between variables were considered only when significant. Quality of fit was done by using half-normal-plot plots with simulated envelopes at the 95% significance level. When the effect of variables was significant, the means of the proportion of birds that ingested solid waste were compared using the maximum likelihood multiple comparisons test of the "cld" function in the "multcomp" package of the R software. We performed the same analysis for four target well represented species with potential as bioindicators.

Results

A total of 11 593 birds were necropsied between 2017 and 2020, with 71 species assessed, of which 1 041 had ingested marine debris (FO of 13%). Among seabird species characterized by Gaston (2004) that had interacted with marine debris, 10 793 individuals were sampled, of which 1 011 were affected (FO of 13%, Table 1), comprising 28 species in 4 orders (Charadriiformes, Procellariiformes, Sphenisciformes and Suliformes) out of 42 seabirds species. The data involving all necropsied birds (seabirds and shorebirds) is presented in Supplementary Material (Table S3). We also report the data by Brazilian States (Table S4) and by order (Table S5) for national diagnosis and usage.

Regarding the type of marine debris ingested, the active keyword search representing the marine debris categories revealed mostly plastic and other synthetic waste (Figure 3). The most common items were nylon (139 birds), hard plastic (104 birds), flexible plastic (75 birds) and rubber (28 birds) (Fig. 3.). Other items included foamed synthetic, microplastic, balloon, and pellets, with all items amounting to 88% of the seabirds (Fig. 3).

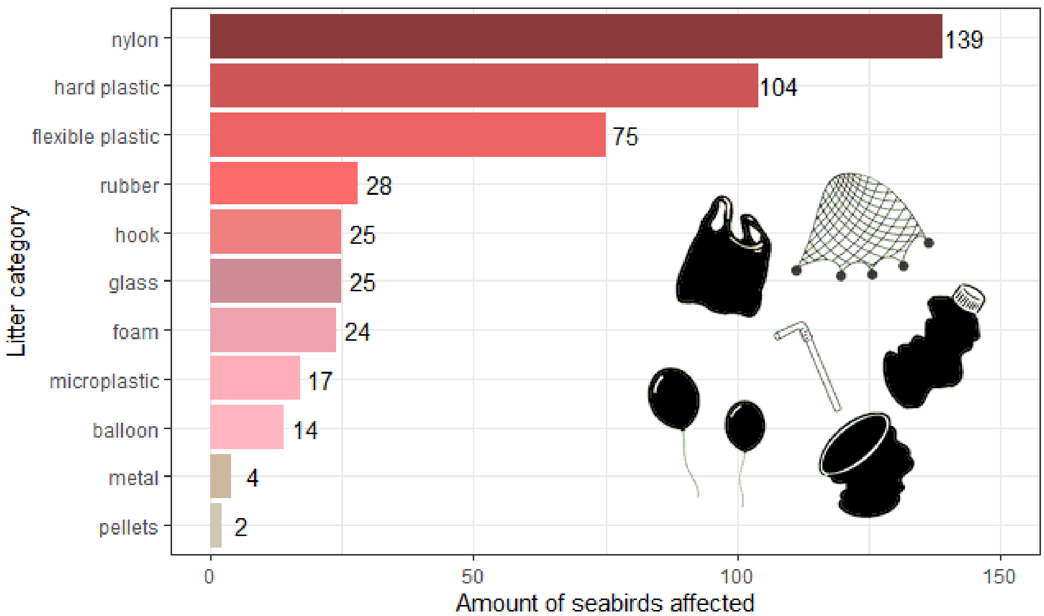


Figure 3. Types of solid waste diagnosed in the gastrointestinal tract of seabirds.

Table 1. Marine species that had ingested solid waste. Total = all birds necropsied, Debris = number of birds with marine debris ingestion, Absent = number of birds without marine debris ingestion, NA = birds not analyzed. Bolded species are those for which this was the first record of debris ingestion.

Order	Family	Species	Common name (ENG / PT-BR)	Total	Debris	Absent	NA	FO
Charadriiformes	Laridae	*Larus dominicanus*	*Kelp Gull / Gaivotão*	1 362	120	1 138	104	10%
		Rynchops niger*	*Black Skimmer / Talha-mar*	31	2	24	5	8%
		Sterna hirundinacea*	*South American Tern / Trinta-réis-de-bico-vermelho*	91	1	77	13	1%
		Sterna hirundo	*Common Tern / Trinta-réis-boreal*	54	3	43	8	7%
		Thalasseus acuflavidus	*Sandwich Tern / Trinta-réis-de-bando*	134	2	108	24	2%
	Stercorariidae	*Stercorarius maccormicki*	*South Polar Skua / Mandrião-do-sul*	2	1	0	1	100 %
Procellariiformes	Diomedeidae	*Thalassarche chlororhynchos*	*Atlantic Yellow-nosed Albatross / Albatroz-de-nariz-amarelo*	559	3	63	493	5%
		Thalassarche melanophris	*Black-browed Albatross / Albatroz-de-sobrancelha*	176	11	36	129	23%
	Hydrobatidae	*Oceanites oceanicus*	*Wilson's Storm-petrel / Alma-de-mestre*	32	6	18	8	25%

Procellariidae	*Ardenna gravis*	*Great Shearwater / Pardela-de-barrete*	101	28	16	57	64%
	Ardenna grisea	*Sooty Shearwater / Pardela-escura*	62	6	10	46	38%
	Calonectris borealis	*Cory's Shearwater / Cagarra-do-mediterrâneo*	187	33	74	80	31%
	Calonectris edwardsii	*Cape Verde Shearwater / Cagarra-de-cabo-verde*	1	1	0	0	100%
	Daption capense	*Cape Petrel / Pomba-do-cabo*	10	2	2	6	50%
	Fulmarus glacialoides	*Southern Fulmar / Pardelão-prateado*	11	5	2	4	71%
	Halobaena caerulea	*Blue Petrel / Petrel-azul*	2	1	1	0	50%
	Macronectes giganteus	*Southern Giant Petrel / Petrel-grande*	50	10	15	25	40%
	Pachyptila belcheri	*Slender-billed Prion / Faigão-de-bico-fino*	5	2	0	3	100%
	Pachyptila desolata	*Antarctic Prion / Faigão-rola*	12	9	2	1	82%
	Pachyptila vittata	*Broad-billed Prion / Faigão-de-bico-largo*	2	1	1	0	50%
	Procellaria aequinoctialis	*White-chinned Petrel / Pardela-preta*	296	42	56	198	43%

		Procellaria conspicillata	*Spectacled Petrel / Pardela-de-óculos*	5	2	2	1	50%
		Pterodroma mollis	*Soft-plumaged Petrel / Grazina-delicada*	31	12	13	6	48%
		Puffinus puffinus	*Manx Shearwater / Pardela-sombria*	1 175	129	592	454	18%
Sphenisciformes	Spheniscidae	*Spheniscus magellanicus*	*Magellanic Penguin / Pinguim-de-magalhães*	3 911	417	2 403	1 091	15%
Suliformes	Fregatidae	***Fregata magnificens****	*Magnificent Frigatebird / Fragata, tesourão*	652	50	557	45	8%
	Phalacrocoracidae	*Nannopterum brasilianum*	*Neotropical Cormorant / Biguá*	547	27	448	72	6%
	Sulidae	*Sula leucogaster*	*Brown Booby / Atobá-pardo*	1 292	85	1 021	186	8%
		Total		**10 793**	**1 011**	**6 722**	**3 060**	**13%**

* Species with first debris ingestion record

When the species are examined across each state from 2017-2020 (Figure 4), Paraná (PR) had a continuous increase in FO through the years (PR – 8.0%, 12.06%, 21.6% and 31.42%). São Paulo (SP) presented the highest FO in 2019 with the latest 2 years higher than the first ones (SP – 16.3%, 12.15%, 22.98% and 18.8%). Rio de Janeiro (RJ) presented similar FO for 2017 and 2018 with a later increase as seen for SP state with the highest in 2019 (RJ – 5.14%, 4.51%, 14.69% and 10.69%). Santa Catarina (SC) had the least variability within the years, with the highest FO in 2020 (SC – 10.3%, 8.86%, 9.76% and 12.31%).

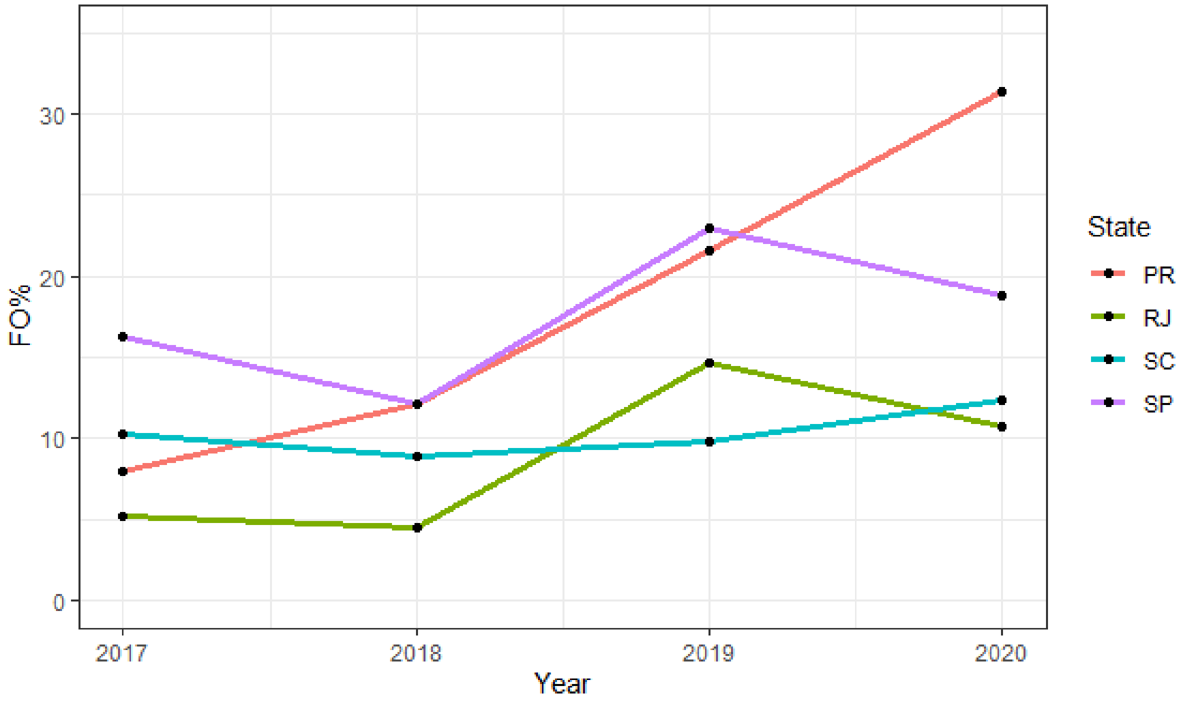


Figure 4. Frequency of occurrence of marine debris in the stomachs of all seabird species, across four states in Brazil; Santa Catarina (SC), Paraná (PR), São Paulo (SP) and Rio de Janeiro (RJ), by year.

Some species were well represented across all years. These include the Manx Shearwater *Puffinus puffinus*. (n=235-376 per year), the White-chinned Petrel *Procellaria. aequinoctialis* (n=30-133 per year), the Cory's Shearwater *Calonectris borealis* (n=13-75 per year) and Great Shearwater *Ardenna gravis* (15-28 per year), though plastic ingested was not available for all individuals. Among these four well-represented species, the FO of ingested plastic increased from 2017 to 2020 in the Manx Shearwater (13.4% in 2017 – 21.7% in 2020), Cory's Shearwater (29.6% in 2017 – 53.8% in 2020) and Great Shearwater (40.0% in 2017 –

83.3% in 2020) (Figure 5). The FO of ingested plastic increased in White-chinned Petrel from 20% in 2017 to 58.1% in 2019 but decreased to 42.3% in 2020 (Fig. 5).

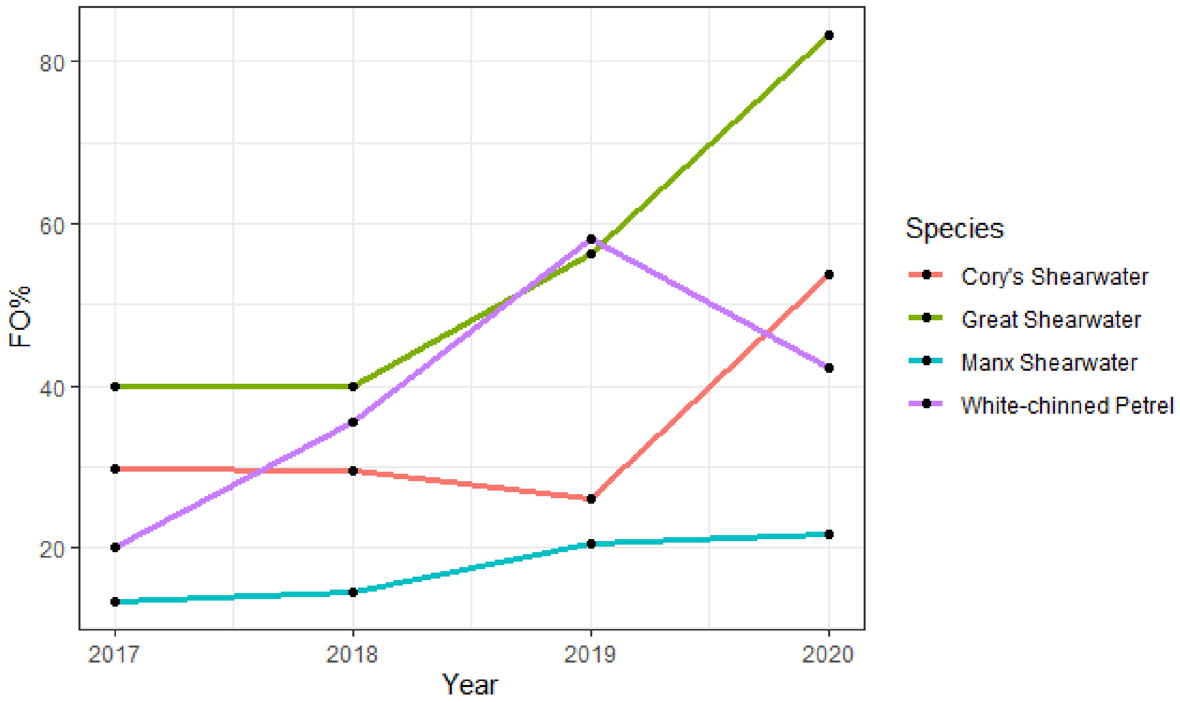


Figure 5. Frequency of occurrence of marine debris in the stomachs of four seabird species by year.

Our statistical model did not find significance for the Year:State interaction, being dropped from the model. The reporting of seabirds related to plastic ingestion increased across years (LVR = 9.7006, df = 1, df = 14, p = 0.0098). In addition, there was a difference in reporting between States (LVR = 6.7502, df = 3, df = 11, p = 0.0075). Differences by the maximum likelihood between groups with $p < 0.05$ highlighted two similar groups encompassing the States of SP-PR and RJ-SC (SP – 16.44% and PR – 19.58%; RJ – 8.12% and SC – 10.20%). For the four well represented species, there was an increase in reporting plastic ingestion for the Great Shearwater (LVR = 5.0811, df = 1, df = 8, p = 0.02419) and the Manx Shearwater (LVR = 5.9444, df = 1, df = 14, p = 0.0147643) (Fig. 5). We also found difference in reporting between States for the Cory's Shearwater (LVR = 5.9444, df = 1, df = 14, p = 0.0147643), the Manx Shearwater (LVR = 6.6727, df = 3, df = 11, p = 0.0001683) and the White-chinned Petrel (LVR = 4.2835, df = 3, df = 10, p = 0.004971).

Discussion

This study used necropsy records to better understand the interaction between seabirds and plastic pollution in Brazil, with three key findings. First, we found that 28 seabird species reported as beached in Brazil interact mostly with plastic, with interaction rates varying from 1% (e.g., South American Tern) to 100% (e.g., South Polar Skua; Cape Verde Shearwater, and Slender-billed Prion) (Table 1). Second, we found that the rate of seabird interactions has increased over time in Brazil between 2017 and 2020. Finally, we identified four seabird species with plastic pollution biomonitoring potential: the Cory's Shearwater, the Great Shearwater, the Manx Shearwater and the White-chinned Petrel. This research has significant implications for the state of seabird conservation and plastic pollution monitoring in Brazil and the South Atlantic.

Seabirds and plastic pollution in Brazil

The first major result of this study is the high frequency of interactions between seabirds and shore birds in Brazil and plastic pollution. Among the 28 beached seabird species reported here, three possibly present their first record of marine debris ingestion from necropsy (the Magnificent Frigatebird *Fregata magnificens*, the Black Skimmer *Rynchops niger*, and the South American Tern *Sterna hirundinacea*. Considering all examined birds, including shorebirds (Table S3), the number rises to eight species, with the Cocoi Heron *Ardea cocoi*, the Snowy Egret *Egretta thula*, the White-backed Stilt *Himantopus melanurus*, the Black-crowned Night-heron, *Nycticorax nycticorax*, and the Bare-faced Ibis *Phimosus infuscatus*. Of all the seabirds, three are globally threatened: the Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos* (endangered), the White-chinned Petrel *Procellaria aequinoctialis*, and the Spectacled Petrel *Procellaria conspicillata* (vulnerable); and two near threatened: the Sooty Shearwater *Ardenna grisea* and the Cape Verde Shearwater *Calonectris edwardsii*; all of them Procellariiformes. The other species have the status of least concern (BirdLife International IUCN Red List for birds, 2022). High frequencies of ingested plastics among the marine and aquatic birds sampled raise the question of whether marine litter may pose a conservation concern for these species in Brazil.

Previous studies have reiterated our finding that plastic waste is well-represented among the main debris ingested by seabirds (Provencher et al., 2017). Some bird species can eliminate large plastic items they have ingested through their natural behavior of regurgitating indigestible solid items from the stomach. However, regurgitation is not common in all species, and others have gut physiologies that retain solid items (Rothstein, 1973). For example, Procellariiformes have a constriction between the pro-ventricle and gizzard that retains ingested plastic (Rothstein, 1973). Due to their propensity for plastic ingestion and retention, Procellariiformes are likely to be utilized as useful indicators to track plastic pollution. In our study, Procellariiformes were the taxonomic order that presented the highest FO% of ingested plastic in all analyzed states (Table S4) and, within it, members of the Procellariidae family (petrels) were the birds with the highest frequency of occurrence of marine debris ingestion, with 9 species presenting a FO% of ingested plastic greater than or equal to 50% (Table 1), reflecting the high occurrences of plastic ingested by petrels that are also seen in other studies of seabird plastic ingestion in Brazil (Colabuono et al., 2009; Tourinho and Fillmann, 2010; Vanstreels et al., 2021).

We observed that the frequency of plastic ingestion varied along Brazil's coastline, with carcasses in some States having higher frequencies of debris than others. There are two broad groups in the FO of marine debris ingestion, encompassing the States of São Paulo and Paraná (SP-PR) in a central region of the monitored area and the States of Rio de Janeiro and Santa Catarina (RJ-SC) at the extremities (Figure 1). The higher frequency of birds with marine debris in their gastrointestinal contents is evidenced for the SP-PR states, which may indicate that birds stranding in this region are possibly exposed to a greater load of plastic pollution in the South Atlantic, differing from the lower FO found at the extremities of the PMP-BS for the SC-RJ states (Table S5).

Most studies reporting plastic ingestion in Brazil are from the State of Rio Grande do Sul, the last Brazilian state after SC to the South, indicating a considerably higher FO for the analyzed birds compared to the results found here (e.g. Colabuono and Vooren, 2007; Petry et al., 2008; Colabuono et al. 2009; Tourinho and Fillmann, 2010; Petry and Benemann, 2017). Barbieri (2009) found an FO in Procellariiformes in the state of SP of 64.54% when sampling 110 individuals of 10 species between 2000 and 2002, contrasting with an FO here of 28% for the state of SP (Table S4, 640 individuals analyzed, 16 species). These studies, with one exception, were published more than a decade ago, before many of the standards for recording this type of data were published. Up-to-date data, such as those presented here, benefits our understanding of the current state of seabird plastic interactions in Brazil.

More recently, Vanstreels et al. (2021) quantified marine debris ingestion in birds stranded on the coast from Arraial do Cabo in RJ state to Conceição da Barra in Espírito Santo state (ES) between 2019 and 2021 through the Beach Monitoring Project of the Campos and Espírito Santo Basins (PMP-BC/ES), another monitoring program from the same federal environmental licensing of PETROBRAS. The study uses the same monitoring methodology of the PMP-BS and the region monitored is the continuation to the north of PMP-BS. They evaluated 126 individuals in 392 km of the coastal area, representing 19 bird species, with a total FO of 30%, higher than found here (FO of 13%, 10793 individuals, 28 species). Considering species level, the FO in ES was also higher. The number of stranded birds from PMP-BC/ES is considerably smaller, as well as the extent of the monitored area. However, proportionally more birds seem to be ingesting marine debris, which could indicate the existence of coastal patches for plastic ingestion of stranded birds. Such information brings new questions to evaluate plastic ingestion in seabirds on the Brazilian coast, such as the influence of latitude and ocean currents on stranded seabirds, and there is not an up-to-date survey on other Brazilian states comprehensively monitoring plastic ingestion in seabirds. The SP-PR coastal area may be important for biomonitoring purposes.

Twenty-eight seabird species beached along the Brazilian coast ingested plastic pollution prior to death, raising concerns about the potential for widespread impacts on animal health and conservation (Dias et al., 2019). Ingestion of plastic can cause a direct obstruction or perforation of the gastrointestinal tract (Pierce et al., 2004; Roman et al., 2019a). Additionally, the presence of plastic-associated chemicals, such as polychlorinated biphenyls and organochlorines (often used in pesticides) (Colabuono et al., 2010), may lead to sublethal impacts on the reproductive condition of species (Provencher et al., 2017). Three classes of marine debris: fishing debris (ropes, nets, and tackle), flexible plastics and rubber latex/balloons have been previously identified to be responsible for the main risk of mortality when ingested in several species of seabirds (Roman et al. 2019a). Given that, nylon (associated with fishing debris), flexible plastic and rubber (Fig. 3) represented in this study three of the four most common items ingested by seabirds, later found beached. The risk to these species may be reduced by addressing the mismanagement of these items. We recommend that policy actions could focus on reducing the waste through regulations, bans, and replacement of items that can cause a high risk of mortality, such as plastic bags and packaging, ropes, fishing nets and balloons.

These studies cited above better elucidate objectives to combat plastic for a monitoring program considering an acceptable level of pollution that would not cause harm to the species (Fossi et al., 2018) and so far, there is no kind of research like this published from Brazil. Nonetheless, the biggest country that borders the South Atlantic Ocean has great scientific potential in contributing to the plastic pollution commitment based on the PMP-BS necropsy approach, with a starting point here consistently diagnosing species related to debris ingestion.

<u>Increasing in plastic ingestion in seabirds reflects inconsistency in the effectiveness of Brazilian public policies</u>

The second major finding of this study is an increase in FO% of plastic ingested by all birds over 4 years, a trend which broadly remained consistent when individual species were examined (Fig. 5). Here, we did not analyze the individual plastic load (mass) of ingested plastic, what is recommended to better quantify and elucidate the temporal trend over at least 10 years of recent sampling from linear regression (Van Franeker et al., 2021). The increased reporting of birds ingesting plastic is most likely explained by the consistent increase of pollution itself in the oceans (Geyer and Jambeck et al., 2017; Lebreton and Andrady, 2019), which would increase the exposure of greater numbers of individual seabirds. In Brazil, Petry and Benemann (2017) detected an increase in FO% in White-chinned Petrels in recent decades, however, the plastic load did not show a significant change. They conducted surveys once a month during three distinct periods (1990, 1997 to 1998, and 2007 to 2014), focusing on dead beached White-chinned Petrels (n = 114). For a robust temporal analysis, consistent, sufficient, and standardized sampling is needed, which is done by the PMP-BS with daily monitoring and necropsy of stranded birds on the coast, a novel methodology for assessing marine debris ingested by marine megafauna in Brazil.

Monitoring is important both for quantifying the current 'state-of-environment' as well as evaluating mitigation actions. Some countries with comprehensive management strategies to combat marine plastic are already beginning to report reductions. One example is the OSPAR convention for the North Sea (Van Franeker et al., 2021) which has been detected by effectively using seabirds in biomonitoring plastic pollution. Its latest time trend modeling performed indicates that the individual mass of plastic ingested by the target species from 2009 to 2018 has declined significantly, predicting that the environmental goal set by the commission may be reached in 2054 (Van Franeker et al., 2021). Many countries have undertaken management actions over the past decade to reduce plastic leakage into the environment. For example, in Australia, a variety of municipal waste management strategies, undertaken at the local government level, have been associated with a decrease in coastal plastic pollution across the whole continent, amounting to an average reduction in the coastal litter of 29% over 6 years at the continental scale (Willis et al., 2022). Long-term reductions of plastic litter off Australia have also been detected through seabird biomonitoring. For example, Lavers et al. (2021) found that ingested plastic retrieved by stomach-flushing of Flesh-footed Shearwaters breeding on Lord Howe Island, Australia, had decreased over the long term during 2005–2019. While further evidence is required to determine whether the reduction in coastal plastic is linked to the long-term reduction in plastic ingested by Flesh-footed Shearwaters in this specific case, Willis et al. (2022) argue that action through policy at local scales does work to reduce the coastal plastic pollution at broader scales, what would decrease plastic leakage from land into the ocean and, accordingly, the opportunity for wildlife to interact with plastic.

The opposite is seen in Brazil, where the delay in dealing with solid waste management keeps exacerbating plastic pollution in the South Atlantic. The National Solid Waste Policy of Brazil (PNRS), Law 12 305/2010 (Brasil, 2010), was ultimately enacted in the last decade. From the PNRS, municipalities are the main actors in the execution of the law, including the planning and management of services. However, there are political changes in which the decentralization proposed by the policy creates obstacles for its implementation, lacking resources and efforts of federal and state support, training of technical staff, planning and social participation (Scardua and Bursztyn, 2003; Santiago, 2016). Considering the planning for solid waste management on the coastal sphere, out of the 274 coastal municipalities, 58.8% (153) declared they have a Municipal Integrated Solid Waste Management Plan (PMGIRS) until 2017 (Brasil, 2019). Another example is the presence of selective collection for recyclable waste in the municipalities: only 22.3% (61) municipalities have this service (Brasil, 2019). At the national level, from 4589 municipalities, nearly half (49%, 2268) declare to have the PMGIRS according to the PNRS (SINIS, 2022).

In this way, our findings reflect inconsistency in the effectiveness of Brazilian public policies, and the data suggests that the increasing pollution may continue unless there are effective actions in Brazilian national scale, as seen in other countries. Brazil has recently developed the National Plan to Combat Litter at Sea (Brasil, 2019), but has not been implemented yet due to political challenges at national scale, being necessary specific plans for the Brazilian regions according to the national guideline. Furthermore, there is the brand-new Strategic Plan for Monitoring and Evaluation of Litter at Sea for the state of São Paulo (PEMALM, 2021) to better understand how plastic pollution is beavering through time nearshore the São Paulo state. The use of bioindicators for plastic pollution and target goals are still in their infancy, hence, continuous monitoring is needed to evaluate the newborn Brazilian policies that aims to face plastic pollution in the South Atlantic Ocean.

Targeting bioindicator species

The third major finding of this study is a potential suite of bioindicator seabirds that could be employed to track the change in marine pollution through time, and in response to changing policy and public behavior surrounding plastic use and disposal. Previous studies indicated that sampling 30-40 birds per year provides robust background to track plastic pollution variation through time from the necropsy of beached individuals (Van Franeker and Meijboom, 2002; Provencher et al., 2017). With the PMP-BS approach of daily monitoring, we assume that all beached seabirds are found, providing a robust assessment for debris ingestion in a continuous term. Since Procellariiformes have a propensity for plastic ingestion and retention, we recommend four species with potential for bioindicator purposes in the South Atlantic based on the number of individuals stranded, FO, feeding behavior and habitat: the Great Shearwater, the White-chinned Petrel, the Cory's Shearwater, and the Manx Shearwater.

These species all have pelagic lifestyles, so it's possible to assess their exposure to plastic pollution of the nearshore and open ocean. Shearwaters are pursuit plungers that are likely to forage at deeper depths, meanwhile petrels are surface seizers exploring a limited depth on the surface (Tavares et al. 2017), thus, such animals allow the assessment of plastic pollution floating in a range of depths, not just from the surface. The Manx Sherwater and the Cory's Shearwater are common migrators from the North Atlantic to the South after breeding whereas the Great Shearwater and the White-chinned Petrel are breeders from the South, the last one exclusive to the South Hemisphere. Though some authors suggest that plastic ingested integrate the levels found in their foraging area for a period of up to a few weeks (Van Franeker and Kühn, 2020), retention time of plastic ingested are still not known with confidence, so it may reflect pollution from other ocean areas. Procellariiforms usually ingest hard plastic items (Colabuono el at., 2009; Roman et al., 2019b), yet, other kinds of items can be found, such as industrial pellets, flexible plastic, and foam synthetic (Vanstreels et al., 2021). However, not all individuals of all species in this dataset had been assessed for plastic ingestion, and we suggest that greater coverage and recording of presence or absence of ingested plastic would add significant plastic monitoring value to the PMP-BS.

The Great Shearwater had the highest FO% within the Brazilian States except for RJ where there is no information (PR – 88%, SC – 62% and SP – 57%, Table S4; Total – 64%, Table 1) with a significant increase through years (Fig. 5). Even though it had the lowest sample size compared to the others, it has a great potential for a proper temporal trend analysis considering long term. For this species, we didn't find difference in reporting between the

Brazilian States, which indicates that it may be well-represented for the coastal area monitored by PMP-BS. The Manx Shearwater also had a significant increase through years and additionally a difference between States, with the highest sample size (n = 1175), yet the lowest FO (18%). For biomonitoring purposes, efforts for sampling may be higher compared to the Great Shearwater, which more individuals are needed to be necropsied to access ingested debris due to their low FO. However, the increasing in reporting also raises concern for the conservation of such animals in the South Atlantic. The other species (the White-chinned Petrel and Cory's Shearwater) presented a higher sample size compared to the Great Shearwater, but lower FO (43% and 31%, respectively). They also presented differ in reporting between States, with no statistically significant increase in the FO of plastic through years. Yet, the quantity of individuals ingesting plastic in these species may also be suitable for biomonitoring purpose (42 and 33, respectively) and a long-term analysis with plastic load can better elucidate whether it is increasing or not.

It's also of value to consider coastal species, which may ingest different kinds of debris compared to the ones found in open ocean. For example, the Magellanic Penguin *Spheniscus magellanicus* was also well-represented across years and had the highest FO of ingested plastic (n = 3911, FO = 15%) compared to other well-represented Charadriiformes and the Suliformes species, which are the main coastal species in this region. The Magellanic Penguins are coastal visitors of southern Brazil during their winter migration from colonies in Patagonia, and mostly ingest flexible plastic as in plastic bags, and plastic threads as in nylon lines from fisheries activities (Brandão et al., 2011; Vanstreels et al., 2021). Considering what kind of debris species are ingesting in coastal and pelagic areas can tailor the monitoring purpose for specific policies of different kinds of waste management.

Overall, seabirds are suitable organisms to assess floating plastic pollution in the ocean (Kershaw et al., 2019), including through regular opportunistic necropsy of individuals with pelagic habits to access open ocean regions, the place of higher concentration and accumulation of marine debris due to ocean currents (Eriksen et al., 2014). This approach has already been used with a target petrel by the OSPAR Convention for the North Sea. There are similar methodologies that use other marine megafauna species as bioindicators, such as sea turtles (Matiddi et al, 2017), which are also target species in PMP-BS. However, the usage of birds seems to be more appropriate for monitoring plastic as they ingest smaller plastic load (e.g. mean of 5.3 ± 12.5 particles for birds, Vanstreels et al., 2021; versus 38.4 ± 88.5 particles for sea turtles, Petry et al., 2021), which makes sampling and quantification easier, and more affordable. They also have great diversity and distribution of species throughout the ocean (Croxall et al., 2012), and specific bioindicator species can be established for each marine region according to their ecological attributes related to plastic pollution, such as taxonomic level, feeding behavior, diet, and plastic exposure (Roman et al., 2019b).

Kershaw et al. (2019) describe the criteria for establishing a bioindicator species for monitoring plastic pollution. In our study, seabirds meet several of them, such as the regional representation of a specific geographic range, an abundance of organisms in the environment, opportunistic sampling (through necropsy of stranded animals), cost of sampling and easy analysis with the PMP-BS approach, species directly linked to environmental impact, and globally similar species for comparison, i.e., with comparable ecological niches and behaviors. In addition to enabling the quantification of ingested plastic, it is also possible to assess the probable cause of death of the animal and its health condition until the time of death with veterinary analysis through PMP-BS, evidencing possible risks associated with plastic pollution (Roman et al., 2021b) and other anthropic impacts, such as stranding and drowning in fishing gear (e.g. Ewbank et al., 2020) and interaction with oil (e.g., Waugh et al., 2022). It is also possible to use such organisms to detect other changes in marine ecosystems, such as fish stocks, changes in food chains/transfer of contaminants, and climate change (Provencher et al., 2019b). We highlight here that the necropsy of stranded seabirds can align with several other conservation goals besides tracking plastic pollution, and PMP-BS provides a unique dataset to contribute to the understanding of many conservation issues.

For plastic pollution, we recommend further research with continuous sampling giving attention for the species discussed here. In the South Atlantic Ocean, there is a need to link ecological drivers to plastic ingestion in seabirds to better understand the most feasible bioindicator species to track plastic pollution through time, considering what kind of debris, its load, and direct and indirect impacts to follow their conservation.

Though PMP-BS provides an opportunity for monitoring, there are some caveats

Another important factor is the technical development of the PMP-BS itself, which since its inception in 2015 has undergone several processes of expansion and improvement, with training of the technical staff and adjustment of methodologies for standardization in data collection among all the Executive Institutions. In the beginning, the reporting of marine debris found in necropsies was not one of the program’s objectives. Today, the institutions are instructed to perform a complete diagnosis of the gastrointestinal contents of the necropsied animals, including description of diet, marine debris, or oily waste when present. However, the database on the SIMBA platform does not include a detailed description for solid waste with quantity, mass and type of debris found, being up to each institution to perform individually such quantification in a non-integrated way.

Besides the PMP-BC/ES as seen in Vanstreels et al. (2021), there are also the Beach Monitoring Program of the Sergipe-Alagoas Basin (PMP-SE/AL) and the Beach Monitoring Project of the Potiguar Basin (PMP-BP/RN and CE), both in northeastern Brazil. All these projects came after the PMP-BS and they also take part in the Aquatic Biota Monitoring Information System (SIMBA). They have the same working method with veterinary care of stranded marine animals, and studies involving the diagnosis of plastic ingestion in seabirds in those regions are scarce. When several actors are considered (e.g., the Executive Institutions within PMP-BS), designating a bioindicator species is of great use by saving sampling efforts, focusing on methodological quality, and bringing practicality to technical performance.

In the global scenario, monitoring with indicators is already described within the sustainable development goal (SDG) 14 of the UN 2030 Agenda (Colglazier, 2015). The first specific objective (14.1) corresponds to prevent and significantly reduce marine pollution from land-based activities by 2025, including marine litter and nutrient pollution; to be assessed from 4 possible indicators, one of them being plastic ingested by biota. In Brazil, this comes in agreement with the Plan to Combat Litter at Sea (BRASIL, 2019), unprecedented in the country to address marine litter, as well as the Strategic Plan for Monitoring and Evaluation of Litter at Sea of the State of São Paulo (PEMALM, 2021). The latter is the first plan for the country to monitor marine pollution, in order to incorporate Brazil in the fight against pollution proposed by the 2030 Agenda. The plan follows the instructions of The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) and comes up with the use of bioindicators to assess the impacts on ingestion, entanglement, contamination, and dispersion of organisms by marine debris.

The PEMALM suggests as indicators the frequency of occurrence of ingestion (FO), the amount or mass ingested per organism, a specific description of the type of material found, the number of individuals killed by ingestion, and the number of injured individuals. The document is an important Brazilian advance in political-scientific planning regarding the problem and it discusses an integrated action of several sectors of society, governance, and institutional partnerships. We highlight here the need for alignment and standardization among actors, especially for sampling, which is a new global trend for the problem. The main difficulty found in the literature on marine debris ingestion related to megafauna is the lack of standardized methods (Provencher et al., 2017). The inconsistency of data among most studies ultimately hampers spatio-temporal comparative analyses, which is important for understanding the distribution of plastic pollution in the oceans. In addition, standardization provides more scientific basis and consistency as a premise for policy making. There are already protocols and recommendations to be followed to assess plastic ingestion in marine megafauna (Provencher et al., 2017), as well as specific protocols for seabirds (Provencher et. al., 2019a).

Brazil has a strong scientific potential regarding the new academic trends that seek to track plastic pollution in the oceans and to understand its impact, mostly because of the high occurrence of species. The PMP-BS is a tool already consolidated in the Brazilian scenario, providing data with greater standardization that can incorporate the indicators proposed by PEMALM, for example. Even though the latter plan to track plastic pollution corresponds only to the state of São Paulo, the PMP-BS allows the expansion of data to three other Brazilian states (SC, PR, and RJ), as reported here. The data presented here support the potentiality of the PMP-BS to compose a monitoring area for plastic pollution in the South Atlantic Ocean.

Conclusion

Ocean conservation and marine debris pollution are cross-cutting themes, which raises the complexity of public policies for marine pollution. Plastics, especially, are a major threat to conservation, bringing to light the existing political challenges to contain them. In this scenario, it is observed that there are already several actors capable of carrying out actions to monitor marine pollution on the Brazilian coast, for example the institutions that act within the PMP-BS. We provided a starting point to discuss plastic pollution monitoring through seabirds in the South Atlantic with a novel and consistent diagnosis of the species interacting with marine debris, mostly from plastic pollution. We have evidenced high rates of interaction within 28 seabird species along four Brazilian States and an increase over time, addressing this issue for the conservation of the marine environment that demands urgent actions. In Brazil, recent developed public policies can incorporate the use of such data provided by PMP-BS into their strategy and encourage a joint action of other institutions for a greater scientific basis with the publication of data according to existing national and international guidelines. It should be valuable to make a deeper comparison between other geographical areas in Brazil considering specific attributes of plastic ingestion, such as taxonomic level, type, amount, and load of plastic; to target coastal areas for monitoring. Worldwide, we address this issue in the South

Atlantic where there are fewer up-to-date and standardized data on seabirds-plastic interactions, suggesting four potential bioindicator species to be evaluated to track plastic pollution from beached seabirds. Unceasing reports are important to detect changes in plastic pollution and further research is still needed to better understand how species in the South Atlantic are interacting with plastic and, especially, how they are being impacted, to set the most feasible bioindicator specie. When several actors are considered, the need for data standardization shows the importance of the joint articulation of institutions as a commitment to the global problem. Finally, the monitoring of marine debris from beached seabirds with the PMP-BS approach has a great potential to outline and evaluate implemented measures to reduce pollution surrounding plastic use and disposal in the long term for the South Atlantic Ocean.

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Supplementary material

The PMP-BS is developed as a condition of the federal environmental licensing of PETROBRAS' activities for production and flow of oil and natural gas in the Santos Basin Pre-Salt Pole. It was initially divided into two Phases. Phase 1 began in August 2015, involving only the States of Santa Catarina, Paraná and São Paulo. Phase 2 began in September 2016, involving the southern coast of the state of Rio de Janeiro. Aiming to standardize the actions and data of the PMP after technical development of the project itself in its Phases 1 and 2, a new integrated project was approved by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) in May 2019, unifying both phases and thus dividing the PMP-BS into 15 sections, each one with at least one Executive Institution responsible, and 3 Coordinations (PETROBRAS, 2019). Information regarding the project is available at the official website https://comunicabaciadesantos.petrobras.com.br/programa-ambiental/projeto-de-monitoramento-de-praias-pmp.html. All data from PMP-BS is publicly accessible after validation by the Executing Institutions and Technical Coordinations in Aquatic Biota Monitoring Information System (SIMBA, n.d.), where all data for this study were extracted.

We choose to use data from 2017 to 2020 so we would have a full 4-year sampling because Phase 2 only started in September 2016. In SIMBA, the data are stratified into PMP-BS Phase 1, PMP-BS Phase 2, PMP-BS Area SC and PR, PMP-BS Area SP, and PMP-BS Area RJ, the latter three after consolidation of PMP-BS. For data extraction, we downloaded the dataset from each division (Phase 1 and 2 and Areas SC and PR, SP and RJ) regarding the "occurrence of individual target fauna" and "pathological examinations" at SIMBA. This was done only for the taxonomic level of birds. The extraction of raw data was done dynamically, unifying it into a single dataset.

The occurrence of individual target fauna and pathological examinations data (necropsy records) of the entire PMP-BS from its inception until August 2021 were downloaded and integrated through the PROCX function of Excel, using as reference the individual identifier code (ii) of each bird (identification number of the PMP-BS). The occurrence data utilized were "individual identifier (ii)", "date of occurrence" and "state". Pathological examination data extracted were “individual identifier (ii)”, “necropsy date”, “carcass condition (COD)” (Table S1), “Is there evidence of anthropogenic interaction?” (yes or no), “Anthropic interaction” (description of which interaction was observed with 3 levels of evidence described in methodology; categories of interaction are ‘interaction with aggression/vandalism/hunting’, ‘interaction with dredging’, ‘interaction with vessels’, ‘interaction with fisheries activities’, ‘interaction with oil’, and ‘interaction with solid waste (litter)’), “Collection of gastrointestinal contents” (yes or no), “Presence of solid waste" (yes or no)”, “Detailed screening of gastrointestinal contents” (yes or no) and its description, “Reason for not collecting gastrointestinal contents”, and information regarding the organs of the gastrointestinal tract (esophagus, stomach, and intestines) with information on whether or not they were collected plus the reason for not collecting them. The latter data was used to identify if necrophagy was involved. After pairing the data, only the birds that had their occurrence from 2017 to 2020, found dead or that eventually died, were selected.

Table S1. Description of carcass condition for seabirds.

COD	Status	Description
1	alive animal	found alive.
2	carcass in good condition	external examination: normal appearance, no or little action of scavengers, firm feathers, and beaks, with normal coloring for the species. internal examination: firm musculature and fat, intact organs, no architectural changes, or consistency.
3	moderate decomposition	external examination: normal appearance, slight protrusion of cloaca, skin of abdominal region with bile soak, dried eyes, detachment of skin from legs. internal examination: organs tinged by hemolytic and biliary soaking, maintenance of the architecture and consistency of the organs and viscera, intestines dilated by gas.
4	advanced decomposition	external examination: detachment of feathers, detachment of skin from subcutaneous tissue, evident signs of carcass predation by scavengers, fetid smell. internal examination: soft or liquefied fat, loss of normal architecture and consistency of the organs (liquefied or with gas bubbles).
5	mummified carcass or skeletal remains	-

Source: PETROBRAS, 2019.

We realized that there were birds in the dataset that were neither listed for "interaction with solid waste (litter) level 3" nor for "presence of solid waste", but there was an indication of marine debris in the "description of gastrointestinal contents collection" and "reason for not collecting gastrointestinal contents" spaces. Thus, it was based on the classifications used by Provencher et al. (2017) and Roman et al. (2019) to establish marine debris categories that target keywords were assigned to search/filter the data (Table S2). The searching and filtering processes were done in Portuguese (PT-BR).

Table S2. Keywords to identify the marine debris types.

Type	**Keywords**	**Keywords (PT-BR)**
nylon	nylon, thread	nylon, fio, linha
hard plastic	hard plastic,	plástico rígido, plástico duro
flexible plastic	flexible plastic, soft plastic, plastic bag(s)	plástico flexível, plástico maleável, sacolinha, sacola
rubber	rubber	borracha
hook	hook, fishing gear	anzol, petrecho (de pesca)
glass	glass	vidro
foam	styrofoam	isopor
microplastic	microplastic	microplástico, microplastico
balloon	balloon,	balão, bexiga
metal	metal	metal
pellets	pellets, industrial pellets	pellets, pelletes, pellete, pellet

As recommended by Provencher et al. (2017), all necropsied birds are reported here, including those not related to plastic ingestion (Table S3). Other seabird species (characterized by Gaston, 2004) not related to marine debris ingestion are *Anous stolidus*, *Chroicocephalus maculipennis*, *Larus atlanticus*, *Macronectes halli*, *Onychoprion fuscatus*, *Pterodroma arminjoniana*, *Pterodroma incerta*, *Stercorarius antarcticus*, *Stercorarius chilensis*, *Stercorarius longicaudus*, *Stercorarius parasiticus*, *Stercorarius pomarinus*, *Sterna trudeaui* and *Thalasseus.maximus*. We also report the data by Brazilian States (Table S4) and by order (Table S5) for national diagnosis and usage.

All data extracted from SIMBA, unified and processed for the present work is available by formal request to the first author (Laura Baes, laurabaescaetano@gmail.com).

Table S3. List of all species of birds accessed by PMP-BS from 2017 to 2020. Total = all birds necropsied, Debris = number of birds with marine debris ingestion, Absent = number of birds without marine debris ingestion, NA = birds not analyzed. Bolded species are those for which this was the first record of debris ingestion.

Order	Family	Species	Total	Debris	Absent	NA	FO
Charadriiformes	Charadriidae	*Charadrius collaris*	3	0	3	0	0%
		Charadrius semipalmatus	4	0	4	0	0%
		Pluvialis dominica	1	0	1	0	0%
		Vanellus chilensis	4	0	4	0	0%
		NA	2	0	2	0	0%
	Haematopodidae	*Haematopus palliatus*	16	0	12	4	0%
	Laridae	*Anous stolidus*	13	0	13	0	0%
		Chroicocephalus maculipennis	1	0	0	1	0%
		Larus atlanticus	1	0	1	0	0%
		Larus dominicanus	1 362	120	1 138	104	10%
		Onychoprion fuscatus	1	0	1	0	0%
		Rynchops niger*	31	2	24	5	8%
		Sterna hirundinacea*	91	1	77	13	1%
		Sterna hirundo	54	3	43	8	7%
		Sterna trudeaui	11	0	11	0	0%
		Thalasseus acuflavidus	134	2	108	24	2%
		Thalasseus maximus	24	0	20	4	0%
		NA	36	0	19	17	0%
	Recurvirostridae	***Himantopus melanurus****	14	1	11	2	8%
	Scolopacidae	*Calidris alba*	8	0	8	0	0%
		Calidris canutus	2	0	2	0	0%
		Calidris fuscicollis	5	0	5	0	0%
		Calidris himantopus	1	0	1	0	0%

		Gallinago paraguaiae	1	0	1	0	0%
		Tringa flavipes	1	0	1	0	0%
		Tringa melanoleuca	1	0	1	0	0%
		NA	1	0	1	0	0%
	Stercorariidae	*Stercorarius antarcticus*	3	0	3	0	0%
		Stercorarius chilensis	6	0	2	4	0%
		Stercorarius longicaudus	3	0	3	0	0%
		Stercorarius maccormicki*	2	1	0	1	100%
		Stercorarius parasiticus	11	0	5	6	0%
		Stercorarius pomarinus	5	0	5	0	0%
		NA	16	0	8	8	0%
Coraciiformes	Alcedinidae	*Chloroceryle americana*	1	0	1	0	0%
		Megaceryle torquata	2	0	2	0	0%
Gruiformes	Rallidae	*Aramides saracura*	1	0	1	0	0%
		Porphyrio martinica	1	0	1	0	0%
Pelecaniformes	Ardeidae	*Ardea alba*	100	4	96	0	4%
		Ardea cocoi*	33	1	31	1	3%
		Botaurus pinnatus	1	0	1	0	0%
		Bubulcus ibis	7	0	6	1	0%
		Butorides striata	5	0	5	0	0%
		Cochlearius cochlearius	1	0	1	0	0%
		Egretta thula*	30	1	29	0	3%
		Ixobrychus exilis	2	0	2	0	0%
		Ixobrychus involucris	1	0	1	0	0%
		Nyctanassa violacea	5	0	5	0	0%

		Nycticorax nycticorax*	99	7	90	2	7%
		NA	1	0	1	0	0%
	Threskiornithidae	***Phimosus infuscatus****	4	1	2	1	33%
Procellariiformes	Diomedeidae	*Thalassarche chlororhynchos*	559	3	63	493	5%
		Thalassarche melanophris	176	11	36	129	23%
		NA	101	0	1	100	0%
	Hydrobatidae	*Oceanites oceanicus*	32	6	18	8	25%
		NA	2	1	0	1	100%
	Procellariidae	*Ardenna gravis*	101	28	16	57	64%
		Ardenna grisea	62	6	10	46	38%
		Calonectris borealis	187	33	74	80	31%
		Calonectris edwardsii	1	1	0	0	100%
		Daption capense	10	2	2	6	50%
		Fulmarus glacialoides	11	5	2	4	71%
		Halobaena caerulea	2	1	1	0	50%
		Macronectes giganteus	50	10	15	25	40%
		Macronectes halli	5	0	1	4	0%
		Pachyptila belcheri	5	2	0	3	100%
		Pachyptila desolata	12	9	2	1	82%
		Pachyptila vittata	2	1	1	0	50%
		Procellaria aequinoctialis	296	42	56	198	43%
		Procellaria conspicillata	5	2	2	1	50%
		Pterodroma arminjoniana	1	0	0	1	0%
		Pterodroma incerta	11	0	8	3	0%
		Pterodroma mollis	31	12	13	6	48%
		Puffinus puffinus	1 175	129	592	454	18%
		NA	156	14	26	116	35%

	NA	NA	31	0	1	30	0%
Sphenisciformes	Spheniscidae	*Spheniscus magellanicus*	3 911	417	2 403	1 091	15%
Suliformes	Fregatidae	***Fregata magnificens****	652	50	557	45	8%
	Phalacrocoracidae	*Phalacrocorax brasilianus*	547	27	448	72	6%
		NA	2	0	1	1	0%
	Sulidae	*Sula leucogaster*	1 292	85	1 021	186	8%
		NA	2	0	0	2	0%
		Total	**11 593**	**1 041**	**7 183**	**3 369**	**13%**

* Species with first debris ingestion record

Table S4. List of all species of birds accessed by State. Total = all birds necropsied, Debris = number of birds with marine debris ingestion, Absent = number of birds without marine debris ingestion, NA = birds not analyzed.

State	Order	Family	Species	Total	Debris	Absent	NA	FO
PR	Charadriiformes	Laridae	*Larus dominicanus*	114	6	92	16	6%
			Rynchops niger	3	0	2	1	0%
			Sterna hirundinacea	3	0	2	1	0%
			Sterna hirundo	6	1	4	1	20%
			Thalasseus acuflavidus	24	0	16	8	0%
	Procellariiformes	Diomedeidae	*Thalassarche chlororhynchos*	113	0	5	108	0%
			Thalassarche melanophris	37	1	3	33	25%
		Hydrobatidae	*Oceanites oceanicus*	3	1	1	1	50%
		Procellariidae	*Ardenna gravis*	28	7	1	20	88%
			Ardenna grisea	29	1	0	28	100%
			Calonectris borealis	14	6	2	6	75%
			Daption capense	1	0	0	1	NA
			Fulmarus glacialoides	3	1	0	2	100%
			Macronectes giganteus	6	1	0	5	100%
			Pachyptila desolata	1	1	0	0	100%
			Procellaria aequinoctialis	77	9	6	62	60%
			Procellaria conspicillata	2	1	0	1	100%
			Pterodroma mollis	2	1	0	1	100%
			Puffinus puffinus	247	30	78	139	28%
	Sphenisciformes	Spheniscidae	*Spheniscus magellanicus*	243	48	100	95	32%

	Suliformes	Fregatidae	*Fregata magnificens*	39	2	24	13	8%
		Phalacrocoracidae	*Phalacrocorax brasilianus*	62	3	40	19	7%
		Sulidae	*Sula leucogaster*	216	8	137	71	6%
RJ	Charadriiformes	Laridae	*Larus dominicanus*	75	3	69	3	4%
			Rynchops niger	1	0	1	0	0%
			Sterna hirundinacea	3	0	3	0	0%
			Sterna hirundo	10	1	8	1	11%
			Thalasseus acuflavidus	26	1	24	1	4%
	Procellariiformes	Diomedeidae	*Thalassarche chlororhynchos*	50	2	15	33	12%
			Thalassarche melanophris	6	2	3	1	40%
		Hydrobatidae	*Oceanites oceanicus*	5	1	4	0	20%
		Procellariidae	*Ardenna gravis*	4	0	0	4	NA
			Ardenna grisea	1	1	0	0	100%
			Calonectris borealis	5	0	2	3	0%
			Fulmarus glacialoides	1	1	0	0	100%
			Halobaena caerulea	1	0	1	0	0%
			Macronectes giganteus	2	1	1	0	50%
			Procellaria aequinoctialis	9	0	6	3	0%
			Pterodroma mollis	2	1	1	0	50%
			Puffinus puffinus	62	1	49	12	2%
	Sphenisciformes	Spheniscidae	*Spheniscus magellanicus*	306	28	272	6	9%
	Suliformes	Fregatidae	*Fregata magnificens*	412	40	366	6	10%
		Phalacrocoracidae	*Phalacrocorax brasilianus*	269	17	247	5	6%
		Sulidae	*Sula leucogaster*	341	26	295	20	8%

SC	Charadriiformes	Laridae	*Larus dominicanus*	1 014	98	842	74	10%
			Rynchops niger	23	2	17	4	11%
			Sterna hirundinacea	56	0	46	10	0%
			Sterna hirundo	30	0	24	6	0%
			Thalasseus acuflavidus	42	0	33	9	0%
		Stercorariidae	*Stercorarius maccormicki*	1	0	0	1	NA
	Procellariiformes	Diomedeidae	*Thalassarche chlororhynchos*	276	1	25	250	4%
			Thalassarche melanophris	75	1	11	63	8%
		Hydrobatidae	*Oceanites oceanicus*	12	0	7	5	0%
		Procellariidae	*Ardenna gravis*	32	8	5	19	62%
			Ardenna grisea	12	2	4	6	33%
			Calonectris borealis	88	7	25	56	22%
			Calonectris edwardsii	1	1	0	0	100%
			Daption capense	7	1	2	4	33%
			Fulmarus glacialoides	4	0	2	2	0%
			Halobaena caerulea	1	1	0	0	100%
			Macronectes giganteus	29	4	12	13	25%
			Pachyptila belcheri	2	0	0	2	NA
			Pachyptila desolata	2	1	0	1	100%
			Procellaria aequinoctialis	106	6	18	82	25%
			Procellaria conspicillata	2	0	2	0	0%
			Pterodroma mollis	8	1	3	4	25%
			Puffinus puffinus	399	25	159	215	14%
	Sphenisciformes	Spheniscidae	*Spheniscus magellanicus*	2 266	154	1 247	865	11%
	Suliformes	Fregatidae	*Fregata magnificens*	81	2	68	11	3%

		Phalacrocoracidae	*Phalacrocorax brasilianus*	118	6	83	29	7%
		Sulidae	*Sula leucogaster*	311	14	245	52	5%
SP	Charadriiformes	Laridae	*Larus dominicanus*	159	13	135	11	9%
			Rynchops niger	4	0	4	0	0%
			Sterna hirundinacea	29	1	26	2	4%
			Sterna hirundo	8	1	7	0	13%
			Thalasseus acuflavidus	42	1	35	6	3%
		Stercorariidae	*Stercorarius maccormicki*	1	1	0	0	100%
	Procellariiformes	Diomedeidae	*Thalassarche chlororhynchos*	120	0	18	102	0%
			Thalassarche melanophris	58	7	19	32	27%
		Hydrobatidae	*Oceanites oceanicus*	12	4	6	2	40%
		Procellariidae	*Ardenna gravis*	37	13	10	14	57%
			Ardenna grisea	20	2	6	12	25%
			Calonectris borealis	80	20	45	15	31%
			Daption capense	2	1	0	1	100%
			Fulmarus glacialoides	3	3	0	0	100%
			Macronectes giganteus	13	4	2	7	67%
			Pachyptila belcheri	3	2	0	1	100%
			Pachyptila desolata	9	7	2	0	78%
			Pachyptila vittata	2	1	1	0	50%
			Procellaria aequinoctialis	104	27	26	51	51%
			Procellaria conspicillata	1	1	0	0	100%
			Pterodroma mollis	19	9	9	1	50%
			Puffinus puffinus	467	73	306	88	19%
	Sphenisciformes	Spheniscidae	*Spheniscus magellanicus*	1 096	187	784	125	19%

Suliformes	Fregatidae	*Fregata magnificens*	120	6	99	15	6%
	Phalacrocoracidae	*Phalacrocorax brasilianus*	98	1	78	19	1%
	Sulidae	*Sula leucogaster*	424	37	344	43	10%
		Total	**10 793**	**1 011**	**6 722**	**3 060**	13%

Table S5. Order of seabirds related to marine debris ingestion by State. Total = all birds necropsied, Debris = number of birds with marine debris ingestion, Absent = number of birds without marine debris ingestion, NA = birds not analyzed. (Note: all individuals identified from taxonomic level up to order are included here).

State	Order	Total	Debris	Absent	NA	FO
PR	Charadriiformes	155	7	118	30	6%
	Procellariiformes	639	65	102	472	39%
	Sphenisciformes	243	48	100	95	32%
	Suliformes	317	13	201	103	6%
RJ	Charadriiformes	117	5	105	7	5%
	Procellariiformes	149	10	82	57	11%
	Sphenisciformes	306	28	272	6	9%
	Suliformes	1 022	83	908	31	8%
SC	Charadriiformes	1 204	100	984	120	9%
	Procellariiformes	1 147	64	286	797	18%
	Sphenisciformes	2 266	154	1 247	865	11%
	Suliformes	510	22	396	92	5%
SP	Charadriiformes	250	17	210	23	7%
	Procellariiformes	1 072	179	461	432	28%
	Sphenisciformes	1 096	187	784	125	19%
	Suliformes	644	44	522	78	8%
	Total	**11 137**	**1 026**	**6 778**	**3 333**	**13%**

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4. Capítulo 2

Title: Human activity impacted on half of seabirds beach-cast in Brazil.

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Highlights

- Nearly half of seabirds collected beach-cast were impacted by anthropogenic activities at the time of death.
- Fisheries major cause of death for the Magellanic penguin.
- Plastic ingestion is prevalent in some seabird species.
- Plastic may contribute to starvation death in tube-nosed seabirds.
- Anthropogenic activities additionally stress threatened seabird populations.

Abstract

Seabirds are the most threatened birds in the world and many threats stress seabird populations, such as by-catch fisheries and climate change. However, one threat that is rising to the conservation of these animals is plastic pollution. The main causes of death related are obstruction of the gastrointestinal tract and little is known about the secondary impacts, although, it is undeniable the impact on seabird health, rising concern. In the South Atlantic, there is a lack of knowledge on anthropogenic threats including plastic impacts on many seabird species. It is not clear how sublethal effects of less visible threats, such as plastic pollution, take part in cause of death of animals that die and wash up along Brazil's coastlines. Given the above, our aim is to report threats to seabirds in the South Atlantic focusing on the relation of plastic ingestion on cause of death from stranded seabirds in southeast Brazil. From the Beach Monitoring Program of Santos Basin (Projeto de Monitoramento de Praias da Bacias de Santos, PMP-BS), full necropsies of 368 seabirds were performed by veterinary pathologists between 2017-2019 comprising 10 species through daily monitoring efforts of 120.94 coastal km in Southeast Brazil, and we related the cause of death and the main pathologies identified to plastic ingestion. We used generalized additive models (GAMs) to determine whether the amount and mass of plastic ingested were significantly related to the cause of death and the main pathological processes. Nearly half (49.18%) of 368 seabirds had been influenced by anthropogenic activity at time of death (drowning due to fisheries, plastic ingestion, and oiling). Drowning due to fisheries was the main cause of death for the Magellanic penguin. We found a link between starvation cause of death and ingested plastic, especially in tube-nosed seabirds when it comes to starvation as a pathology. Plastic may contribute to the starvation deaths of these species, a key finding with significant ramifications for seabirds worldwide. We also diagnosed four potential plastic obstructions. The data presented here is important mostly to diagnose threatened species in Brazil and to the understanding of secondary effects of plastic pollution.

Keywords: plastic ingestion; cause of death; sublethal effects; anthropogenic activities; bycatch-fisheries; starvation; oiling.

Introduction

Seabirds are the most threatened birds in the world and there are many disturbs that stress populations in the open ocean, with some well-established, such as bycatch-fisheries and climate change (Croxall et al., 2012; Dias et al., 2019). However, these factors alone do not explain the great population decline that the species face (Paleczny et al., 2015). There is a variability of other disturbances that may act together with others (e.g., change in marine prey, pollutants, plastic ingestion, pathogens, fisheries interaction, etc., Provencher et al., 2019). Pelagic and endangered species are of great concern, mostly because in the open ocean disturbs are not simply accessed or completely understood, what is the case for plastic ingestion and its impacts.

Back to the first record of ingested plastic by animals, we find seabirds with increscent reports (Provencher et al., 2017) being well documented (Wilcox; Van Sebille; Hardesty, 2015; O'Hanlon et al., 2017; Kühn; Van Franeker, 2020). More recently, there is an effort to understand how plastic plays a role in bird populations' health (Vegter et al., 2014; Roman et al., 2019a; Roman et al., 2021a). Plastic ingestion has already been associated with ecological parameters (Roman et al., 2016; Tavares et al., 2017; Roman et al, 2019b) and causes of death (Roman et al., 2020a) for seabirds, yet it is not a consolidated worldwide trend.

The morbidity of a seabird is complex and encompasses a set of factors, such as cachexia syndrome (starvation), diseases and infections, trauma, and accidental capture in fisheries (Provencher et al., 2019). Few studies report obstruction or perforation of the gastrointestinal tract by plastic, what could lead to sepsis if so, causing a direct cause of death (Pierce et al., 2004; Roman et al., 2019a). It's been revealing new pathways for the impacts of plastic exposure in wildlife, giving importance to the conservation of species and leading concern (Roman et al., 2021b).

These pathways are called indirect or sublethal effects. As an example, plastic can adsorb pollutants, such as polychlorinated biphenyls and organochlorines (Colabuono; Taniguchi; Montone, 2010), trace metals (Homes; Turnes; Thompson, 2012), and other additives (Rani et al., 2015). The transport of these pollutants through the plastic to the animal may cause negative effects (e.g., Lavers; Bond; Hutton, 2014; Tanaka et al., 2015; Roman et al., 2020b), lacking knowledge about the cause-effect plastic ingestion. Furthermore, the indigestion of plastic inside the gut may affect the function of the organ, with some suggestions that it leads to satiety in green turtles (Santos et al., 2020), and that it's related to a lack of essential nutrients via diet in seabirds (Roman et al., 2020b). Multiple threats have cumulative and/or interactive effects on populations' health and their role in mortality is still not well understood (Provencher et al., 2019; Roman et al, 2021a), what can bias political decisions when it's an urgent matter.

One potential method that disentangles these effects is *postmortem* examinations of stranded animals inshore by veterinary pathologist's care and ecological overview/discussion. Whereas it is possible to access direct plastic ingestion, performing a necropsy is also a promising way to deeply reveal the cause of death and characterize health conditions, especially in species that live offshore that are difficult to access, but eventually, strands dead inshore. Relating plastic ingestion to pathological processes and cause of death is an emerging topic in science, providing a grounded overview of the understanding of its risks for the species (Roman et al., 2019a, Roman et al. 2021a). Anatomopathological and histopathological analyzes are promising approaches to target the direct and indirect effects of plastic ingestion (Puskic; Lavers; Bond, 2020), as well as disentangling the primary cause of death and animal health conditions (Daoust et al., 2021).

In the South Atlantic, there is a lack of knowledge on anthropogenic threats (bycatch-fisheries, oiling and plastic pollution) for many seabird species. It is not clear how the sublethal effects of less visible threats take part in the cause of death of animals that die and wash up along the coastline. Given the above, we aimed to report threats to seabirds in the South Atlantic focusing on anthropogenic activities and the relation of plastic ingestion on seabird health from a complete *postmortem* analysis of stranded seabirds in southeast Brazil.

Methods

Data collection takes part of the Beach Monitoring Project of Santos Basin (Projeto de Monitoramento de Praias da Bacia de Santos, PMP-BS) executed by Instituto de Pesquisas Cananéia (IPeC). This monitoring program is required by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), as a condition of the federal environmental licensing of PETROBRAS' activities for the production and flow of oil and natural gas in the Santos Basin Pre-Salt Pole. Its main objective is to evaluate the possible impacts of the activities on the target marine megafauna (seabirds, sea turtles, and marine mammals) by monitoring the coastal extension of South and Southeast Brazil to perform veterinary care, including necropsy and rehabilitation processes, for the stranded animals (PETROBRAS, 2019).

Full necropsies of 368 seabirds were performed by veterinary pathologists between 2017-2019 and 10 species related to plastic ingestion were evaluated - Procellariiformes, Procellaridae: *Ardenna gravis* (Great Shearwater), *Ardenna grisea* (Sooty Shearwater), *Calonectris borealis* (Cory's shearwater), *Daption capense* (Cape petrel), *Procellaria aequinoctialis* (White-chinned petrel) and *Puffinus puffinus* (Manx shearwater), Diomedeidae: *Thalassarche melanophris* (Black-browed albatross), and Hydrobatidae: *Oceanites oceanicus* (Wilson's storm petrel); Sphenisciformes, Spheniscidae: *Spheniscus magellanicus* (Magellanic penguin); and Suliformes, Sulidae: *Sula leucogaster* (Brown booby).

The birds were collected stranded during monitor efforts of 120.94 km on the South coast of São Paulo state, Southeast Brazil (Figure 1, 25° 0' 54'' S 47° 55' 37'' W), of which 99.14 km were daily monitored (Fig. 1, green line) and 5.44 km weekly (Fig. 1, yellow line), both by land with active search, and 16.36 km by community notification of a net of collaborators (Fig. 1, red line). Most of them were collected dead and a few were found alive, being assigned to the rehabilitation process with eventual death in care.

All animals were sent to the Cananéia Rehabilitation and Depetrolization Center (state of São Paulo) for anatomopathological, histopathological, and laboratory examinations to identify the cause of death, to assess the animal's health condition, and to characterize its biological parameters. External examination of the animal was performed when the carcass did not present a high level of autolysis. The main macroscopic alterations in the anatomopathological examination were diagnosed for all body systems, including the digestive apparatus, body cavities, cardiovascular system, endocrine system, lymphohematopoietic system, skeletal muscle system, central nervous system, reproductive system, respiratory system, urinary system, and cutaneous and subcutaneous tissue. Tissue samples of the organs were collected for histopathological analyses.

Figure 1. Coastal region with daily monitor efforts (green line), weekly effort (orange line) and notification by community (red line). Source: PETROBRAS, 2019.

The gastrointestinal tract of each seabird was dissected, and its contents were screened in a sequence of granulometric sieves (2 mm, 1 mm, 0.5 mm). Plastic debris up to 1 mm were counted and weighted to the nearest 0.0001 g. Some seabird carcasses were related to necrophagy, being accessed by vultures, therefore, when the gastrointestinal tract wasn't found intact or if there was a disruption on it, we assigned it as non-analyzed (NA) for plastic ingestion (NA = 25) because gastrointestinal content was not considered reliable. Plastic ingested is reported as recommended by Provencher et al. (2017) with frequency of occurrence (FO), mean, SE and range.

Based on the external evaluation, anatomopathological and histopathological examination, the main pathological processes diagnosed were fishing interaction, oiling, renal failure, respiratory failure, starvation, trauma, secondary infections (bacterial or fungal), and parasitism. The following categories of primary causes of death were assigned to each seabird from an overview of all examinations:

- Disease/infection, severe infections by bacteria or fungi, systemic diseases.
- Drowning fisheries, external findings of net marks resembling interaction with fisheries, and macro/microscopic findings (respiratory failure, edema in the lungs, generalized congestion, pulmonary hemorrhage, etc.) that conclude drowning in by-catch interactions.
- Drowning non-fisheries, macro/microscopic findings (respiratory failure, pulmonary edema, generalized congestion, pulmonary hemorrhage, etc.) that conclude drowning without apparent cause.
- Euthanasia, the animal was found alive and due to its bad health condition and the impossibility of reintroduction, it was euthanized.
- Neoplasm, neoplastic foci and metastasis.
- Oiling, histopathological lesions of contamination by environmental pollutants, and presence of oil in feathers or ingested.
- Renal failure, findings of severe renal necrosis in histopathological analysis with intense renal parasitism.
- Starvation, cachexia syndrome concluded by corporal score, emaciation, muscle atrophy, absence of food in the stomach, and immunosuppression parameters, comprising liver and kidney health and parasitism.
- Trauma, presence of internal bruises and bone fractures without a determined cause.
- Unknown, autolysis prevented the classification of the cause of death.

Statistical analyses were performed using R (Version 4.0.3). We used generalized additive models (GAMs) to determine whether the amount and mass of plastic ingested were significantly influenced by the cause of death and by the main pathological processes.

Results

Causes of seabird death and human activity

Primary causes of death were drowning due to fisheries interaction (n=112), starvation (n=108), disease/infection (n=15), trauma (n=15), euthanasia (n=15), drowning non-fisheries (n=13), renal failure (n=4), oiling (n=1) and neoplasm (n=1) (Table 1, Figure 2). The cause of death of some birds was unknown or unable to be determined due to decomposition and tissue autolysis (n=84). Nearly half (n=181, 49.18%) of 368 seabirds had been influenced by anthropogenic activity at the time of death (drowning due to fisheries, plastic ingestion, and oiling, Figure 3), with 22 birds affected by both plastic ingestion and drowning due to fisheries. It is unknown how many of the trauma deaths were due to anthropogenic interactions nor how many birds were indirectly affected by anthropogenic activities, such as exposure to environmental contamination causing disease and/or starvation.

If we consider anthropogenic activity not as a cause of death, but until the animal strands inshore, more than half (n=200, 54.35%) of 368 seabirds necropsied beach-cast in Brazil had been influenced. Anthropogenic activities include fisheries interaction (n=134, with 112 drowning due to fisheries interaction as cause of death), plastic ingestion (n=90), and oiling (n=8, with 1 as cause of death). A minority of birds were affected by both plastic ingestion and fisheries interaction (n=29), plastic ingestion and oiling (n=1), fisheries interaction and oiling (n=1), and plastic ingestion, fisheries interaction, and oiling (n=1) (Table 1, Fig. 2).

Fishing and seabird death

Drowning due to fisheries interaction accounted for 112 seabird deaths, of which the main specie related was the *Magellanicus penguin* (n=108). The other birds impacted were the Brown booby (n=3) and the Scopoli's shearwater (n=1).

Plastic ingestion

Plastic ingestion was determined in 10 species of seabirds (Table 2): the Cape petrel (FO=100%, n=2), the Sooty shearwater (FO=67%, n=3), the Great shearwater (FO = 60%, n=10) the Wilson’s storm petrel (FO=50%, n=2), the White-chinned petrel (FO=42%, n=24), the Scopoli's shearwater (FO=37%, n= 38), the Black-browed albatross (FO=38%, n=13), the Manx shearwater (FO=24%, n=66), the Magellanic penguin (FO=20%, n=145) and the Brown booby (FO=13%, n=40). The Great shearwater had ingested the greatest amount (mean=19.6, SE= 8.4198) and mass of plastic (mean=407.58, SE= 166.6835). One single individual had ingested 95 pieces of plastic. We identified 4 potential plastic obstructions (Figure 4), yet it didn’t account for the primary cause of death, but contributive.

Relationship between plastic and starvation death

There is a relationship between the amount of plastic and starvation cause of death (P=0.013, Deviance explained = 30.9%) across all species (Figure 5) and a negative relationship between the mass of plastic and renal insufficiency cause of death (P=0.031, Deviance explained = 21.5%) across all species.

Relationship between plastic and pathologies

There is a link between the amount of plastic and starvation as a pathology ($P < 0.001$, Deviance explained = 20.2%) across all species and within the Procellariiformes (P=0.0373, Deviance explained = 16.1%) (Figure 6).

There is a negative relationship between the amount of plastic and parasitism as a secondary infection (P=0.0025, Deviance explained = 20.2%) as well as the mass of plastic (P=0.0002, Deviance explained = 14.4%) across all species, and within the Procellariiformes (Amount: P=0.009, Deviance explained = 16.1%; Mass: P=0.0157, Deviance explained = 14.9%).

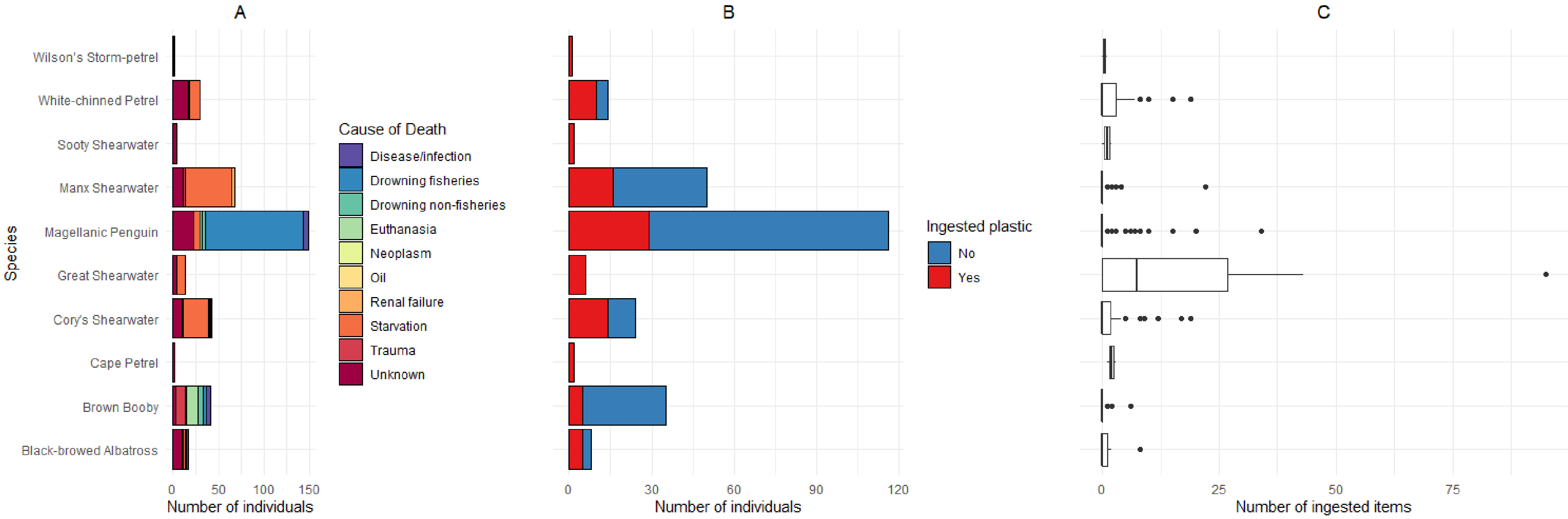

Figure 2. A: Causes of death in all seabirds (n = 284 seabirds. Eighty-four birds were excluded as COD was unable to be determined). B: Ingested plastic presence (n = 343. Twenty-five birds were excluded as they were related to necrophagy). C: Amount of ingested items (n = 343).

Figure 3. Anthropogenic impacts on seabirds. A: Oiled brown booby on its back and belly. B: Great shearwater (left) and pieces of hard plastic found in its stomach (right). C: *Magellanic penguin* with bruises and plucking on its fin (left) and hemorrhage on right lung from respiratory failure (right).

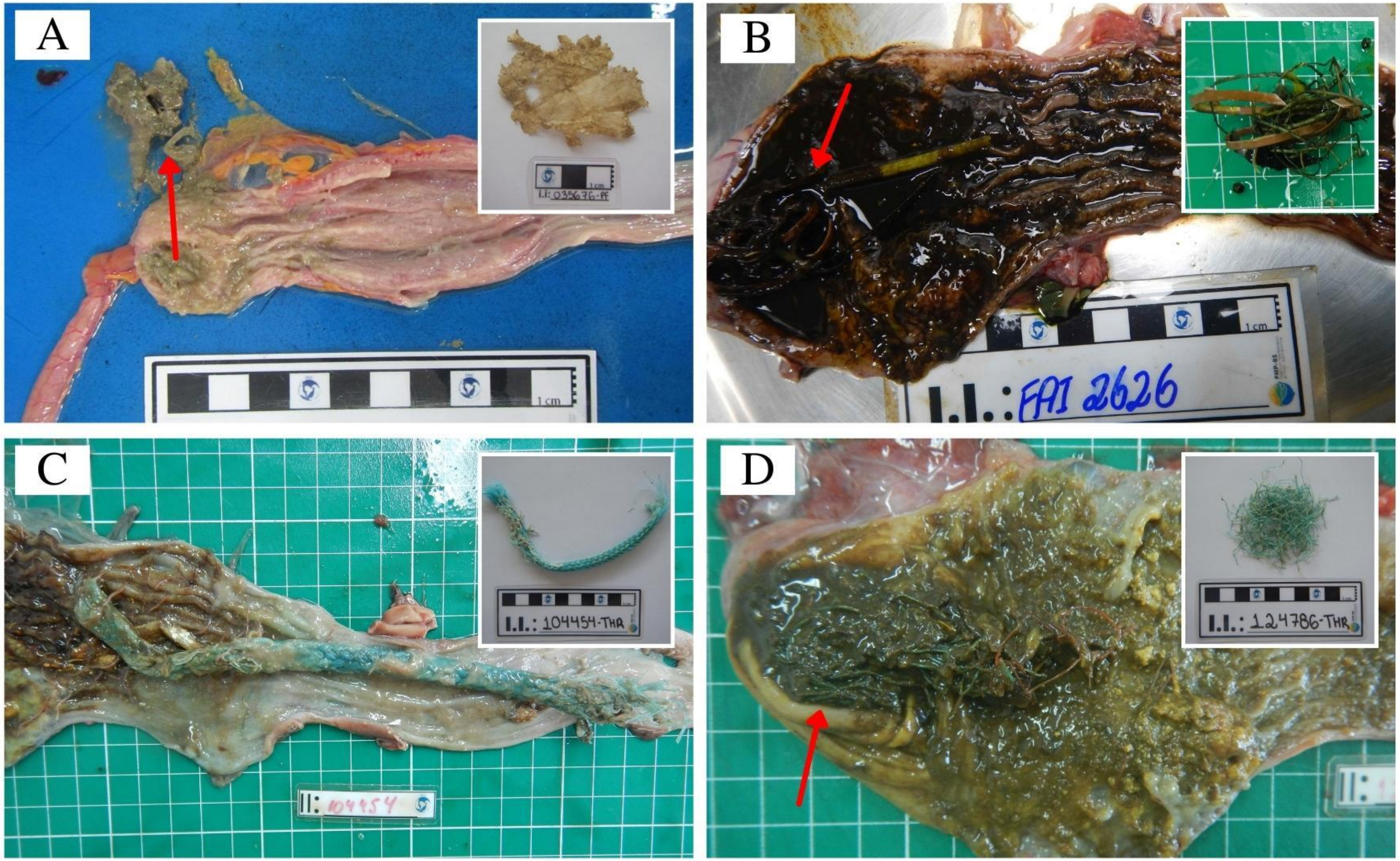

Figure 4. Potential plastic obstruction. A: Piece of soft plastic found in a brown booby stomach. B: 9 pieces of threadlike plastic stuck together that potentially caused ulceration in the stomach of a penguin. C: Large piece of rope partially obstructing the esophagus of a penguin. D: Set of nylon threads that were associated with mucosal ulcerations in the stomach of a penguin.

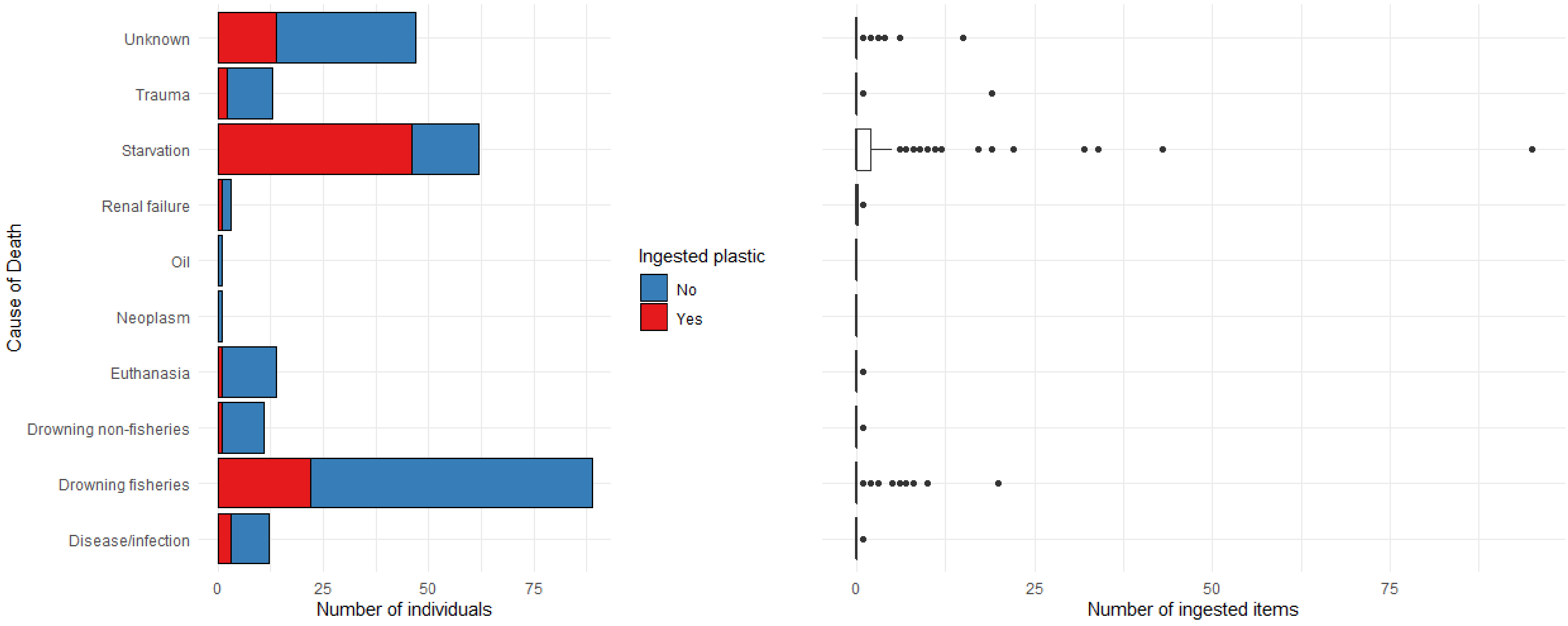

Figure 5. Causes of death and ingested plastic presence (left) and amount of ingested item (right) in all seabirds (n= 343 seabirds. Twenty-five birds were excluded as they were related to necrophagy).

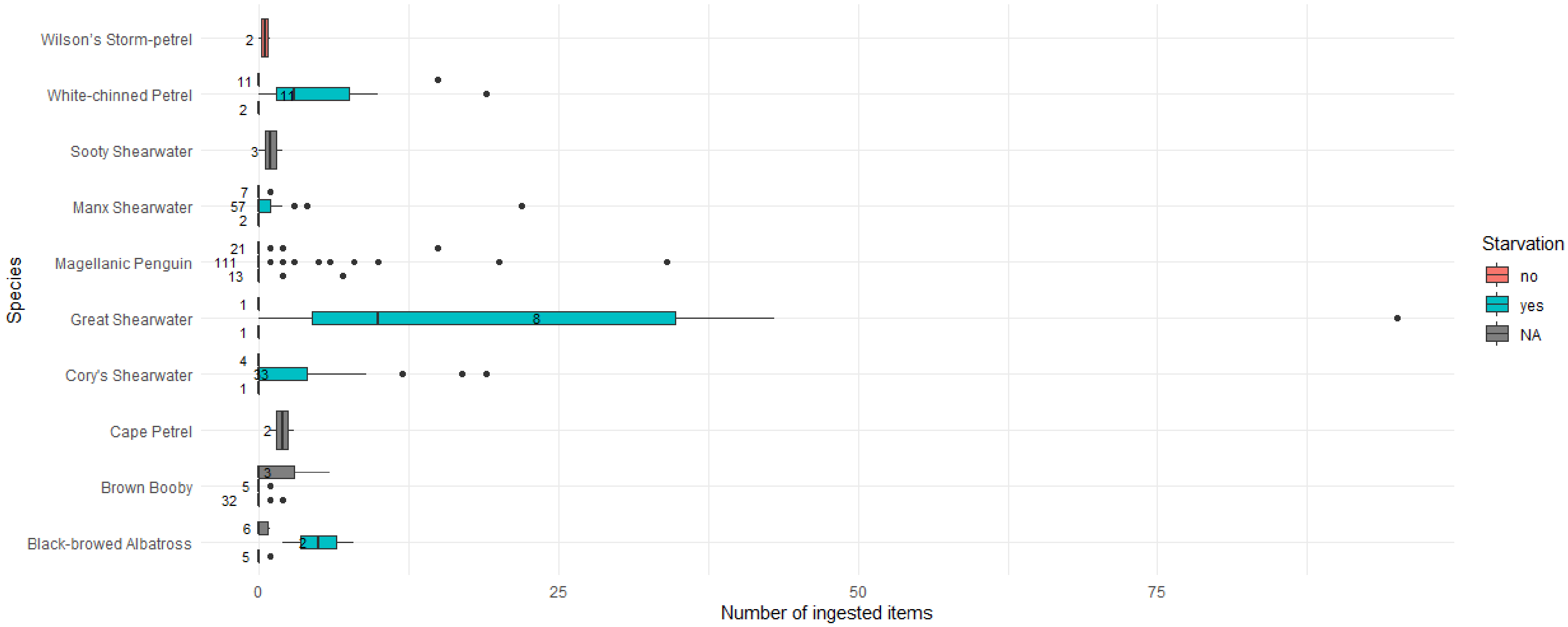

Figure 6. Starvation as pathology and amount of plastic ingested in seabirds (n = 285. Eight-three birds were excluded as autolysis prevented to diagnose starvation).

Table 1. Causes of death and ingested plastic in seabirds beach-cast in Brazil. (Note: N includes all birds necropsied, mean and range are calculated without NA plastic).

Species	Cause of death	N	N ingested plastic	Mean count ingested plastic	Range ingested plastic	Mean mass ingested plastic (mg)	Mass range ingested plastic (mg)
Ardenna gravis	Starvation	9	6	21.78	0-95	452.87	0 -1669.5
(Great Shearwater)	Unknown	4	0	0	0-0	0	0-0
Ardenna grisea (Sooty Shearwater)	Unknown	4	2	1	0-2	5.4	0-10.8
Calonectris diomedea	Disease/infection	1	0	0	0-0	0	0-0
(Scopoli's Shearwater)	Drowning fisheries	1	0	0	0-0	0	0-0
	Neoplasm	1	0	0	0-0	0	0-0
	Starvation	28	12	2.46	0-17	53.39	0-465.3
	Trauma	1	1	19	19-19	63.7	63.7-63.7
	Unknown	10	1	0.67	0-4	9.85	0-59.1
Daption capense (Cape Petrel)	Unknown	2	2	2	1-3	27.85	22.8-32.9
Oceanites oceanicus	Disease/infection	1	1	1	1-1	1	1-1
(Wilson's Storm-petrel)	Drowning non-fisheries	1	0	0	0-0	0	0-0
Procellaria aequinoctialis	Drowning non-fisheries	1	0	0	0-0	0	0-0
(White-chinned Petrel)	Starvation	11	9	5	0-19	75.61	0-243
	Trauma	1	0	0	0-0	0	0-0
	Unknown	17	1	1.36	0-15	20.48	0-225.3

Puffinus puffinus (Manx Shearwater)	Renal failure	4	1	0.25	0-1	0	0-0
	Starvation	51	14	0.94	0-22	12.1	0-475.8
	Trauma	2	0	0	0-0	0	0-0
	Unknown	11	1	0.11	0-1	0.18	0-1.6
Spheniscus magellanicus (Magellanic Penguin)	Disease/infection	6	1	0.17	0-1	4.77	0-28.6
	Drowning fisheries	108	21	0.8	0-20	104.04	0-4345.4
	Drowning non-fisheries	3	0	0	0-0	0	0-0
	Euthanasia	2	0	0	0-0	0	0-0
	Starvation	7	3	5.43	0-34	113.09	0-446.5
	Unknown	23	4	0.9	0-15	6.38	0-62.8
Sula leucogaster (Brown Booby)	Disease/infection	5	1	0.2	0-1	157.22	0-786.1
	Drowning fisheries	3	1	0.67	0-2	191.53	0-574.6
	Drowning non-fisheries	6	0	0	0-0	0	0-0
	Euthanasia	13	1	0.08	0-1	6.05	0-78.7
	Oil	1	0	0	0-0	0	0-0
	Trauma	10	1	0.1	0-1	19.46	0-194.6
	Unknown	3	1	3	0-6	99.6	0-199.2
Thalassarche melanophris (Black-browed Albatross)	Disease/infection	2	0	0	0-0	0	0-0
	Drowning non-fisheries	2	1	0.5	0-1	329.95	0-659.9
	Starvation	2	2	5	2-8	215.55	98.4-332.7
	Trauma	1	0	0	0-0	0	0-0
	Unknown	10	2	0.33	0-1	35.8	0-141.8

Table 2. Ingested plastic in seabirds beach-cast in Brazil. (Note: FO, mean and range are calculated without NA plastic).

Species	Common name	N	NA	N ingested plastic	FO	Mean count ingested plastic	SE	Range ingested plastic	Mean mass ingested plastic (mg)	SE	Mass range ingested plastic
Ardenna gravis	Great Shearwater	13	3	6	60%	19.6	8.4198	0-95	407.58	166.6835	0-1669.5
Ardenna grisea	Sooty Shearwater	4	1	2	67%	1	0.5000	0-2	5.4	3.8184	0-10.8
Calonectris borealis	Cory's Shearwater	42	4	14	37%	2.42	0.7375	0-19	42.57	14.5117	0-465.3
Daption capense	Cape Petrel	2	0	2	100%	2	1.0000	1-3	27.85	5.0500	22.8-32.9
Oceanites oceanicus	Wilson's Storm-petrel	2	0	1	50%	0.5	0.5000	0-1	0.5	0.5000	0-1
Procellaria aequinoctialis	White-chinned Petrel	30	6	10	42%	2.92	0.9493	0-19	42.67	13.9808	0-243
Puffinus puffinus	Manx Shearwater	68	2	16	24%	0.76	0.3404	0-22	9.47	7.2470	0-475.8
Spheniscus magellanicus	Magellanic Penguin	149	4	29	20%	0.99	0.3065	0-34	83.6	37.5099	0-4345.4
Sula leucogaster	Brown Booby	41	1	5	13%	0.28	0.1581	0-6	45.83	24.3470	0-786.1
Thalassarche melanophris	Black-browed Albatross	17	4	5	38%	1	0.5332	0-8	100.45	46.9727	0-659.9

Discussion

This research has significant implications for the state of seabird conservation considering multiple threats in the South Atlantic, and for the understandings of the pathways that plastic ingestion can impact on the animal's health. First, we found that nearly half of the seabirds stranding inshore the Brazilian coast are being impacted by anthropogenic activities at time of death (drowning due to fisheries, plastic ingestion, and oiling), with a note for the Magellanic penguin that mostly died from drowning due to fisheries. Second, we found that plastic ingestion is prevalent in some species and may be a symptom of starvation cause of death and as pathology, especially for tube-nosed seabirds (Order: Procellariiformes). Anthropogenic activities additionally stress threatened seabird populations in the South Atlantic and plastic may contribute to the starvation deaths of some species.

Human activity impacts on seabirds

Seabirds stranding in the Southeast Brazil are considerably impacted by anthropogenic threats until and at the time of death. The stranding of a carcass inshore depends on species abundance, mortality rate, carcass buoyancy, drift conditions (Brusius et al., 2020), and especially, finding and reporting. The monitoring effort here was homogeneous through time and space, with 99.14 km covered daily. Therefore, we assume that during time sampling all possible stranded birds were found and necropsied. Only a fraction of animals that dies in open ocean strands inshore and it is estimated that beach-cast seabirds represent 3% – 30% of the total mortality at sea (Piatt and Ford, 1996; Provencher et al., 2019). Therefore, the actual number of seabirds affected by anthropogenic threats presented here must be even higher considering the population level. Of all the seabird species presented here, the White-chinned Petrel is globally threatened (vulnerable), the Sooty Shearwater is near threatened and the other species have the status of least concern (BirdLife International IUCN Red List for birds, 2022). The Sooty Shearwater, the White-chinned Petrel, the Magellanic Penguin, and the Brown Booby have decreasing populations, whereas it is unknown the population status for Cory's Shearwater and the Manx Shearwater.

The Magellanic penguin was the most affected by fisheries. Most of them had bruises and net marks resembling interaction with fisheries (Vanstreels et al., 2016) and presented respiratory failure (edema in the lungs, pulmonary hemorrhage, generalized congestion, cardiac insufficiency, etc.) that conclude drowning due to fisheries (Ewbank et al., 2020) (Fig. 3C). Bycatch fisheries poses a threat to penguin conservation, and it has been largely reported in the

Atlantic and Pacific Oceans (Crawford et al., 2017). Most penguins found stranded in this study were juvenile ones. The animals exchange their infant plumage for the juvenile after 3 months of birth and then abandon their reproductive colonies in the south of Argentina, Chile, and the Falkland Islands, to start their pelagic life at sea, mostly migrating to southern Brazil (BirdLife International, 2022). Juveniles play an important role in maintaining populations and since it is decreasing (BirdLife International, 2022), the high ratio of death by drowning due to fisheries presented here raises concern.

There was only one direct cause of death from oiling, but other seven seabirds were affected as well. We do not know if they oiled before or after death adrift, and we only concluded the one oiling as the cause of death because all the body was covered with oil (Fig. 3A) and there was also evidence in histopathological analysis suggesting metabolization of environmental pollutants. The microscopical analysis showed pulmonary edema and hemorrhage, splenic hemosiderosis, and lymphoid reactivity, which were associated with the presence of oil on the body surface, suggesting intoxication. Oiling can impact seabirds in many ways, causing high levels of mortality. The oil affects the feathers decreasing their insulative properties and leaving the animal vulnerable to hyphothermia. If the seabird ingests the oil trying to preen it off, it impacts the animal's health through a series of oil-induced diseases, such as aspergillosis, cachexia, hemolytic anemia, ulceration of the stomach, and immunosuppressant effects (Crawford et al., 2000; Haney et al., 2014, Provencher et al., 2019).

Trauma is also a cause of death that may be related to anthropogenic activities. Costa et al. (2021) found that 30% of seabird live admissions in The Marine Animal Rehabilitation Centre in Ílhavo (Portugal) had their main cause of entry by trauma, mostly associated with fishing activities. Here we could not conclude which of them had a part with it because seabirds were found beach-cast and trauma may be from other sources, such as from diving behavior with a possible displacement of members as an example. The Brown booby was the species most affected by trauma as a cause of death, and they usually feed near the coast. In the Cananéia region of this study (southeast Brazil), the specie is commonly seen near fisheries spots and a potential way of getting trauma is getting intentionally hit by humans when the animal is foraging near the fisheries. Even though we could not directly access trauma causes of death from human activity, we highlight the need for environmental education to protect seabirds within fisheries activities and other possible sources of trauma.

Unraveling plastic ingestion in seabird beach-cast in Brazil

We found that plastic is prevalent in some species (the Cape petrel, the Sooty shearwater, and the Great shearwater). A high frequency of interactions for these species is also seen in other Brazilian reports (Colabuono et al., 2009; Barbieri, 2009, Tourinho and Fillmann, 2010, 2010, Tavares et al., 2017). All Procellariforms species presented here have pelagic lifestyles, thus, plastic ingested reflects their exposure to the nearshore and open ocean. They usually ingest hard plastic items (Colabuono et al., 2009; Roman et al., 2019b) as seen in Fig. 3B, yet, other kinds of items can be found, such as industrial pellets, flexible plastic, and foam synthetic (Vanstreels et al., 2021). The Magellanic penguin and the Brown booby, in its turn, are coastal species, with the last one occurring in the open ocean sometimes. The type of plastic here must resemble those mismanaged in coastal counties in the first place. The Brown booby is seen to ingest hard plastic, flexible plastic, and plastic threads (Vanstreels et al., 2021), whereas the Magellanic penguin mostly ingests flexible plastic as in plastic bags, and plastic threads as in nylon lines from fisheries activities (Brandão et al., 2011; Vanstreels et al., 2021).

Plastic pollution is addressed here as a potential contributory effect to starvation mortality in seabirds, especially in tube-nosed seabirds. Starvation was the second most common cause of death after drowning due to fisheries over all seabirds. Yet, as a pathology, it accounted for 227 individuals. It's a common condition seabirds face offshore, especially for migratory species, with a scarcity of food through migration and, occasionally, bad weather (Provencher et a., 2019). The number of seabirds starving represented 79.64% of the seabirds analyzed for starvation as a pathology, a similar rate found for Northern Fulmars and Shearwaters necropsied in Canada (Daoust et al. 2021). The White-chinned Petrel, the Great Shearwater, the Cory's Shearwater, and the Black-browed Albatross were well-represented in starvation as pathology and plastic ingestion (Fig. 6), being addressed here as potential species vulnerable to plastic pollution.

However, our model may be biased because of the Great shearwater as this species comes out significantly different from others on the number of plastics eaten (Fig. 6). It was the one that ate the greatest amount of plastic among all individuals and most of them also died/suffered from starvation. More data and further research are required to better disentangle whether there is a bias or not: more data points are needed from other causes of death expecting that these individuals would eat less or no plastic against the ones that died from starvation to provide empirical support for the relationship found here. Nevertheless, it is the start of evidence for indirect risks of plastic ingestion when it does not cause a visible cause of death, such as obstruction or perforation (Pierce et al., 2004; Roman et al, 2019a). Sublethal effects related to plastic ingestion are poorly understood and quite difficult to evaluate (Oro, 2014) and it is an emerging topic in science for species conservation (Puskic et al, 2020).

One question that is quite difficult to answer is whether seabirds starve because they have eaten plastic, or whether they eat plastic because they are starving. For this, there are some suggestions that plastic leads to a state of satiety in green turtles and negatively influences the absorption of mineral nutrients via the diet (Santos et al., 2020). Plastic ingestion is also seen to impact seabird nutrition, leading to a lack of essential elements in the diet derived from a state of malnutrition (Roman et al., 2020b). The presence of plastic in the stomach also decreases the absorbable surface of nutrients (Ryan, 1988) and may cause a nutritional imbalance in the individual. If it causes a direct obstruction, the whole absorption of nutrients is impacted, leading to starvation (Pierce et al., 2004).

We also found a negative relationship between the mass of plastic ingested and renal failure as a cause of death, though, there is no empirical support because renal insufficiency was the cause of death of only 4 Manx Shearwaters with one ingesting a single plastic item, of which mass couldn’t be measured, presenting the opposite bias for the Great Shearwater with a majority of zeros-inflated in the data. Parasitism was also negatively related to plastic in amount and mass. On the other hand, it is a common condition in seabirds, and when they can’t keep up with a good immune system, parasitism load increases. It is more related to starvation conditions as an immunosuppression parameter. A total of 206 seabirds presented parasitism of which 178 were suffering from starvation and 55 had ingested the least quantity of plastic. To disentangle a better relationship between parasitism and plastic ingested, a quantification of parasitism would be useful. Since parasitism is common within individuals, we would hypothesize that a great load of parasitism is related to the greatest load of plastic ingested since plastic can impact one’s health in several ways, including starvation, contributing to an immunosuppression state.

Potential plastic obstructions

Plastic ingestion can cause a direct death of an individual if the item causes gastrointestinal obstruction or perforation (Pierce et al., 2004; Roman et al, 2019a). Yet, this phenomenon is not well reported or represented in most studies, which leads us to the question of whether it is uncommon or unobserved. To better diagnose potential cases of foreign-body gastrointestinal obstruction, there are already some clinical findings and checklist methodologies (Roman et al., 2021a).

Here, we report four potential plastic obstructions that didn't account for the primary cause of death but were contributive (Fig.4). One Brown booby had a piece of soft plastic in its gut (Fig. 4A) with reddish and swollen mucosa, suggestive of gastritis. It was also suffering from starvation and bacterial infection, which is a sign of immunosuppression. The animal was euthanized due to its condition, yet it might have its pylorus obstructed by the size and location of the plastic, which would've contributed to its bad health condition. One penguin had 9 pieces of threadlike plastic stuck together (Fig. 4B) that potentially caused ulceration in stomach mucus in the fundic region. The poor body condition, scarce food in the digestive tract, absence of adipose tissue, high parasite load, and full gallbladder indicate that the animal was already in the process of chronic weakness. To cause such alteration in stomach mucus, the plastic ingested was probably stuck in the gut, contributing to the death of the animal. One penguin had a large piece of rope partially obstructing the esophagus (Fig. 4C) and another (Fig. 4D) ingested a set of nylon threads (Fig. 4D) that were associated with mucosal ulcerations and represented more than 50% of the stomach contents. Both had signs of starvation and died from drowning due to fisheries.

Fishing debris (ropes, nets, and tackle) and flexible plastics, as seen in the four potential obstructions here, have been previously identified to be responsible for the main risk of mortality when ingested in several species of seabirds (Roman et al. 2019a). The mismanagement of fishing waste (nets, fishing, etc.) is ultimately another problem that adds to the potential cause of death from fisheries activity, already highlighted here as the main threat to the Magellanic penguin. This illustrates how species face multiple and interactive threats, raising the complexity of public policies to tackle not only plastic pollution, but other anthropogenic activities in the marine environment. We recommend that policy actions could focus on reducing waste through regulations, bans, and replacement of items that can cause a high risk of mortality, such as plastic bags and packaging, ropes, and fishing nets, as well as oversee regulations for fisheries activities in Brazil.

Other causes of death

Drowning non-fisheries were most diagnosed with respiratory failure with no apparent cause. Most of these seabirds were already suffering from starvation. In the environment, they face several challenges, such as disease, reduced food availability, predation, and occasionally bad weather and severe storms, which could potentially drown an individual that is already debilitated. Adverse climatic conditions in the open ocean are highly harmful to migratory seabirds (Underwood and Stowe, 1984), and increased mortality has already been related to storm activity for the Atlantic yellow-nosed albatross, the Manx Shearwater and the Magellanic penguin (Tavares et al., 2020), bringing to light another impact from climate change.

Disease/infection mortality is not well explored regarding the effects of pathogens on seabird populations, most studies focus on detection and surveillance (Provencher et al., 2019). Seabirds are potentially exposed to a wide range of pathogens from bacteria, viruses, and fungi; and many diseases are often detected in healthy individuals, so they might suffer sublethal impacts or are carriers (Provencher et al., 2019). Nevertheless, the pathogenesis of infectious agents in seabirds presents a potential risk for conservation, mostly due to migratory behavior, so that a single individual can be a vector of local pathogens to new regions.

Renal failure was the primary cause of death for four Manx Shearwater. The main macro and microscopic findings were intense parasitism in the kidney, indicating renal failure, and starvation. For these species, parasitism is quite common especially when they are not in good health condition. Parasites are ubiquitous in seabirds, and little is known about how they impact seabird health at the population level (Provencher et al., 2019). The only neoplasm cause of death found is for one Cory's Shearwater and such an exceptional case is already well described and reported by Duarte-Benvenutto et al. (2020).

Conclusion

Seabirds are ubiquitous sentinels of the oceans, responding to many disturbs and representing the ocean's health. The conservancy of such animals is also the conservancy of the whole environment. The data presented here is important mostly to diagnose threatened species from human impact in Brazil. We state that anthropogenic activities additionally stress threatened seabird populations in the South Atlantic. The Magellanic penguin is a potential species for monitoring purposes and attendance of fisheries policies, including coastal management of solid waste from fisheries. There are numerous and interactive threats to seabirds, raising the complexity of conservation efforts. Plastic pollution may contribute to the starvation and deaths of some species. The White-chinned Petrel, the Great Shearwater, the Cory's Shearwater, and the Black-browed Albatross might be vulnerable species considering plastic ingestion and its impact on health. Further research is needed to better disentangle this relationship, nevertheless, our results add to the knowledge and understanding of sublethal effects and pathways of plastic pollution impact.

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5. Discussão geral

A presente dissertação teve como principal objetivo entender como a ingestão plástica impacta as espécies de aves marinhas que ocorrem no Brasil, desde sua ocorrência até impactos na saúde animal. Os Procellariiformes foram as aves mais afetadas, apresentando altas frequências de interação em quatro estados brasileiros e indicando um potencial impacto subletal da ingestão plástica ao contribuir com causas de morte relacionadas à síndrome de caquexia/inanição. Embora no capítulo 1 não se tenha avaliada a quantidade de plástico ingerido pelas aves, apenas a frequência de ocorrência, evidenciou-se no capítulo 2 a intensa ingestão plástica com a quantificação dos dados provenientes do IPeC, uma das Instituições Executoras do PMP-BS responsável por um dos 15 trechos monitorados no Sul e Sudeste brasileiro. A frequência de ocorrência das aves necropsiadas pelo IPeC foi similar à evidenciada em PMP-BS, sendo considerada uma boa representação (Tabela 1).

Tabela 1. Comparação entre a frequência de ocorrência de plástico ingerido entre os estudos do capítulo 1 (PMP-BS) e 2 (IPeC).

Espécie	Nome comum	FO	
		PMP-BS	IPeC
Ardenna gravis	Pardela-de-barrete	64%	60%
Ardenna grisea	Pardela-escura	38%	67%
Calonectris borealis	Cagarra-do-mediterrâneo	31%	37%
Daption capense	Pomba-do-cabo	50%	100%
Oceanites oceanicus	Alma-de-mestre	25%	50%
Procellaria aequinoctialis	Pardela-preta	43%	42%
Puffinus puffinus	Pardela-sombria	18%	24%
Spheniscus magellanicus	Pinguim-de-magalhães	15%	20%
Sula leucogaster	Atobá-pardo	8%	13%
Thalassarche melanophris	Albatroz-de-sobrancelha	23%	38%

Os Procellariiformes são bioindicadores úteis para monitorar a poluição plástica, sendo empregados mundialmente (PROVENCHER et al., 2014; ACAMPORA et al., 2016; O'HANLON et al., 2017; VAN FRANEKER et al., 2021). De forma a integrar as tendências mundiais de combate à poluição plástica, é imprescindível que haja mais pesquisas no Brasil para entender como a poluição plástica se distribui no Atlântico Sul e como as medidas existentes e a serem desenvolvidas estão sendo efetivas. Com os resultados apresentados aqui, algumas espécies possuem potencial como bioindicadoras e devem ser consideradas.

A Pardela-de-barrete (*Ardenna gravis*, the Great Shearwater) apresentou um significativo aumento dentro das interações plástica ao longo dos anos (2017-2020) e não se verificou divergência de reportes entre os estados PR, RJ, SP e SC. Além disso, foi a ave que mais se destacou na ingestão plástica, um único indivíduo ingeriu 95 itens plástico. Sua frequência de ocorrência foi similar regionalmente e em toda a área monitorada pelo PMP-BS (Tabela 1), assim, espera-se que a quantidade de plástico ingerido seja similar para as outras áreas. Desse modo, a espécie é uma potencial candidata para a vulnerabilidade à poluição plástica. Os dados apresentados no capítulo 2 indicam uma possível influência da ingestão plástica na síndrome de caquexia/inanição, entretanto a análise pode esta enviesada por esta espécie. As aves marinhas, por habitarem o oceano aberto, são de difícil acesso para estudo, dependendo unicamente do encalhe na costa. Um dos desafios é o tamanho amostral para prover robustez estatística, sendo esse cenário comum entre os estudos. Nesse cenário, o PMP-BS produz um vasto banco de dados que supre tal deficiência em alguma medida. Mais estudos como este seriam interessantes no âmbito do PMP-BS, principalmente para desvendar melhor a relação plástico-inanição.

A Cagarra-do-mediterrânio (*Calonectris borealis*, the Cory’s Shearwater) apresentou uma boa representação amostral ao longo dos anos, entretanto não apresentou aumento significativo entre os reportes de interação com plástico, bem como a Pardela-Preta (*Procellaria aequinoctialis*, the White-chinned Petrel). Sua representação também foi similar entre ambos os capítulos (Tabela 1). Tais indivíduos também são potenciais espécies vulneráveis à poluição plástica, em que a maioria dos indivíduos com inanição também ingeriram consideráveis quantidades de plástico. Destaca-se aqui que a Pardela-preta é uma espécie vulnerável globalmente, sendo de interesse da conservação diagnosticar a mortalidade de indivíduos conforme feito aqui. Análises temporais considerando a carga plástica ingerida (quantidade e massa) podem melhor elucidar se a ingestão plástica em tais indivíduos está aumentando ou não.

A pardela-sombria (*Puffinus puffinus*, the Manx Shearwater), apresentou aumento significativo na ingestão de plástico e foi a espécie mais abundante dentro dos Procellariiformes, em ambos os capítulos com frequências similares. (Tabela 1). Os esforços de amostragem para tal espécie devem ser maiores, uma vez que mais indivíduos precisam ser necropsiados para avaliar uma frequência de poluição baixa. O Albatroz-de-sobrancelha (*Thalassarche melanophris*, the Black-browed Albatross) representa outra espécie vulnerável à poluição plástica, podendo o plástico influenciar nas causas de morte por inanição. Albatrozes já são identificados como espécies sensíveis à poluição plástica, sendo denotado como um risco para a conservação (ROMAN et al., 2021).

Definir uma espécie bioindicadora não é uma tarefa fácil. Iniciou-se aqui uma diagnose de espécies relacionadas à poluição plástica no Brasil. Espécies específicas podem ser melhor estabelecidas ao se entender seus atributos ecológicos relacionados a poluição plástica, como nível taxonômico, comportamento alimentar, dieta e exposição plástica (ROMAN et al., 2019b). A partir dos resultados apresentados aqui, duas espécies foram selecionadas, as quais possuem comportamento alimentares diferentes: a Pardela-de-barrete (*Ardenna gravis*, the Great Shearwater) e a Pardela-Preta (*Procellaria aequinoctialis*, the White-chinned Petrel). A primeira persegue a presa em mergulho, explorando profundidades maiores que a superfície, enquanto a segunda é exploradora de superfície (TAVARES et al., 2017). Monitorar o plástico a partir de tais espécies, em conjunto, possibilitaria o acesso tridimensional da poluição plástica em oceano aberto. Análises conjuntas e comparativas contribuem na avaliação ampla da poluição plástica marinha. Além disso, a Pardela-Preta é uma espécie vulnerável, demonstrando a urgência em ações conservacionistas e produção de dados para acompanhar sua situação. Novos estudos devem ser realizados, considerando os atributos ecológicos, distribuição geográfica de encalhes no Brasil, carga e tipo de resíduo plástico ingerido e impactos na saúde animal (causa de morte e processos patológicos).

6. Conclusão

O Projeto de Monitoramento de Praias da Bacia de Santos (PMP-BS) fornece dados constantes do estado de saúde das aves marinhas encalhadas, de parâmetros ecológicos e, adicionalmente, da ingestão de plástico. É um programa pioneiro de monitoramento dividido em 15 trechos que abrangem 4 estados do Sul e Sudeste do Brasil. O PMP-BS é uma oportunidade valiosa para aprofundar estudos relacionados à poluição plástica, conforme foi possível diagnosticar aqui, para as espécies de aves marinhas, um aumento de interações aos longos dos anos, impactos antrópicos e potenciais impactos indiretos da poluição plástica na saúde animal. Mais dados podem ser analisados para desvendar melhor a ingestão de plástico e seus efeitos secundários.

Há uma quantidade considerável e crescente de plástico se acumulando no oceano e as aves marinhas são organismos úteis para avaliar a poluição em oceano aberto. O Brasil iniciou recentemente sua discussão sobre "lixo marinho" e o país é um grande poluidor devido à sua grande área costeira. Desse modo, definir uma espécie bioindicadora no Brasil para monitorar a poluição plástica seria um passo à frente no compromisso global de enfrentamento à poluição plástica. Espécies ameaçadas estão expostas à crescente poluição plástica e deve haver maiores esforços de conservação.

Os resultados apresentados nesta pesquisa, considerando o cenário atual brasileiro, podem refletir na inconsistência e na ineficácia das políticas públicas brasileiras nacionais, tanto na poluição plástica quanto na regulação e monitoramento da atividade pesqueira, conforme é evidenciado para o Pinguim de Magalhães. Caso nada seja feito no âmbito de um monitoramento contínuo e bem planejado, as ações existentes podem estar inconsistentes, impactando diretamente em questões ambientais que requerem ações urgentes. No Brasil, o PMP-BS apresenta-se como uma ferramenta valiosa que provê diversos dados que podem ser incorporados como indicadores.

Por fim, programas de monitoramento baseados em bioindicadores têm sido considerados nas últimas décadas atuando em conjunto com a conservação das espécies. Com eles, é possível elaborar ações mitigadoras adequadas e realistas com base na resposta dos organismos impactados pela atividade humana. De fato, o primeiro passo para definir um bioindicador viável é entender quais espécies ocorrem na área, como elas se relacionam à poluição, quais são os principais impactos para a mortalidade populacional e quais são as mais vulneráveis, o que foi iniciado aqui. Além disso, o trabalho apresentado pode ser aplicado em programas de monitoramento de aves marinhas existentes no Brasil, incluindo todo o Programa de Monitoramento de Praias, para rastrear causas de morte e poluição plástica ao longo do tempo.

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