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Barau's petrel, *Pterodroma baraui*, as a bioindicator of plastic pollution in the South-West Indian Ocean: A multifaceted approach

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ABSTRACT

Marine plastic pollution is well described by bioindicator species in temperate and polar regions but remains understudied in tropical oceans. We addressed this gap by evaluating the seabird Barau's petrel as bioindicator of plastic pollution in the South-West Indian Ocean. We conducted a multifaceted approach including necropsies of birds to quantify plastic ingestion; GPS tracking of breeding adults to identify their foraging areas; manta trawling of plastic debris to measure plastic pollution at sea and modelling of plastic dispersal. We developed a spatial risk index of seabird exposure to plastic ingestion. Seventy-one percent of the analysed birds had ingested plastic. GPS tracking coupled with manta trawling and dispersal modelling show that adults consistently foraged at places with high level of plastic concentration. The highest ingestion risk occurred in the northwest of Reunion Island and at latitude 30°S. Our findings confirm that Barau's petrel is a reliable bioindicator of plastic pollution in the region.

1. Introduction

Plastic debris entering the global ocean is estimated to be between 0.13 and 3.8 million metric tons yearly (Zhang et al., 2023). This amount arrives through various pathways, including riverine inputs (Lebreton et al., 2017; Meijer et al., 2021; Weiss et al., 2021), atmospheric transport (Bianco and Passananti, 2020), beach litter (Okuku et al., 2020), aquaculture (Tian et al., 2022), maritime traffic (Ryan et al., 2019), and fishing activities (Lebreton et al., 2022). Once in the ocean, plastic debris are exposed to UV radiation, wind, waves, sea currents, and salt, all of which contribute to its degradation and fragmentation into smaller particles.

Marine species interact with plastic debris of all sizes through ingestion or entanglement (Avery-Gomm et al., 2012; Moore et al., 2001). Some species can be used as indicators of the concentration and composition of plastic debris in their marine habitats (Franeker and Meijboom, 2006; GESAMP et al., 2019; Savoca et al., 2022). Depending on their feeding areas and strategies, marine animals can indicate the presence of a wide range of plastic debris (Acampora et al., 2016; Van Franeker and Bell, 1988). For example, coastal filter-feeding or deposit-feeding species such as bivalves or echinoderms are used to assess plastic pollution in coastal environments (Frère, 2017; Pierrat et al., 2022). Conversely, oceanic species like sea turtles (loggerhead, *Caretta caretta*, Pham et al., 2017; Thibault et al., 2023) and seabirds (northern fulmar, *Fulmarus glacialis,* Avery-Gomm et al., 2102; Van Franeker and Law, 2015; Van Franeker and Meijboom, 2006) are used to assess marine plastic pollution in their oceanic foraging areas. The evaluation of marine species as a bioindicator of plastic pollution requires meeting the criteria recommended by GESAMP, (2019) and Savoca et al. (2022): (i) the species must be regionally representative of

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a given area, (ii) the analysis performed must be ethically sound, (iii) the species must be abundant in the chosen environment, (iv) it must already be used as a bioindicator for another type of pollution, (v) the species must not have a selective diet for any colour or type of plastic debris; (vi) and finally, the species should be ecologically comparable to other bioindicator species already identified in other parts of the world.

Among seabirds, procellariids (petrels and shearwaters) are the most at risk species of plastic ingestion (Berr et al., 2020; Cartraud et al., 2019; Clark et al., 2023; Ryan, 2008; Ryan, 2015; Van Franeker and Bell, 1988; Van Franeker and Meijboom, 2006). Petrels and shearwaters forage over large oceanic areas, many of them feed opportunistically at the surface, and some are scavengers. These characteristic increase their risk of ingesting plastic incidentally (Clark et al., 2023; Van Franeker and Law, 2015). Indeed, like many other marine predators, seabirds mistake plastic debris for prey. Several studies have combined GPS tracking of seabirds to identify their foraging areas and assess the relative risk of plastic ingestion (Clark et al., 2023; De Pascalis et al., 2022; Nishizawa et al., 2021). The research of Clark et al. (2023) adopts a more global perspective by including all subtropical convergence zones and analyzing 77 species of petrels. They compared the distribution and abundance of the monitored birds with plastic concentrations, calculated using a model of plastic debris dispersion in the global ocean. They highlighted the Mediterranean and Black Seas, the North East Pacific, the North West Pacific, the South Atlantic, and the Western Indian Ocean (WIO) as areas with a high encounter risk.

In the Indian Ocean, the concentration, composition, distribution, and impacts of plastic pollution are poorly documented because this ocean is under-sampled compared to the others (Connan et al., 2021; Honorato-Zimmer et al., 2022). Although the Indian Ocean is suspected of having the second-largest floating plastic concentration after the North Pacific Ocean (Eriksen et al., 2014), there are insufficient *in situ* measurements to support this assumption. Global modelling studies have delineated different areas of accumulation of floating plastic debris within the southern Indian Ocean subtropical gyre. These areas are predicted to be either in the western Indian Ocean (Maximenko et al., 2012; Van der Mheen, 2020; Van Sebille et al., 2015), or in the eastern Indian Ocean (Lebreton et al., 2012; Maes et al., 2018; Van der Mheen, 2020). As these predicted plastic patches are located at the foraging grounds of numerous seabirds, including endemic petrels, they are recognized as high-risk zones for plastic exposure during the breeding season in the western area and during the non-breeding season in the eastern sector (Clark et al., 2023). Therefore, it is important to conduct an *in-situ* evaluation of the plastic pollution at the surface of the sea and to evaluate plastic ingestion by petrels in the region.

In this study, we assessed the Barau's petrel (*Pterodroma baraui*) as a bioindicator of plastic pollution in the South-West Indian Ocean (SWIO). Barau's petrel breed in Reunion Island, were the study was conducted. Our study consisted of a multifaceted approach: (i) we did necropsies of dead birds to assess the concentration and composition (shape, weight, size class, colour, polymer) of plastic ingested by these species; (ii) we determined the foraging areas with GPS tracking of breeding adults; (iii) we measured the *in situ* concentration and composition (shape, weight, size class, colour, polymer) of plastic debris at the sea surface using a series of manta trawls conducted at the regional scale, including in the main seabird foraging area identified with GPS tracking; (iv) we modelled plastic dispersal and accumulation using a regional dynamic oceanographic model incorporating inputs from all rivers of the Indian Ocean during the seabird breeding season. We calculated a spatially explicit risk index of plastic exposure, combining seabird foraging concentration and predicted plastic accumulation at the same scale.

2. Material and methods

2.1. Seabird data

2.1.1. Seabird collection

The Barau's petrel is an endemic seabird of Reunion Island, a volcanic island of the South-West Indian Ocean (21.5°S, 55.3°E), with breeding colonies located in the central mountainous part of the island, between 2300 and 3000 m. During their breeding season (September to April) they forage in the SWIO (Fig. 1, Pinet et al., 2012). They migrate eastward to the central and eastern Indian Ocean, from May to August (their non-breeding season, Pinet et al., 2011; Legrand et al., 2016). Their breeding population is estimated to be 33,000 pairs (Chevillon et al., 2022).

Fledgling Barau's petrels are disoriented by artificial lights in urban areas, resulting in a high number of grounded birds (Chevillon et al., 2022; Le Corre et al., 2002). These massive fallouts happen synchronously every year in April and May (Chevillon et al., 2022). Since 1996, the Société d'Etudes Ornithologiques de La Réunion (SEOR) organizes every year an island-wide rescue campaign to save as many grounded birds as possible. After being rescued, these birds are checked and most of them (>80%) are released immediately or the following day. Some birds are kept in the rescue center for a few days for rehabilitation. Some of these birds are released after 1 day (without supplemental feeding) and others are kept for a longer period with daily feeding. The food used is small smelts bought frozen in local stores. The species is *Atherina boyeri*, caught with a seine net in Lake Hirfanli, Turkey.

Despite these rehabilitation efforts, between 11% and 19% of the rescued birds succumb to fatal injuries, either immediately or after several days at the rescue center (Chevillon et al., 2022). For each bird that died, SEOR recorded the number of days it spent in the rescue center from the time of grounding until its death and if the bird was fed or not. Dead birds were stored at −20 °C for further analysis. Once in the laboratory, necropsies were performed on the birds as part of various research projects, including those focused on marine plastic pollution.

2.1.2. Necropsies: plastic debris ingestion

Before necropsy, the following information was recorded for each bird: (i) age class (juvenile, adult); (ii) body mass (g); and (iii) date of discovery. During necropsy, a ventral incision was made, and the skin was removed to access the general cavity. The digestive system, including the oesophagus, proventriculus, gizzard and intestines, was removed and weighed after removing the pectoral muscles, and sternum. Plastic debris found in the gizzard, and proventriculus were collected using dissecting microscope and ultra-fine forceps (300 μm diameter). We analysed the content of the intestine of a subsample of birds (years 2017–2023) to check for plastic debris in the lower part of the digestive track. Plastic debris was then stored in Eppendorf tubes or Petri dishes. The frequency of occurrence (FO%) of plastic debris ingested by seabirds was calculated annually and globally from 2004 to 2021 as the ratio of the number of seabirds in which we found plastic debris in their guts to the total number of seabirds analysed multiplied by 100.

2.2. Manta trawling: plastic sampling and processing

In October 2021 and October 2022, a total of 94 samples were collected using a manta trawl during three oceanographic campaigns in the SWIO and around Reunion Island (Fig. 1). During each campaign, plastic debris was collected using a manta net (mouth: rectangular, width: 0.88 m, height: 0.165 m, mesh size: 500 μm). A flowmeter (designed by ©General Oceanic, Inc., model 438,110) was fixed at the net entrance to estimate the length and volume of the trawled area (Hydro-bios: https://www.hydrobios.de). At each site, three consecutive 30-min transects were conducted at 2 knots. The manta net was deployed to one side of the boat, positioned at more than 2 m from the

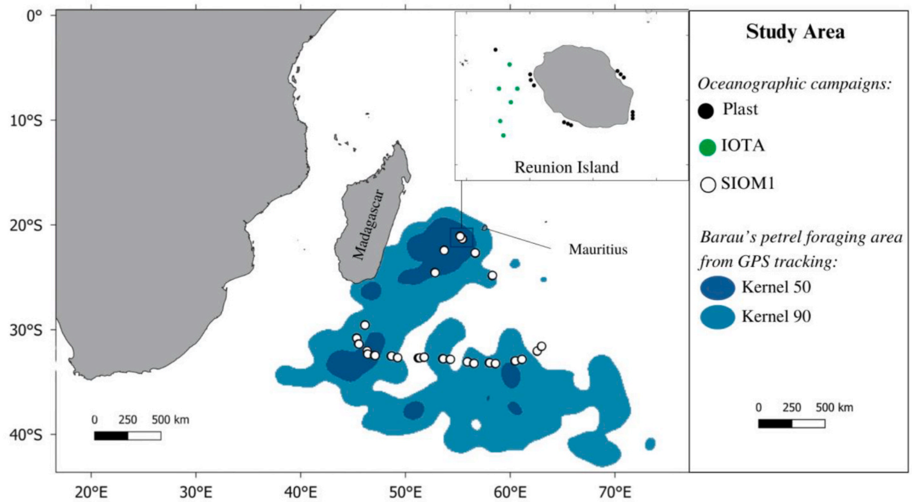

Fig. 1. Study area. Plastic debris sampling with manta trawl during three oceanographic campaigns ($N_{total} = 94$): Plast (October 2021, $N_{manta\ sampling} = 12$), IOTA 2 (Initiation à l'Océanographie TropicAle 2, October 2022, $N_{manta\ sampling} = 6$), and SIOM1 (South Indian Ocean Mission 1, January 2022, $N_{manta\ sampling} = 76$). Kernel density contour of foraging area during the breeding season for the Barau's petrel thanks to GPS tracking data from this study (resolution 2°).

side of the boat and more than 30 m behind the boat to minimize disturbance from the boat's wake. The manta net was externally rinsed with seawater between each transect to collect any plastic debris in the disposable cod-end. This cod-end was then removed, stored in a freezer, and replaced with a new one. For each transect we recorded: (i) the name of the oceanographic campaign (Fig. 1); (ii) the coordinates of the sampling; (iii) the location (onshore or offshore); (iv) the season; (v) the air pressure; (vi) the sea state (Beaufort); and (vii) the wind speed (m.s^{-1}, see Supplement: Appendix A.1). When wave heights exceeded 2 m, sampling was suspended to avoid the potential underestimation of plastic debris concentrations. This precaution was taken to mitigate the effects of wave mixing in the surface layer, which could redistribute plastic debris in the water column (GESAMP et al., 2019). Each cod-end was externally rinsed to remove plastic debris in the laboratory and passed into a sieve with the same mesh size as the manta net (500 µm). All plastic debris was placed on a Petri dish and counted under a microscope using ultra-thin forceps (300 µm diameter).

2.3. Concentration of plastic debris: correction by wind-driven mixing

To consider the impact of wind-driven mixing in the calculation of plastic debris concentration at the sea surface, we used the dynamic equation of Kukulka et al. (2012):

$$C_i = \frac{c_s}{1 - e^{-dW_b\left(1.5\sqrt{\frac{\rho_a}{\rho_w}C_d U^2}\; k\frac{0.96}{g}\sigma^{\frac{3}{2}}\, C_d\, U^2\right)^{-1}}}$$

where, for each i sample, *Ci* is the depth-integrated concentration for the upper 5 m of the water column (item.km^{-2}), *Cs* is the raw concentration of plastic debris measured in the laboratory according to the shape and size class (item.km^{-2}), *d* is the depth of the manta net (0.165 m), *Wb* is the rising velocity according to the plastic shape and size class (m.s^{-1}, with data used by Lebreton et al., 2018), ρ_a is the air density (1.225 kg m^{-3}), ρ_w is the seawater density (1024 kg m^{-3}), C_d is the drag coefficient (0.0012), *U* is the wind speed during the sampling (m.s^{-1}), *k* is the Karman constant (0.4), *g* is the gravitational constant (9.81 m s^{-2}) and σ is the wave age equal to 35.

2.4. Plastic debris composition

2.4.1. Shape, colour, mass, size class determination

The following procedure was used for each plastic debris, whether obtained from bird necropsies or collected from the sea surface. First, all plastic debris from each sample was placed in a Petri dish and photographed using a Nikon D7500 camera with an AF-S MICRO NIKKOR 105 mm lens. A unique number was then assigned to each plastic item. For each item, we documented its characteristics, including shape (rigid plastic, foam, pellet, fibre), colour (black, blue, green, red, transparent, yellow, white), mass (precision balance 10^{-5} g), and size classes (in Lebreton et al., 2018: small microplastics [0.05–0.15[cm, large microplastics [0.15–0.5[cm, small mesoplastics [0.5–1.5[cm, large mesoplastics [1.5–5[cm, small macroplastics [5–10[cm and large macroplastics [10–50[cm). Size was determined using ImageJ software by measuring the maximum length of each object.

2.4.2. Polymer identification using ATR-FTIR

The polymer type of the debris was determined by Fourier Transform InfraRed (FTIR) spectroscopy using a Thermo Nicolet Nexus 6700 instrument equipped with a diamond crystal Attenuated Total Reflection (ATR) mode and a deuterated triglycine sulphate detector. The analysis was carried out at Paul Sabatier University, Toulouse, France.

During the analysis, white background and debris spectra were obtained using 16 scans covering the wavelength range 400–4000 cm^{-1} with a resolution of 4 cm^{-1}. A white background spectrum was taken every 2 h to ensure accuracy. The pieces of debris were analysed as they were, without being cleaned with alcohol or wiped down in any way. Each piece of plastic debris was pressed between the diamond crystal and the base. The diamond crystal was cleaned between two measurements to avoid any bias between spectra. The resulting spectra were corrected using the ATR thermo-correction method to obtain transmission-like spectra (ter Halle et al., 2017). The final infrared spectra were observed using the Omnic version 9.9.0.473 software. Only spectra with more than 80% similarity to one of the database spectra were validated.

2.5. Manly selectivity test

The Manly selectivity test (Manly, 1974; Chesson, 1978) was calculated as the ratio between plastic debris ingested and collected by manta trawling for different characteristics: shape, colour, and size class. The selectivity index ranges from 0 to 1, with 0 indicating a completely opportunistic diet and 1 indicating a completely selective diet.

$$\alpha i = \frac{ri/pi}{\sum_{j=1}^{m}(rj/pj)}, i = 1, 2, \ldots m$$

Where αi = selectivity index for plastic debris (shape, colour or size class) *i*, *i* plastic debris (shape, colour or size class), *ri* proportion of plastic debris *i* (shape, colour or size class) ingested by a bird, *pi* proportion of plastic debris (shape, colour or size class) *i* available at the sea-surface. *m* is the total number of shapes, colours or size classes. All analyses were performed in R (v3.2.3, R Core Team, 2022), and using the "selectapref" package for Manly selectivity index (Richardson, 2020).

2.6. Overlap between seabird foraging areas and modelled plastic concentration

2.6.1. Foraging area of Barau's petrels during the breeding season: GPS telemetry

From December 2022 to February 2023, we monitored the at-sea distribution of fifteen Barau's petrels during their breeding period (incubation and chick-rearing stages). This was achieved by deploying solar-powered GPS loggers (nanoFix-GO + RF, Pathtrack Ltd, United Kingdom) on birds at their colonies. Birds were caught at their nests, weighed, banded, and fitted with a GPS device attached to the base of the four central tail feathers using Tesa® tape. The total mass of the loggers and tape combined was 6.8 g (5.8 g and 1 g, respectively), representing approximately 1.5% of the body mass of the equipped birds (443 ± 37 g, N = 15). The location data (one location every 30 min) were transmitted to a UHF solar-powered base station (Pathtrack Ltd, UK) located near the burrows of the equipped birds. Data transmission occurred when the petrels returned to their burrows to feed their chicks. For all locations (N = 13,469), we first classified behaviours from the tracking data into resting, flying, and two types of foraging (extensive and intensive). This classification was done using the expectation maximization binary clustering (EMbC) algorithm implemented in the 'EMbC' R package (Garriga et al., 2016, 2019). Extensive foraging behaviour was characterized by high speeds and high turns between points, while intensive foraging behaviour was defined as low speeds and high turns between points.

For this study, we filtered and retained only locations of extensive and intensive foraging behaviours (N = 3719 locations). Using QGIS version 3.30.2 software and the tracking data, we generated a raster layer representing the density of Barau's petrel locations (foraging only), with a spatial resolution of 0.2° covering the entire foraging area (10°S to 50°S and 30°E to 80°E).

2.6.2. Modelling: plastic debris dispersion from river inputs

We used the SYMPHONIE hydrodynamic model (Marsaleix et al., 2008) and its Lagrangian drift module (Guizien et al., 2012; Weiss et al., under review) to estimate floating plastic debris concentration at the surface of the SWIO. The ocean currents used to calculate the particle trajectories were taken from the 3D SYM INDOC simulation, developed to study plastic transfers in the basin (Weiss et al., submitted). The grid resolution is about 3 km in the study region from −10°S to −50°S and 30°E to 80°E. This high-resolution configuration allows the representation of eddies and sub-mesoscale dynamics that affect plastic debris trajectories in such an energetic region. We simulated the ocean circulation for the year 2017, which was characterized by no significant ENSO pattern, a relatively weak positive IOD anomaly, and a single notable cyclone in the WIO, hitting northern Madagascar. We looped this year's circulation over ten years to allow time for particles emitted along the coast to reach long-term accumulation zones, such as the subtropical gyre (Chenillat et al., 2021). Our scenario considers daily plastic debris sources located at 336 river mouths of the Indian Ocean and calculated from daily freshwater discharges and population densities in the corresponding river basins (based on the empirical equation of Weiss et al., 2021). This results in an annual discharge of 2.2 million Lagrangian particles, representing 22 billion pieces of plastic debris, subject to the seasonality of inputs and basin dynamics. The virtual particles are characterized by vertically rising velocities (between 0.1 and 100 mm s^{-1}) to simulate different floating 3D behaviours in the sea surface layer.

After ten years of dispersal, we mapped plastic debris concentrations in the surface layer during the wet season (December to February) to compare results with Barau's petrel tracking data and manta trawls from the SIOM1 wet season campaign. Concentrations were plotted in items.km^{-2} on a 0.2° grid covering the foraging area (using the QGIS raster toolbox). Correlations between modelled concentrations and observed concentrations from the SIOM1 expedition were tested using the Spearman test.

Finally, we calculated the exposure risk to plastic debris for Barau's Petrel by multiplying the densities of foraging Barau's petrels by the modelled plastic concentrations (items.km^{-2}, Wilcox et al., 2015; Clark et al., 2023).

2.7. Data processing

The normality and homoscedasticity of our data were tested using the Shapiro and Levene tests, respectively. As explained earlier, some birds died immediately at their arrival at the rescue center while others stood in the rescue center for various periods of times, before dying as a consequence of fatal injuries. Some of these birds were fed while others were not. Birds kept in captivity and fed manually may passively ingest plastic debris from the food used to rehabilitate them, which may bias the results. This may happen for instance if the fish used to feed them have some plastic debris in their own guts. We tested this possible bias by testing the difference in plastic abundance between bird fed and not fed. For those that were fed, we also tested if the plastic debris abundance was related to the duration of the rehabilitation period. We compared differences in abundance by i) shape, ii) colour, iii) size class, and iv) polymer type for plastic data from necropsies and manta trawls (offshore and onshore). For each comparison, non-parametric tests were performed with Kruskall-Wallis, and then the Wilcoxon test was adjusted with Bonferroni correction to identify significant differences. We ran linear models (LMs) to explore the relationships between the number or mass of plastic debris found in birds or at the sea surface, age class, body mass, year of death for seabird data, and latitude, longitude for sea-surface data. For each LM, we inspected visually the normality and homoscedasticity of residuals and selected the best models using Akaike's information criteria adjusted for a small sample size (AICc).

3. Results

3.1. Plastic debris ingested by seabirds

A total of 146 dead Barau's petrel collected between 2004 and 2021 (34 adults and 112 fledglings) were analysed. Among them, 109 birds (74%) arrived already dead, while the others were fed on the second day (N = 37) for an average of 5.38 ± 0.63 days (minimum of 2 days - maximum of 16 days) before dying. There was no difference in the abundance of plastic debris ingested by individuals fed and not fed (Kruskal-Wallis chi-squared = 0.019073, df = 1, p-value = 0.8902, N = 146; supplement: Appendix A.2; A.3). 71% of the Barau's petrels have ingested plastic debris (adult = 65%, juvenile = 72%). Since 2013, the average annual frequency of occurrence (FO% ± se) of plastic ingestion was 70.4 ± 7.29%. There was no difference in the FO% by individuals between years (LM, p-value >0.05, Fig. 2).

A total of 465 plastic debris items were found in Barau's petrels, corresponding to a total mass of 685,531 mg. The mean number ±se of plastic debris items was 3.18 ± 0.44 items.ind^{-1} (max = 37). The mean mass was 4.69 ± 1.41 mg (max = 172.6 mg). The mean maximum length of plastic debris was 2.24 ± 0.39 cm (min = 0.05, max = 30 cm).

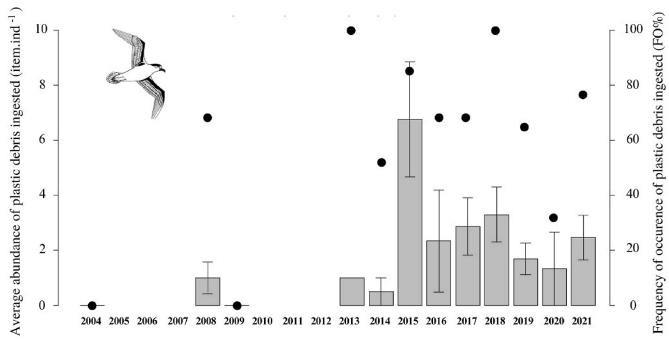

Fig. 2. Abundance (mean ± se, grey bar graph) and frequency of occurrence (FO%, black dots) of plastic debris ingested (item.ind^{-1}) by Barau's petrels per year between 2004 and 2021.

No plastic was found in intestines of the 42 individuals tested from 2017 to 2021. The linear model indicated that none of the selected control factors explained the number or weight of plastic debris ingested by seabirds (LM, p-value >0.05; supplement: Appendix A.3; A.4; A.5).

3.1.1. *Plastic concentration at the sea surface*

Among the 94 manta net samples, 99% contained plastic debris. A total of 1689 plastic debris were collected and analysed in the laboratory, for a total mass of 7.55 g. The mean concentration of plastic debris ±se (500 μm- 5 cm) was 79,113 ± 15,303 items.km^{-2} (max = 712,761 items.km^{-2}) for the offshore campaign (SIOM1). The concentration was much higher along the latitude 30–33°S (45,161 ± 17,770 items.km^{-2}, with a maximum of 712,761 items.km^{-2} at the location 33°S-56°E). Around Reunion Island, the concentration of plastic debris was 182,289 ± 147,197 items.km^{-2}. This concentration was significantly higher in IOTA 2 sampling (525,478 ± 430,794 items.km^{-2}; max = 2,676,771 items.km^{-2}) than in Plast sampling (10,694 ± 4419 items.km^{-2}; max = 42,995 items.km^{-2}). Overall, there was a longitudinal gradient of plastic debris concentrations, with highest concentrations to the east of the study area (LM, AIC = 2312, F value = 5.8, Pr (>F) = 0.017; supplement: Appendix A.1; A.4).

3.2. *Physico-chemical characteristics of plastic debris*

3.2.1. *Shape*

Among plastic ingested by seabirds or floating at the sea surface, hard plastic debris were the most abundant, followed by fibres. Foams were less commonly found at sea and were absent in seabirds. Pellets were neither ingested by seabirds nor present in samples from the Reunion Island campaigns (Fig. 3, Kruskal-Wallis: $H_{BP} = 2.06$, $df_{BP} = 3$, $P_{BP} = 0.00321$, $n_{BP} = 465$; $H_{SIOM1} = 190$, $df_{SIOM1} = 3$, $P_{SIOM1} = 0.0001$, $n_{SIOM1} = 1076$; $H_{RUN} = 47.9$, $df_{RUN} = 3$, $P_{RUN} = 0.0001$, $n_{RUN} = 613$). Hard plastic debris's mean number (±se) was 1.97 ± 0.35 items.ind^{-1} (56%, N = 465 plastic categorized). The concentration of hard plastic debris was 40,483 ± 29,300 items.km^{-2} at the sea surface close to Reunion Island (86%, N = 613) and 19,502 ± 3613 items.km^{-2} for SIOM1 (79%, N = 1076).

3.2.2. *Colours*

Plastic debris found at the sea surface was predominantly white (43% for Reunion Island, N = 613, and 53% for SIOM1, N = 1076), or transparent (38% for Reunion Island, 16% for SIOM1) and less often blue (8% for Reunion Island, 16% for SIOM1). For Barau's petrel, the dominant colours were transparent at 29% (N = 175), black at 27% and blue at 26%. Red, yellow, and green were less ingested and rarely found at sea (Fig. 4, Kruskal-Wallis: $H_{BP} = 138$, $df_{BP} = 6$, $P_{BP} = 0.0001$, $n_{BP} = 175$; $H_{SIOM1} = 193$, $df_{SIOM1} = 6$, $P_{SIOM1} = 0.0001$, $n_{SIOM1} = 1076$; $H_{RUN} = 28.1$, $df_{RUN} = 6$, $P_{RUN} = 0.0001$, $n_{RUN} = 613$).

3.2.3. *Size class*

Among the six size classes, large microplastics were dominant in seabirds and manta trawl samples (Table 1, Kruskal-Wallis: $H_{BP} = 69.7$, $df_{BP} = 5$, $P_{BP} = 0.0001$, $n_{BP} = 154$; $H_{SIOM1} = 183$, $df_{SIOM1} = 5$, $P_{SIOM1} = 0.0001$, $n_{SIOM1} = 1076$; $H_{RUN} = 50$, $df_{RUN} = 5$, $P_{RUN} = 0.0001$, $n_{RUN} = 613$). This size class accounted for 38% of the plastic debris ingested by Barau's petrel (N = 154), 63% in samples from Reunion Island campaigns (N = 613), and 45% in samples from SIOM1 (N = 1076). Smaller microplastics were found during all campaigns but were less ingested by seabird. Small mesoplastics, ranging from 0.5 to 1.5 cm, constituted the second size class ingested by seabirds. Larger plastic items (>5 cm) were less commonly collected at the sea surface using a manta trawl and were

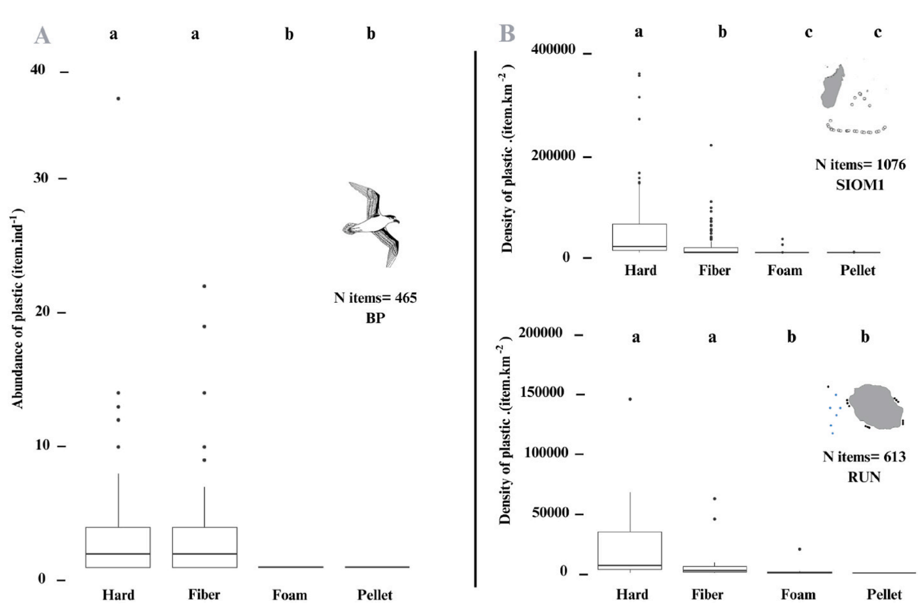

Fig. 3. Boxplots of the abundance concentration of the four types of plastic debris (A) ingested by Barau's petrels (BP) and (B) floating at the sea surface for SIOM1 campaign, Plast and IOTA2 campaigns (RUN) around Reunion Island. Letters indicate differences with p-value <0.05 with the Wilcoxon correction and Bonferroni adjusted.

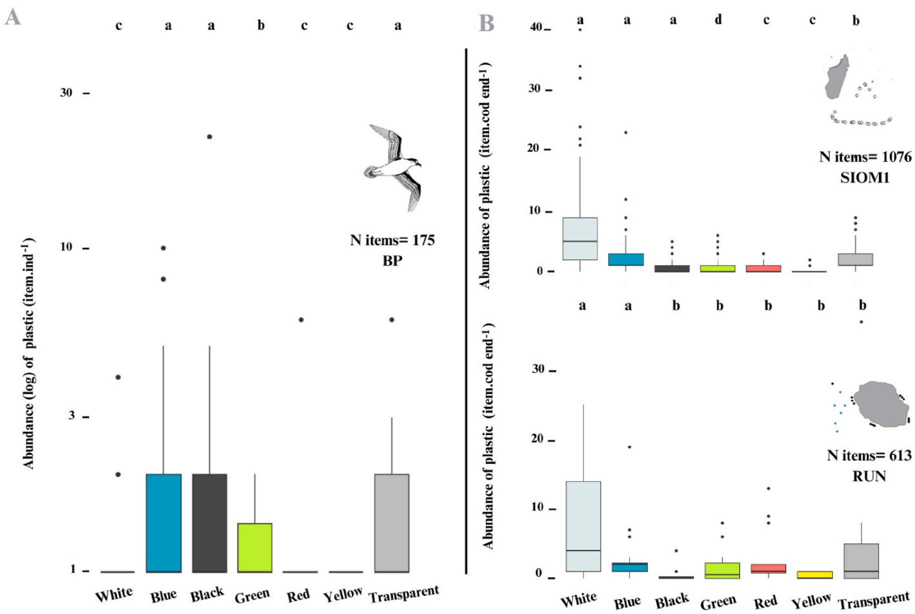

Fig. 4. Boxplots of the abundance in log10 of the seven colours of plastic debris (A) ingested by Barau's petrels (PB) and (B) floating at the sea surface for SIOM1 campaign, Plast and IOTA2 campaigns (RUN) around Reunion Island. Letters indicate differences with p-value <0.05 with the Wilcoxon correction and Bonferroni adjusted.

Table 1
Abundance concentration (mean ± se) of plastic debris ingested by Barau's petrel (BP) and floating at the sea surface from the Reunion Island (RUN) and SIOM1 (SIO) campaigns by size class (cm) defined by The Ocean Cleanup. Letters indicate differences with p-value <0.05 with the Wilcoxon correction and Bonferroni adjusted.

Name size	Size Class	BP (N = 154)				RUN (N = 613)				SIO (N = 1076)			
	(cm)	*item.ind-1*			*letter*	*item.km-2*			*letter*	*item.km-2*			*letter*
Small microP	**0.05–0.15**	0.146	±	0.075	*b*	57.253	±	45.518	*b*	21.141	±	5.049	*a*
Large microP	**0.15–0.5**	0.563	±	0.098	*a*	116.315	±	99.677	*a*	35.857	±	7.833	*a*
Small mesoP	**0.5–1.5**	0.534	±	0.143	*a*	7.977	±	2.825	*c*	18.235	±	4.823	*a*
Large mesoP	**1.5–5**	0.233	±	0.066	*b*	744	±	331	*c*	3.879	±	891	*b*
Small macroP	**5_10**	0.000	±	0.000	*c*	0	±	0	*d*	503	±	254	*c*
Large macroP	**10_50**	0.020	±	0.014	*c*	0	±	0	*d*	165	±	136	*c*

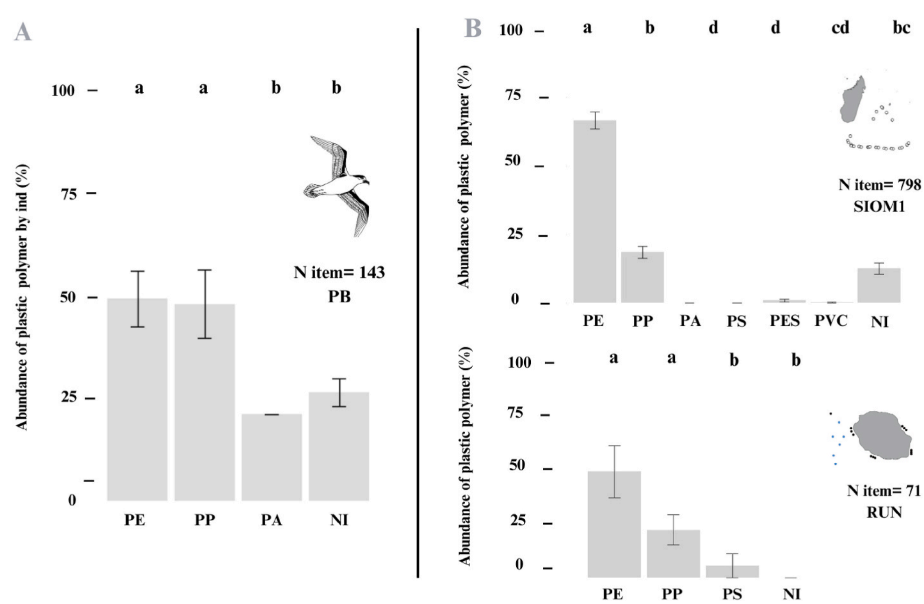

Fig. 5. Proportion of polymer type abundance sampled by the ATR FTIR (A) ingested by Barau's petrels (PB); (B) floating at the sea surface for each manta sampling during SIOM1 campaign, Plast and IOTA2 campaigns (RUN) around Reunion Island. PE: polyethylene, PP: polypropylene, PA: polyamide, PVC: polyvinylchloride, PES: polyester, PS: polystyrene, NI: polymer with match <80%. Letters indicate differences with p-value <0.05 with the Wilcoxon correction and Bonferroni adjusted.

less frequently ingested by seabirds.

3.2.4. Polymers

Among all plastic debris collected from seabirds and at the sea surface (N = 2154), 47% (N = 1012) were analysed by ATR-FTIR for polymer identification (N = 143, from seabirds; N = 869 from the sea surface). Among them, 133 items (92%) for seabirds and 775 items (89%) for the sea surface were successfully attributed to a polymer class. Unidentified particles were combined into a separate type. For both seabirds and sea surfaces, PE and PP were the most abundant polymers identified (Fig. 5, Kruskal-Wallis: $H_{BP} = 49.9$, $df_{BP} = 3$, $P_{BP} = 0.0001$, $n_{BP} = 143$; $H_{SIOM1} = 353$, $df_{SIOM1} = 6$, $P_{SIOM1} = 0.0001$, $n_{SIOM1} = 798$; $H_{RUN} = 18.5$, $df_{RUN} = 3$, $P_{RUN} = 0.0003$, $n_{RUN} = 71$). We noted the presence of polystyrene (PS) only in manta samples from the coastal area of Reunion Island, but none in seabirds and offshore during SIOM1.

To summarize, the characteristics of the plastic debris ingested by seabirds and collected at the sea surface were similar, most debris being large microplastics, hard, white, or transparent, mainly composed of PE and PP.

3.3. Manly selectivity test

A Manly selectivity test was conducted on the number of plastic debris per category, treating abundance concentration as the variable. Overall, Barau's petrels did not exhibit strong selectivity towards any specific shape, colour or size class (Fig. 6. Manly index <0.5). Barau's petrels have a low selectivity for fibre-shaped debris (Manly Index: 0.52 ± 0.21, Fig. 6).

3.4. Risks of plastic ingestion by Barau's petrels when foraging

The first map (Fig. 7. A Petrel tracks) show that the 15 Barau's petrels foraged in the SWIO between 21°S and 43°S and 35°E to 75°E during the breeding season. They typically alternate short trips northwest of Reunion Island and long trips to the south of Madagascar and south of Reunion Island up to latitude 43°S. Barau's Petrels did not forage north of Reunion Island nor in the Mozambique Channel.

The second map (Fig. 7B Model) shows the modelled microplastic concentrations (500 μm-5mm, item.km^{-2}) over the same period. The highest concentration predicted, reaching (10^3 items.km^{-2}), is located between 30°S and 70°/80°E. However, observed concentrations (manta trawling) were higher than those predicted in the subtropical region (30/35°S and 45°/60°E), with (mean ± SE) 68,289 ± 16,521 items.km^{-2} (max: 602,766 items.km^{-2}) and 2696 ± 16 items.km^{-2} (max: 13,734 items.km^{-2}) observed and predicted concentrations respectively.

The concentrations of plastic debris modelled and observed were only weakly correlated (Spearman test: r = 0.46, p-value = 0.04, R^2 = 0.21) and the modelled concentrations were always one order of magnitude lower than the observed concentrations (Fig. 7D).

The overlap between the distribution of foraging Barau's petrels and the predicted plastic concentration at the surface of the sea showed that the encounter risk was maximal during short trips to the northwest of Reunion Island and during long trips between the latitude 30°S and 33°S (Fig. 7D).

4. Discussion

To our knowledge this study is the first to combine seabird necropsies, GPS tracking of foraging adults, *in situ* measurements of plastic concentration at these foraging areas and dispersal modelling to assess the risk of plastic ingestion by seabirds. The results clearly show that Barau's petrels are impacted by plastic pollution in the SWIO during their breeding season.

4.1. Is plastic ingestion by seabirds representative of plastic pollution in the SWIO?

The plastic abundance found in birds was not related to the duration of their stay at the rehabilitation centre, suggesting that the plastic found in their guts was not coming from the food given during their rehabilitation.

The frequency occurrence (FO%) of plastic ingestion by seabirds suggests high exposure to plastic debris in the South-West Indian Ocean, as already suggested by Cartraud et al. (2019). Different studies already demonstrated a high FO% in the temperate Indian Ocean (Savoca et al., 2022) and in the Southern Indian Ocean (Perold et al., 2024). The characteristics (types, colours, polymers) of plastic debris ingested by seabirds and found at the sea surface were similar, suggesting no selectivity in seabirds when incidentally ingesting plastics: they were hard, white, transparent, composed of PE and PP polymers, and predominantly large microplastics. This observation is congruent with other studies conducted on seabirds (Cartraud et al., 2019; Rizzi et al., 2019; Verlis et al., 2018) and at the sea surface offshore (Connan et al., 2021; Egger et al., 2021; Lebreton et al., 2018). These results confirm that plastic ingested by Barau's petrels is representative of plastic pollution in the SWIO.

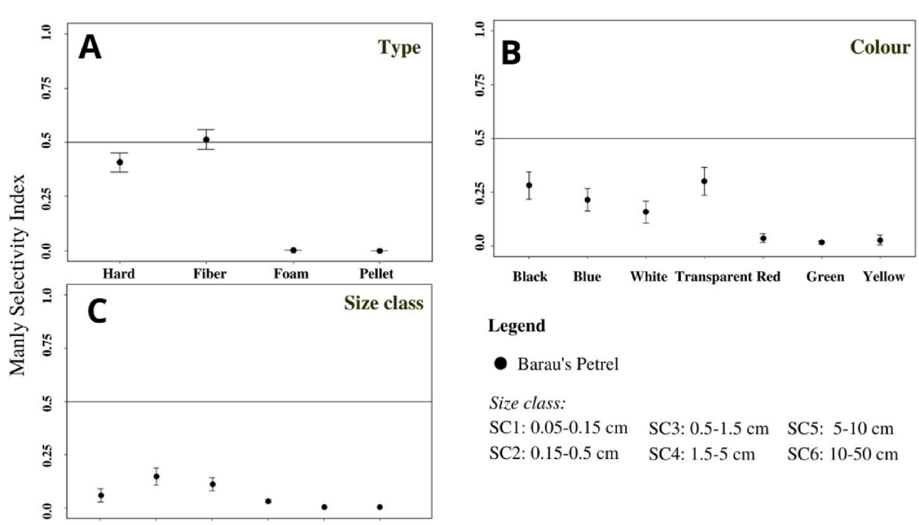

Fig. 6. Manly selectivity test for (A) type, (B) colour, and (C) size class of plastic debris ingested by Barau's Petrels.

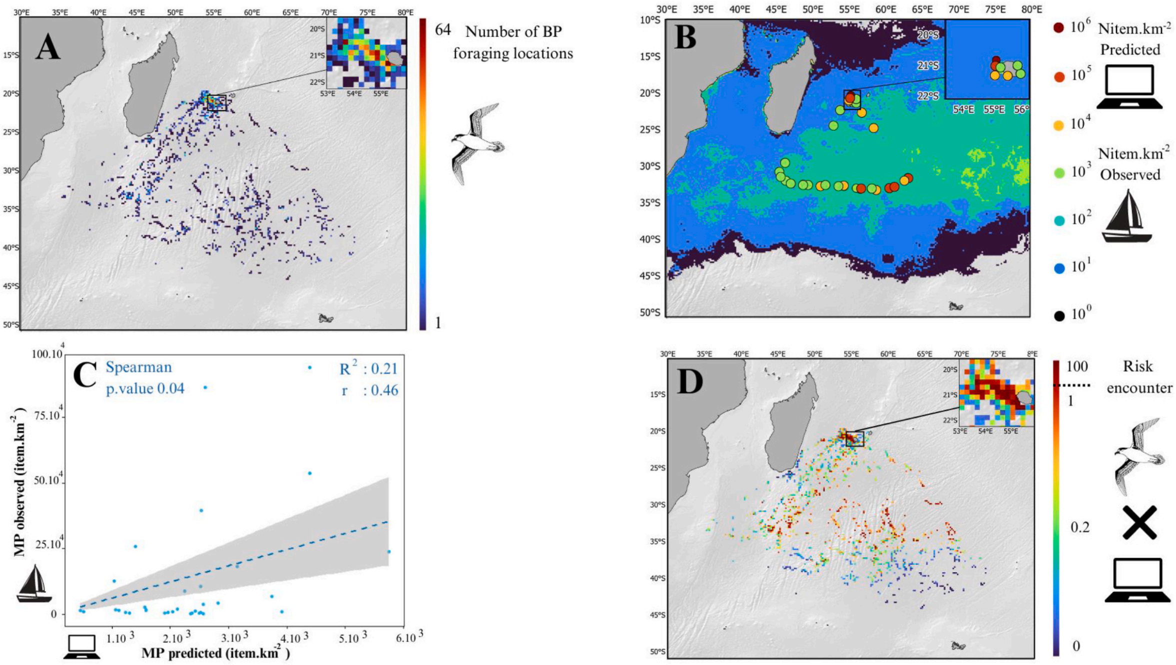

Fig. 7. (A) Number of Barau's petrels (BP) foraging locations recorded by GPS tracking in each grid cell with a spatial resolution of 0.2 × 0.2°, (B) Model: microplastics (Nitem) dispersal model, concentration is several microplastic.km^{-2} for a resolution of 0.2 x 0 0.2° grid cell for the background, circles correspond to concentration observed by manta trawl deployment (plastic items: 0.05–0.5 cm size class, from December to February), (C) Spearman correlation between MP concentration observed by manta trawling and MP concentration predicted, for the same period, (D) Plastic risk encounter for Barau's petrels obtained by multiplying in each cell the density of plastic by the number of individual seabird foraging location.

4.2. Ingestion risk for Barau's petrel and potential impacts

When breeding, Barau's petrels alternate short trips to the North-West of Reunion Island and long trips to the South and South-East of Madagascar (30°–33°S and 40° to 65°E). During both trips, they are at risk of plastic ingestion, as both *in situ* sampling and modelling showed that these places have an important concentration of plastic debris. This explains the high frequency of occurrence of plastic ingested by this species. Furthermore, the concentrations measured *in situ* with manta trawling were always higher than those predicted with dispersal modelling, suggesting that the risk of ingestion is probably higher than what we evaluated. All age classes are concerned by this pollution as breeding adults ingest plastic debris when foraging and regurgitate it to their chicks (Cartraud et al., 2019; Clark et al., 2023). Chicks do not naturally regurgitate hard items which concentrate in their guts (fish bones, otoliths, squid beaks), so they accumulate plastics during their growth (Acampora et al., 2014; Cartraud et al., 2019; Collard et al., 2022; Perold et al., 2020; Tulatz et al., 2023). Our results are consistent with those of Clark et al. (2023), but we found that the northwest of Reunion is also a high-risk area. Chandelier et al., (submitted) identified a mesoscale eddy in this region, creating chlorophyll-rich areas that may attract foraging seabirds. This mesoscale eddy may also concentrate marine litter emitted from Reunion Island (Campan, 2007; Sabadadichetty et al., 2024), or which circulate as a consequence of cyclonic events (Nakajima et al., 2022; Pattiaratchi et al., 2022), or coming from fishing activities (Biais and Taquet, 1992; Sharma et al., 2024).

Plastic debris, once ingested, can have various impacts on seabirds, such as intestinal blockage, endocrine disorders, plasticosis, a false sense of satiety or pathogen transfers (Charlton-Howard et al., 2023). Long-term effects of plastic pollution on survival or breeding success are poorly known (Puskic, 2023), but it is likely that this pollution has negative effects on Barau's Petrels. Reunion Island has two endemic seabird species, the Barau's petrel (Endangered) and the Mascarene petrel (*Pseudobulweria aterrima*, Critically endangered). Both species are threatened on land by invasive mammals and light pollution (Faulquier et al., 2009; Chevillon et al., 2022). Our results show that Barau's petrels ingest plastic debris, and it is likely that Mascarene petrels also do so (see Cartraud et al. 2019), which suggest that plastic marine pollution may be an additional indirect threat at sea for the two species. The next step of the research on plastic effects on seabirds in the region should be 1° to assess the pathogenicity of plastic on adults and chicks of endemic petrels and 2° to evaluate the long-term impact of plastic ingestion on survival, breeding success and population viability.

4.3. Recommendations to define Barau's petrel as bioindicators of plastic pollution in the SWIO

The Barau's petrels meet all recommended criteria to be considered as bioindicators of plastic pollution (GESAMP et al. (2019) Savoca et al. (2022).

- *Comparable globally-similar species identified worldwide and the Indian Ocean representation*

Since 2004, the Northern Fulmar has been employed as the "Fulmar Litter EcoQ" to assess plastic pollution in the North Sea, northern Atlantic, Pacific, and Arctic Oceans, aligning with the Ecological Quality Objectives (Kühn and van Franeker, 2012; Van Franeker and Law, 2015; Savoca et al., 2022).

As Procellarids, Barau's petrels are ecologically similar to the northern Fulmar: they are oceanic foragers, surface-feeders, occasionally scavengers, and they feed on fish, squids and crustaceans (Danckwerts et al., 2016).

- *Species directly linked to impact and effect, plastic FO%*

Our study confirms that the Barau's petrel has a high level of plastic ingestion. The particles found are indeed plastic polymers, as confirmed by the ATR-FTIR analysis, following the guidelines recommended by Savoca et al. (2022). The percentage of occurrence of plastic debris, is

71%, therefore exceeding the 50% threshold suggested by Savoca et al. (2022). Higher ingestion risk areas were identified in the northwest of Reunion Island and the latitudes of 30°S to 35°S at between 40° and 65°E.

- *Ethically sound, abundant in the chosen environment, and easy and practical for analysis*

No birds used in this study have been killed intentionally. All of them have been found grounded as a consequence of light pollution and died during the rehabilitation process. It is estimated that >40,000 seabirds have been grounded on Reunion Island since 1996, among which 11%–19% died (Chevillon et al., 2022). Although guidelines suggest the collection of 40 individuals by species, a collaborative initiative between SEOR and the University of Reunion Island has facilitated the preservation of nearly 100 of these birds in the freezer each year since 2004.

- *Already used as bioindicator species*

Barau's petrels have not been used elsewhere as a bioindicator of plastic pollution. However, this species has already been used to monitor the bioaccumulation of metallic trace elements. (Kojadinovic et al., 2007). As far as we know the only other seabird species used as bioindicator of plastic pollution is the northern fulmar and the Cory's shearwater (Procellariidae, Van Franeker et al., 2011; Rodríguez et al., 2024). As Barau's petrels are also Procellariidae species, we followed the recommendations outlined by Cartraud et al. (2019) to consider them as potential bioindicator species for plastic debris in the South-West Indian Ocean.

5. Conclusion

The comprehensive approach undertaken in this study reveals the suitability of Barau's petrels as a bioindicator species for long-term monitoring of plastic pollution in the SWIO. This species consistently ingested plastic debris since at least 2004 in the Southwest Indian Ocean, revealing high concentration of plastic particles around Reunion Island and in the latitudes 30° to 33°S from 40° to 65°E. We encourage further research on plastic pollution in the Indian Ocean with these bioindicators species.

CRediT authorship contribution statement

Margot Thibault: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Lisa Weiss:** Writing – review & editing, Methodology, Formal analysis. **Romain Fernandez:** Writing – review & editing, Investigation, Formal analysis. **Naïs Avargues:** Writing – review & editing, Investigation. **Sébastien Jaquemet:** Writing – review & editing, Resources, Investigation. **Laurent Lebreton:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Juliette Garnier:** Writing – review & editing, Investigation. **Audrey Jaeger:** Writing – review & editing, Investigation. **Sarah-Jeanne Royer:** Writing – review & editing, Supervision. **Audrey Cartraud:** Writing – review & editing, Investigation. **Alexandra ter Halle:** Writing – review & editing, Supervision, Resources. **Patrick Marsaleix:** Writing – review & editing, Methodology. **Leo Chevillon:** Methodology, Writing – review & editing. **Julie Tourmetzj:** Resources, Investigation. **Matthieu Le Corre:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request https://www.seabirdtracking.org.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2024.106709.

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