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Ecological trap for seabirds due to the contamination caused by the Fundão dam collapse, Brazil

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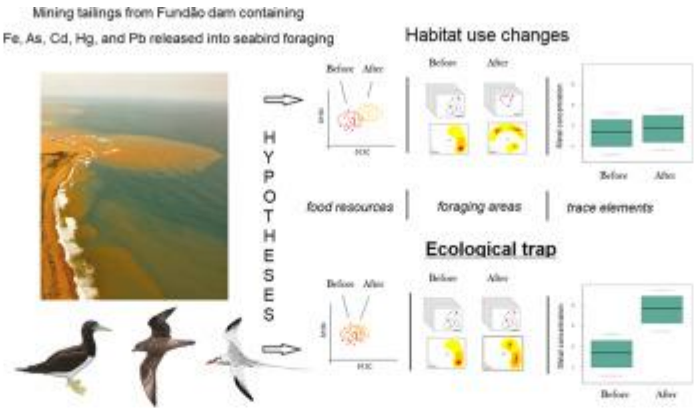
Abstract :

Human-induced rapid environmental changes can disrupt habitat quality in the short term. A decrease in quality of habitats associated with preference for these over other available higher quality is referred as ecological trap. In 2015, the Fundão dam containing iron mining tailings, eastern Brazil, collapsed and released about 50 million cubic meters of metal-rich mud composed by Fe, As, Cd, Hg, Pb in three rivers and the adjacent continental shelf. The area is a foraging site for dozens of seabird and shorebird species. In this study, we used a dataset from before and after Fundão dam collapse containing information on at-sea distribution during foraging activities (biologging), dietary aspects (stable isotopes), and trace elements concentration in feathers and blood from three seabird species known to use the area as foraging site: Phaethon aethereus, Sula leucogaster, and Pterodroma arminjoniana. In general, a substantial change in foraging strategies was not detected, as seabirds remain using areas and food resources similar to those used before the dam collapse. However, concentration of non-essential elements increased (e.g., Cd and As) while essential elements decreased (e.g., Mn and Zn), suggesting that the prey are contaminated by trace elements from tailings. This scenario represents evidence of an ecological trap as seabirds did not change habitat use, even though it had its quality reduced by contamination. The sinking-resuspension dynamics of tailings deposited on the continental shelf can temporally increase seabird exposure to contaminants, which can promote deleterious effects on populations using the region as foraging sites in medium and long terms.

Graphical abstract



Highlights

► 50 million m^3 of mud with Fe, As, Cd, Hg, Pb released into seabird foraging areas ► Seabirds remain using same food resources and foraging areas after the dam collapse. ► Non-essential elements (e.g. As and Cd) increased in seabird tissues. ► Essential elements (e.g. Mn and Zn) decreased concentrations in seabird tissues. ► Poor habitat quality and unchanged use by birds represent an ecological trap.

Keywords : biologging, ecological niche, mining dam failure, stable isotopes, trace elements.

1. Introduction

Environmental changes in the last centuries have impacted biological diversity by changing composition of communities, driving populations and species to extinction (Ceballos et al., 2015). Such changes can occur slowly and gradually, from chronic causes, but also occur acutely, in sudden events which may hinder the possibility of adaptive process. Human-induced rapid environmental changes can disrupt habitat quality in the short term, and the degree of ecological match/mismatch between past and current environments will determine whether local populations will become extinct or pass through an adaptive process under new conditions (Sih, 2013). Spread of invasive species, habitat loss and fragmentation, and chemical contamination are examples of processes which may induce behavioral responses in the wildlife (Sih et al., 2011).

A decrease in quality of habitats associated with preference for these over other available habitats of higher quality is referred as ecological trap (Battin, 2004). Therefore, the concept of falling into an ecological trap is associated with the choice to stay/settle in a habitat with low fitness value (Robertson et al., 2013). The consequences of a maladaptive behavioral scenario can ensure the persistence of local populations in the short term, but it can cause a continuous and severe population decline towards extinction in the medium and long term, especially in organisms with low resilience (Robertson and Chalfoun, 2016). In this context, highly mobile organisms represent good models for evidencing ecological traps, since the permanence in a low-quality habitat is not likely to represent an inability to move away from adverse conditions (Demeyrier et al., 2016; Hollander et al., 2011).

Seabirds have long been used as ecological indicators of environmental changes due to the association of their spatial distribution with seascape features (Furness and Camphuysen, 1997; Parsons et al., 2008). The quality of environments used by seabirds has been assessed by monitoring foraging activities, trophic interactions, and levels of contaminants in biological samples (Durant et al., 2009; Phillips and Waluda, 2020). Despite their high mobility, seabirds have a marked fidelity to their foraging, wintering, and breeding sites (Schreiber and Burger, 2001), which in turn can favor adaptation to local conditions and increase efficiency in obtaining food around colonies (Nunes et al., 2018). However, seabird populations inhabiting areas with distinct environmental conditions and selective pressures may be subject to strong selection against immigrants, resulting in gene flow disruption and population isolation (Friesen et al., 2007). Additionally, as central place foragers during the breeding season, i.e., adults should return regularly to attend the nest, switching to foraging areas away from suitable foraging radius could be deleterious. In this context, events decreasing the foraging habitat quality around breeding areas can pose a threat to the persistence of a population with high local adaptation and low dispersal ability.

In 2015, a dam in eastern Brazil containing iron mining tailings collapsed and released about 50 million cubic meters of metal-rich mud in three rivers and the adjacent continental shelf (IBAMA, 2015). The tailings from the Fundão dam, composed by Fe, As, Cd, Hg, Pb (Hatje et al., 2017), crossed the Doce river damaging areas of natural and cultural heritage, such as watercourses, riparian forests, grasslands, historic villages, in addition to killing 19 people (Carmo et al., 2017). After reaching the ocean it is estimated that the tailings have spread 500 km southwards until the city of Rio de Janeiro (Marta-Almeida et al., 2016), and 200 km northwards (Coimbra et al., 2020), reaching the Abrolhos archipelago. Aquatic biodiversity was shown to be affected by the tailings from the collapsed dam, such as fish larvae (Bonecker et al., 2019) and cnidarians (Miranda and Marques, 2016), including organisms targeted by fisheries (e.g. crabs, shrimps and fishes), which are exposed to metals contamination (Gabriel et al., 2020).

The mouth of the Doce river and its surroundings is also used for foraging and breeding by a range of resident and migratory seabirds, including threatened species. Seabirds are known to be central place foragers and, consequently, the impacted area is used as a foraging site by species breeding on islands located on and off the continental shelf (Alves et al., 2004; Efe, 2004; Leal et al., 2017). Additionally, the area is used for wintering by migratory species from both southern and northern hemispheres including species from sub-Antarctic and sub-Arctic regions, as well as from other ocean basins (Barreto et al., 2021). This demonstrates the importance of the region as a food source for seabirds and, consequently, a high potential for contamination of species using the region as a foraging site. The marine area affected by mud plume at the Doce river mouth had been enriched by several metals and metalloids, including iron (Fe), which is recognized as a limiting element for the primary production in oceans (Longhini et al., 2019). If primary production is affected and replicated toward upper trophic levels, reaching fish and squid consumed by seabirds, a potentially attraction effect could be more dangerous, by exposing birds to other metals (e.g. Pb, Cr, Al, Zn) which also increased post dam collapse (Sá et al., 2021).

Behavioral analysis can be highly informative to assess the extent of impacts caused by contaminants in aquatic ecosystems, and even more powerful when associated with dietary information and datasets obtained before and after an environmental change (Saaristo et al., 2018). In this study, we assessed the effects of contamination from the tailings of the Fundão dam on seabirds that use the mouth of the Doce river and its surroundings as a foraging site. For this, data on the concentration of contaminants in biological tissues and information on diet and at-sea distribution obtained before and after the dam collapse were compared. We hypothesized that the release of mining tailings in seabird foraging area could result in two alternative scenarios: (i) the massive tailings plume could lead to an avoidance of the area if it resulted in food unavailability, which in turn would lead birds to change their foraging areas and not be exposed to contaminants; or (ii) the tailings could not reduce food for seabirds, or even enhance food availability, making birds to remain in the same foraging areas and explore food items as before the collapse, but exposing them to contaminants from Fundão dam.

2. Materials and methods

2.1 Study area, species, and sampling

The Doce river mouth is located along the eastern Brazilian continental shelf in the tropical south Atlantic region and influenced by the Tropical Water and the Brazilian current. The continental shelf can reach up to 200 km and its break is about 60 m deep, where there is an endpoint of the Vitória-Trindade seamount chain (Fig. 1). The region receives a considerable amount of sediments due to the wet climate and the presence of large rivers. It is thus classified as deltaic coast, dominated by waves, mainly controlled by atmospheric circulation and river discharge (Quaresma et al., 2015). Mining tailings spread along the continental shelf adjacent to the mouth of the Doce river, with evidence of dispersal from the city of Rio de Janeiro to the Abrolhos archipelago, covering a latitudinal extent of about 700 km (Coimbra et al., 2020; Marta-Almeida et al., 2016). The impacted area is used as a foraging ground by seabird species breeding in the region, such as brown boobies (*Sula leucogaster*), red-billed tropicbirds

(*Phaethon aethereus*), and Trindade petrels (*Pterodroma arminjoniana*), which were used as model species to assess the effect of contamination on seabirds.

Brown boobies and red-billed tropicbirds have a pantropical distribution and breed in colonies on Atlantic, Pacific, and Indian ocean islands (Nelson, 2005). In Abrolhos, estimated population size is about 300 pairs for brown boobies and 200 pairs for red-billed tropicbirds with breeding activity throughout the year (ICMBio, 2019). Foraging areas are located around colonies, but brown boobies tend to explore the immediate colony surroundings (Weimerskirch et al., 2009; Miller et al., 2018a), while tropicbirds tend to travel further and make longer foraging trips (Diop et al., 2018). Both species are primarily plunge divers and feed on fish occurring at the sea surface, but brown boobies can also interact with fisheries and use discards as a food source (Alves et al., 2004; Castillo-Guerrero et al., 2011). The red-billed tropicbird is currently endangered (EN) in the Brazilian Red List due to its small population size, constrained breeding area, and nest predation by invasive species (Efe et al., 2018).

The Trindade petrel is a migratory species occurring in the Atlantic and Indian oceans (Brown et al., 2011). Most of the global population occurs on the Trindade and Martin Vaz islands in the southern Atlantic Ocean, which hold about 1130 breeding pairs (Luigi et al., 2009). During the non-breeding period, Trindade petrel migrates towards the North Atlantic Ocean (Ramos et al., 2017), and before starting the next breeding cycle (i.e., at the pre-laying phase) it uses the continental shelf adjacent to the mouth of the Doce river as a foraging site (Leal et al., 2017). Trindade petrels are squid specialists but also feed on fish of a broad range of sizes and taxa (Leal et al., 2017). The species is listed as vulnerable (VU) in the IUCN Red List (BirdLife International, 2018) and critically endangered (CR) in the Brazilian Red List (MMA, 2014) mainly due to limited breeding range, small population sizes and threats in breeding areas (Bugoni, 2018).

Biologging data and biological samples were collected at the colonies before (2007–2015; hereafter "before") and after (2016–2020; hereafter "after") the Fundão dam collapse. Brown boobies and red-billed tropicbirds were sampled at the Abrolhos archipelago and Trindade petrels at the Trindade island. The individuals were captured in the nests and the tracking devices were attached following Nunes et al. (2018) for miniaturized GPS and Leal et al. (2017) for light-level geolocators (GLS). The loggers weighed less than 3% of the individual body mass (Phillips et al., 2003). After birds returned from trips devices were retrieved and samples of whole blood and feathers were collected for analysis of stable isotopes and contaminants (Carvalho et al., 2013). Finally, birds were individually identified with metal rings provided by the *Centro Nacional de Pesquisa e Conservação de Aves Silvestres* (ICMBio/CEMAVE) to avoid resampling. Sampling procedures were approved by environmental licenses and ethics committees.

2.2 Biologging

Brown booby and red-billed tropicbird foraging trips were tracked both before and after the dam collapse with miniaturized GPS loggers during the chick-rearing period. Data from 2012 and 2013 were obtained with GiPSy (15 g; TechnoSmart, Italy) set to 1 fix/sec while data from 2018 to 2020 were collected with Axy-Trek Marine (30 g for boobies and 15g for tropicbirds; TechnoSmart, Italy) and i-gotU GT-120/GT-600 (30 g for boobies and 15 g for tropicbirds; Mobile Action, Taiwan) set to 1 fix/10 sec for brown boobies and 1 fix/10 or 15 min for tropicbirds. GPS loggers deployed in boobies (n = 35) and tropicbirds (n = 25) were removed after at least one complete foraging trip. Trindade petrels (n = 29) were tracked throughout the annual cycle before and after collapse with light-level geolocators MK3005 (2.5 g; Lotek, UK).

2.3 Stable isotopes

Whole blood samples were obtained for the 'before' period in 2011 for red-billed tropicbirds; 2011 for brown boobies; and 2006, 2007, 2010, 2011, and 2015 for Trindade petrels. Whole blood samples for the 'after' period were obtained in 2019 and 2020 both for red-billed tropicbirds and brown boobies; and 2016, 2017 and 2019 for Trindade petrels, within the scope of the *Programa de Monitoramento da Biodiversidade Aquática – Rede Rio Doce Mar* (PMBA-RRDM).

Samples were dried and stored in plastic tubes. In the laboratory, samples were lyophilized, homogenized, weighed (1 mg) in tin capsules for stable isotope analysis (SIA) of δ^{13}C and δ^{15}N in an Isotope Ratio Mass Spectrometer (IRMS) coupled to elemental analyzer. Standards applied for carbon and nitrogen were Vienna Pee Dee Belemnite and atmospheric air (N_2), respectively. Isotopic ratio (R) of each element ($^{13}C/^{12}C$ and $^{15}N/^{14}N$) represented in delta notation (*δ*) and expressed in per mil (‰) was obtained through the equation from Bond and Hobson (2012).

2.4 Trace elements

Blood and contour feathers of brown boobies and red-billed tropicbirds were obtained at the Abrolhos archipelago in February and August 2011 (i.e., 'before') and February 2019 (i.e., 'after'). For Trindade petrels, 'before' blood and primary feather (P1) samples were obtained between December 2006 and April 2007, and 'after' blood and contour feathers were obtained in March and April 2019. Blood samples (1 mL) were obtained from the metatarsal vein and stored in microcentrifuge vials at 4°C for transport to the laboratory. Feather samples were stored in plastic bags at room temperature and protected from light until analysis. To avoid external contamination, all feathers were triple washed with a 25M solution of hydrogen peroxide prior to analysis, as described by Bearhop et al. (2000).

Samples were weighed (wet), dried until constant mass, and completely digested at 60°C with 65% ultrapure nitric acid (HNO_3, SupraPur®, Merck, Darmstadt, Germany, using a microwave system (Multiwave 3000 oven, Anton Paar, Graz, Austria). Digested samples and standard solutions were diluted with high purity deionized water (resistivity of 18.2 MΩ/cm). Essential (Cu, Cr, Mn, and Zn) and non-essential (Cd, Fe, Pb, Zn, and As) elements were quantified using a High-Resolution Continuum Source Graphite Furnace Atomic Absorption Spectrometer (HR-CS GF AAS, Analytik Jena, Jena, Germany). Hg analysis was carried out using an atomic fluorescence spectrometer Mercur Duo Plus (Analytik Jena, Jena, Germany). Element concentrations were determined based on calibration curves built for each metal using a serial dilution prepared from a multi-elementary standard solution (1000 mg/L; Merck®, Darmstadt, Germany). Results were expressed as µg/mL and mg/kg for blood and feathers, respectively. Quality control and assurance procedures for element determinations were based on regular analysis of blanks and spiked matrices, as well as through the evaluation of a certified reference materials (TORT-3; DOLT-5; DORM-4; National Research Council Canada, Ottawa, ON, Canada), using the same procedures applied for blood and feather analyses. Procedures were performed in triplicate. For As and metals analyzed, percentage of recovery ranged from 95.3 to 102.6%.

2.5 Statistical analysis

GPS data (lat, long) obtained from red-billed tropicbirds were linearly interpolated at intervals of 15 min (Axy-Trek data) and 1 min (Igot-U data), and at 1 min for brown boobies. Only complete trips were used to calculate total distance traveled (D), maximum distance to the colony (Dmax), trip duration, and sinuosity, which was calculated as D/2Dmax. The temporally regularized data (all trips) was used to segment the trajectories into four behavioral modes for red-billed tropicbirds (travelling, searching for food, foraging, and resting) and into three behavioral modes for brown boobies (travelling, searching for food, and foraging). For this, hidden Markov models (HMM) of four (tropicbird) and three (booby) states were adjusted by using step length and turning angle values, with gamma and Von Mises distributions, respectively, with the *moveHMM* package (Michelot et al., 2016). Initial values of step length and turning angle distributions for the HMMs were determined through clustering based on Gaussian mixture models using the *Mclust* package (Scrucca et al., 2016). The set of step length values with the highest variance of turning angles were assigned to 'foraging'. Utilization distribution (UD) of core range 50% contour polygon within the home range of 'before' and 'after', as well as overlap between periods, were calculated from Kernel density estimations using the *adehabitatHR* package (Calenge, 2006). Due to the limited number of trips for the before period, statistical comparison between before and after were not run for trip parameters but shown in Kernel analysis.

A total of 29 GLS were attached to the metal ring, leg-mounted on breeding petrels in June 2014 and January 2016 and recovered in February 2018. Loggers recorded light intensity and 21 of them also recorded saltwater immersion time proportion and sea surface temperature. To deal with location error of GLS, a specific zone of interest was empirically drawn on the continental shelf (Fig. 1), and the probability of presence of Trindade petrels within this area was assessed. To this end, probable trajectories were simulated for each individual by iteratively sampling likely geolocations with lights, saltwater immersion and temperature data, and to animal movement characteristics (e.g., maximal speed). This was performed using the *probGLS* package (Merkel et al., 2016). By evaluating the proportion of simulated positions within the area of interest, this approach enabled to estimate for each twilight the probability of presence of one individual within the area adjacent to the mouth of the Doce river. Parameters used for the methodological framework are presented in Table S1.

Univariate differences between ‘before’ and ‘after’ values were tested for nitrogen and carbon isotopic ratios by using the Mann-Whitney U test (Legendre and Legendre, 2012). Isotopic niche size and overlap between ‘before’ and ‘after’ periods were estimated considering 50%, 75%, and 95% of the data and using the Kernel-based approach as implemented in ‘rKIN’ package (Eckrich et al., 2020). The isotopic analysis considered samples collected during the breeding period for brown boobies and red-billed tropicbirds, and samples obtained during the pre-laying period for Trindade petrels, when birds are using the area adjacent do Doce river (Leal et al., 2017)

Concentration for essential and non-essential elements, species and periods were calculated as minimum, maximum, and geometric mean ± SD and are shown in Table S2. The Mann-Whitney U test was used for comparison between periods since assumptions for parametric analyses were no met. U test was also used for comparison between tissues, considering the same individual and in the same sampling period. Correlations between different elements in blood or feather were also calculated through Spearman rank correlation coefficient, as well as for comparison of the same element in the different tissues of the same individuals sampled. All analyses were carried out in R (R Core Team, 2020) and considered p-value <0.05 as a threshold for statistical significance.

3. Results

3.1 Foraging areas

Trips of 35 brown boobies (2.1 trips per individual) and 25 red-billed tropicbirds (1.2 trips per individual) were analyzed. Maximum distance to the colony, total distance traveled, sinuosity and trip duration were calculated for a total of 69 trips of brown boobies (3 before and 66 after) and 25 trips of red-billed tropicbirds (2 before and 23 after). Trip statistics were similar between before and after periods (Table 1). For the HMM estimation and identification of foraging areas, all the trips (including those incompletely recorded) of both species were used: 74 of brown boobies (5 before and 69 after) and 30 of red-billed tropicbirds (3 before and 27 after). In general, brown boobies showed a higher consistency in the foraging grounds before and after periods, but both species remained using areas around colony as foraging sites (Fig. 2).

The probability of presence for Trindade petrels in the study area was estimated up to 0.17 and 0.55 for before and after, respectively (Fig. 2). The highest probabilities occurred mainly from January to August, and probabilities were strict to zero during the migration period (i.e., from September to December). The highest median occurred during the pre-laying period (i.e., January–February), revealing that most individuals had probability of presence over 0.05. Overall, only 38% of all tracked birds demonstrated probabilities of presence over 0.1 and about 22% of the tracked birds had the probability of presence higher than 0.2 in the contaminated area after the event.

3.2 Dietary analysis

Univariate differences between before and after were only identified for δ^{13}C in Trindade petrel samples and in δ^{15}N for brown booby samples (Table 2). The isotopic niche area was similar between 'before' and 'after' periods, with a minimum overlap of 50% observed for brown boobies, and for Trindade petrels, and maximum of 93% for red-billed tropicbirds considering 95% of the data (Table 2; Fig. 3).

3.3 Trace elements

Concentrations of essential elements in brown booby blood decreased after the dam collapse for all elements, except Fe, which increased (Table 3; Table S2, and Fig. S1). Significant decrease in concentration was observed for mean values of Cu (96 times), Cr (14 times), and Zn (6 times). Among non-essential elements, As was the only element showing a non-significant increase, while Pb had a significant and the highest decrease (13 times). Concentrations in feathers of brown boobies also significantly decreased for essential elements (Table 3, Table S2, and Fig. S1). From before to after collapse, significant decrease in mean concentrations were observed for Cu (66 times), Fe (10 times), Cr (8 times), and Zn (4 times). For non-essential elements, significant decrease was observed in Hg (75 times), As and Pb (8 times). The exception among non-essential elements was Cd, which had a non-significant increase. Several positive correlations of different elements in blood and feather of brown booby samples from before turned negative after collapse (Fig. 4). Considering the before period, concentrations in blood and feathers of the same brown boobies were positive and significantly correlated for Cu, As, and Hg. For the after period, only Pb concentrations showed a negative and significant correlation (Table S3).

Concentrations of essential elements in blood samples of red-billed tropicbird also decreased and significant reduction was observed in Cu (Table 3, Table S4, and Fig. S2). In contrast, concentrations of non-essential elements significantly increased for As (10 times), and Cd (6 times). Regarding feathers (Table 2, Table S4, and Fig. S2), the essential elements significantly decreased after the collapse for Cu (25 times), Zn (12 times), Cr (5 times), and Fe (4 times). Non-essential elements measured in after samples were significantly higher for Hg (19 times), As (10 times), and Cd (5 times). Significant correlations of different elements in blood and feather samples increased after the collapse (Fig. 4). Correlations of the same elements in blood and feathers of tropicbirds were not significant in both periods (Table S3). Only 40% of the samples used to measure Cd were above the detection limits in blood and 50% in feathers before the collapse, making a correlation between blood and feathers not possible.

Mean concentrations of essential elements in blood samples of Trindade petrel (Table 3, Table S5, and Fig. S3) had a decrease from before to after periods and the significant reductions were observed for Zn (4 times) and Cu (2 times). Trindade petrels had significant increase in concentrations of non-essential elements as observed for As (13 times) and Cd (11 times). Concentrations measured in feathers significantly decreased for essential elements after the collapse, more marked for Zn (19 times), Fe (9 times), Cr and Mn (8 times). Significant differences were also observed in non-essential elements, such as As and Cd (2 times, Table 3, Table S5, and Fig. S3). Considering interactions of different elements in blood and feather samples, a change in strength and sign comparing before and after collapse was observed (Fig. 4). Regarding interactions of the same elements in blood and feather from Trindade petrel samples, all elements showed non-significant correlations in both periods (Table S3). Only 60% of the samples were above the detection limits for Cd, making a correlation between tissues not possible.

4. Discussion

No substantial differences regarding use of foraging areas and food resources were observed for the three seabird species between before and after the Fundão dam collapse, although concentrations of essential and non-essential elements varied between periods. The overlap of isotopic niche of at least 50% suggests that the three seabird species continued to explore food sources similar to those explored before the collapse. Similarly, biologging data indicates that tropicbirds and boobies continue to search for food around breeding areas and that Trindade petrels are still using waters adjacent to the Doce river mouth during the pre-laying and breeding periods. Therefore, the findings indicate that the mining tailings input did not cause a sudden change in food availability on the continental shelf around the mouth of the Doce river, but the trace element analysis suggests a potential contamination of preys consumed by seabirds and, therefore, a decrease in the quality of food resources, which could cause medium- and long-term negative effects on seabirds foraging in the impacted area.

During the breeding period, seabirds become central place foragers being more constrained to explore food resources close to the colonies (Schreiber and Burger, 2001). At Abrolhos, both seabirds feed on Clupeidae, Scombridae and Exocoetidae fish (Alves et al., 2004; Serrano and Azevedo-Júnior, 2005), which are captured in the epipelagic layer of the water column by plunge-diving (Nelson, 2005). Ichthyoplankton assessments indicate that larval stages of fish consumed by birds are found throughout the Abrolhos bank region (Nonaka et al., 2000), including the mouth of the Doce river and its surroundings (RRDM, 2019a). Larvae dispersal and mobility in adult stage should be considered as a factor that increases tailings spread and spatial scope of contamination of their predators. In addition to prey mobility, their availability to seabirds in oligotrophic tropical waters also depend on the distribution of sub-surface predators (e.g., cetaceans and large pelagic fish), which make prey available to seabirds by driving schools close to the ocean’s surface layers, facilitating the feeding opportunities for surface-feeding and plunge-diving seabirds (Ashmole, 1971; Au and Pitman, 1986; Miller et al., 2018b). Therefore, the low overlap of foraging areas between before and after collapse, may be associated with natural variations in spatial distribution of prey and marked differences in sampling effort rather than with potential impacts of tailings on prey availability. Isotopic niche overlap, together with the constant use of colony surroundings as foraging grounds confirm that prey remain available for seabirds breeding in Abrolhos.

The mouth of the Doce river and adjacent waters are being used not only by seabirds, but also by other marine megafauna as foraging and breeding grounds (Barreto et al., 2021). The report from the monitoring carried out by the *Rede Rio Doce Mar* indicates the occurrence of 27 seabird species using the waters around the river mouth and 39 species observed on the adjacent sandy beaches (RRDM, 2019b). Most of the species observed are piscivorous (e.g. Sternidae terns, Ardeidae herons) or benthivores (e.g. Charadriidae, Scolopacidae) and therefore use prey available in the water column or in the sandy substrate and thus is likely to be foraging in the region (Schreiber and Burger, 2001). Occurrence of other large vertebrates in the area, such as dolphins, whales, and sea turtles (Giacomo et al., 2021) is also evidence that tailings from the Fundão dam did not reduce food availability for seabirds on the continental shelf and sandy beaches around the mouth of the Doce river.

The maintenance of prey availability for seabirds may be associated with the non-lethal effect of tailings, due to their composition and dynamics (Sá et al., 2021). Fe was the most abundant element in the tailings, which is considered a limiting factor for primary productivity in the oceans (Martin, 1992; Longhini et al., 2019, 2021). Input in Fe concentrations can stimulate the growth of phytoplankton especially in areas far from the coast where it is a limiting factor for phytoplankton grow (de Baar et al., 1990) and may have contributed to the consistent use of the area by seabirds, as suggested by the biologging data. However, even being an essential element for the maintenance of metabolic activities, Fe can become potentially toxic when absorbed in excess, leading to kidney and liver damage, hemosiderosis, and hemochromatosis (Bulte et al. 1997). Furthermore, the entry of tailings into the sea could have generated a natural dispersion of trace elements in addition to a trend for the tailings to sink to the continental shelf bottom, which could also mitigate the impact on primary productivity and contribute to a non-lethal effect on seabird prey (RRDM, 2019c). However, the sedimentological (RRDM, 2019c; Sá et al., 2021) and hydrogeochemical (RRDM, 2019d) analysis suggest that the dynamics of waves, winds, and rains generate subsequent runoffs, resuspensions, and settlements of the tailings, resulting in seasonal and recurrent pulses of contamination in the marine water column. In summary, the persistence of seabirds in the area due to prey availability, also represents a prolonged exposure to elements present in the tailings, which could be deleterious in the long-term due to bioaccumulation in long-lived animals such as seabirds.

Biological traits place seabirds as important environmental health biomonitors, but at the same time increase conservation challenges (Velarde et al., 2019). Using seabirds for biomonitoring the marine environment is facilitated by their high philopatry (allows inter-annual resampling), colonial reproduction (sampling facilitation), high mobility, and fidelity to foraging areas (monitoring of remote areas) (Burger and Gochfeld, 2004). This has been used to understand environmental contamination by plastics (Avery-Gomm et al., 2012; Phillips and Waluda, 2020), heavy metals (Gatt et al., 2020; Lavers et al., 2020), and persistent organic pollutants (Adrogué et al., 2019; Clatterbuck et al., 2018). However, the usefulness of seabirds as biomonitors also shows the level of impacts on the group, which is considered the most threatened among the entire Class Aves (Croxall et al., 2012), and their K-strategy (i.e. low-resilience organisms) may represent an additional challenge for conservation in events of population decline.

Exposure to contaminants can result in non-lethal consequences, which can evolve to deleterious effects at the population level (Burger and Gochfeld, 2001). The decrease in the mean concentrations of non-essential elements in blood samples, such as Cd, Hg, and Pb, associated to decreased concentrations in feathers, indicates the accumulation of toxic elements. Taking essential elements only, a general decrease is observed in blood and feathers, except for Fe, which increased. Considering that trace elements in seabirds blood reflect their absorption through diet (Carvalho et al. 2013; Janaydeh et al., 2018), the decrease in essential elements may suggest the ingestion of non-essential trace elements, which apparently are not being excreted through feathers, poor nutrition, or consumption of low-quality prey. In addition, it is indicative of competition of binding sites between non-essential and essential elements. Cd and Pb compete for binding sites with essential elements, such as Ca and Zn, and can be excreted through feathers (Malik and Zeb, 2009), eggs (Koster et al., 1996), or allocated and deposited in bones and medulla (Baird and Cann, 2011). Therefore, the decrease in the mean concentrations of non-essential elements in blood samples, associated with decreased concentrations in feathers, could be evidence of the deposition and accumulation of toxic elements in alternative tissues, or a general decrease in bioavailability of trace elements.

Bond establishment and bond site competition are strategies adopted by organisms not only for the regulation of different elements in the same tissue but also for excretion of non-essential elements or exceeding concentrations of essential elements (Baird and Cann, 2011). For example, brown boobies can start molting during the incubation period (Nelson, 2005), and thus comparing trace element concentrations in blood versus feathers can elucidate potential physiological impacts. Alterations in this regulatory system (e.g. the positive interaction of As and Hg) was observed in all species after the collapse. Besides the interaction of different elements in the same tissue, alterations in the regulation of the different elements in the same tissue (blood or feathers) were also observed after the collapse, evidencing a physiological modification (Ahmad et al. 2018; Ziller and Fraissinet-Tachet, 2018). Besides, levels of Cd and Pb increased in the blood of red-billed tropicbird, which reflects recent contamination in the foraging sites (Janaydeh et al., 2018). The increase in the uptake of trace elements by Trindade petrels could also suggest contamination after the dam collapse, as petrels forage in the continental shelf during the pre-laying period (Leal et al., 2017). Despite the differences in the ingestion through diet and regulation of non-essential elements, the absorption and balance of essential elements were likely compromised due to consumption of poor-quality, contaminated prey. In addition to their importance for basic functions, such as respiration and nutrients transportation, Fe increasing can lead to intoxication, anaemia, and disfunctions in kidneys and liver (Cork, 2010). The decrease in Cr concentrations can lead to loss of body mass, decrease in insulin levels, and loss of quality in egg production (Şahin et al., 2001). In addition, the regulation of Cr and Fe in feathers of all species can indicate inefficiency in balancing essential element concentrations which can cause cellular damaging (Zhu et al., 2004). Accordingly, health assessments of birds breeding in Abrolhos had suggested disruption of immune system (RRDM, 2019b).

Disturbances occurring in key areas for biodiversity may represent ecological traps by influencing the life cycle of organisms (Ganser et al., 2019), disrupting trophic interactions (Faldyn et al., 2018), unbalancing population dynamics (Sherley et al., 2017), and changing the composition of communities (Mehdi et al., 2021). This has been widely demonstrated in avian studies (Hale and Swearer, 2016), although evidence of ecological traps in the marine environment is still scarce (Swearer et al., 2021). As hypothesized in the current study, the release of tailings in the foraging area of dozens of seabird and shorebird species and the continued exposure to non-essential elements can pose a threat to the persistence in the medium and long term at the population level, especially for threatened species. This scenario represents evidence of an ecological trap (Robertson and Hutto, 2006; Schlaepfer et al., 2002), as there is a clear decrease in habitat quality due to contamination, but the use of the area for foraging and the food resources remains unchanged. The populations considered in this study of brown boobies (Nunes and Bugoni, 2018), red-billed tropicbirds (Nunes et al., 2017), and Trindade petrels (Brown et al., 2011) represent important pools of genetic diversity at the species level, so that the decrease in habitat quality can transform a source into a sink population and extend the impact to the species level. In this context, long-term studies integrating research techniques associated with habitat use, health status, demographic and breeding aspects, and genetic diversity, are essential to detect potential responses by K-strategists associated with environmental changes.

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Figure Captions

Fig. 1. Study area in the southwestern Atlantic Ocean. Stars indicate breeding sites of brown boobies *Sula leucogaster*, red-billed tropicbirds *Phaethon aethereus* (at Abrolhos archipelago) and Trindade petrels *Pterodroma arminjoniana* (at Trindade island). Tailings from the Fundão dam reached the ocean through the Doce river mouth and spread at least as far as Rio de Janeiro, in the south, and up to the Abrolhos archipelago, in the north.

Fig. 2. Foraging areas during the breeding period identified from biologging data obtained before (blue) and after (red) the Fundão dam collapse for red-billed tropicbirds *Phaethon aethereus* (top left) and brown boobies *Sula leucogaster* (top right) in the Abrolhos archipelago, considering 75% of the data. Maximal probability of presence for Trindade petrels *Pterodroma arminjoniana* in the studied area for each individual by month (bottom).

Fig. 3. Isotopic niches of Trindade petrels *Pterodroma arminjoniana* during the pre-laying period (A), and breeding individuals of red-billed tropicbirds *Phaethon aethereus* (B) and brown boobies *Sula leucogaster* (C) from Abrolhos archipelago. Bayesian ellipses were estimated with carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopic ratios from samples obtained before and after the Fundão dam collapse.

Fig. 4. Correlations between concentrations of chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) in blood (top) and feather (bottom) samples of brown boobies *Sula leucogaster* (left), red-billed tropicbirds *Phaethon aethereus* (middle), and Trindade petrels *Pterodroma arminjoniana* (right) from before (above diagonal) and after (below diagonal) Fundão dam collapse. Color gradient represents Spearman coefficients from -1.0 (brown) to 1.0 (blue); circle sizes are proportional to the coefficients; and significant correlations are indicated with ∗. Please refer to Table S3 for values of correlations.

Ecological trap for seabirds due to the contamination caused by the Fundão dam collapse, Brazil

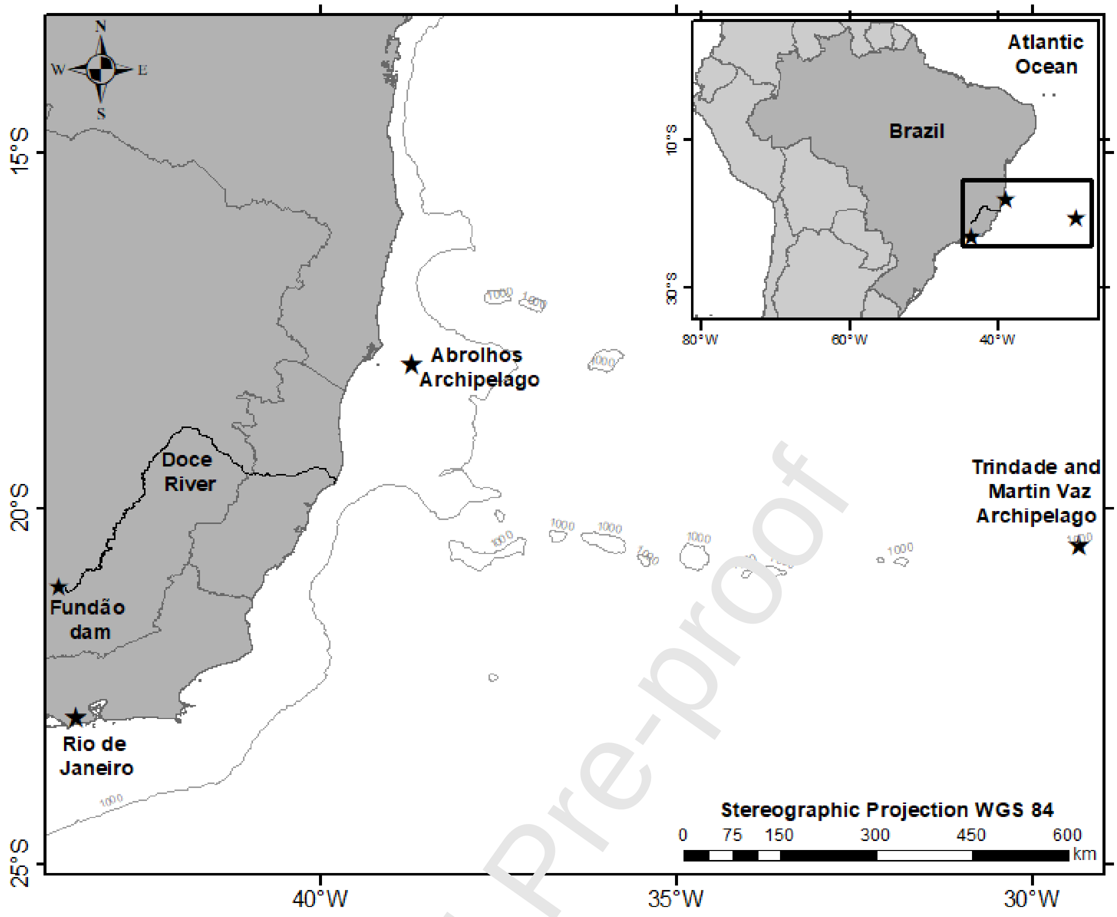
CRediT authorship contribution statement

Guilherme Tavares Nunes: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Supervision; **Márcio Amorim Efe**: Writing – Review & Editing, Funding acquisition, Resources; **Cindy Tavares Barreto**: Formal analysis, Writing – Original Draft; **Juliana Vallim Gaiotto**: Formal analysis, Writing – Original Draft; **Aline Barbosa Silva**: Data Curation, Writing – Original Draft; **Fiorella Vilela:** Formal analysis, Writing – Original Draft; **Amédée Roy:** Formal analysis, Writing – Original Draft; **Sophie Bertrand**: Formal analysis, Writing – Review & Editing; **Patrícia Gomes Costa:** Resources; **Adalto Bianchini**: Resources, Funding acquisition; **Leandro Bugoni**: Conceptualization, Resources, Writing – Review & Editing, Project administration, Funding acquisition.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:


N
W
E
S
Abrolhos Archipelago
Doce River
Fundão dam
Rio de Janeiro
Trindade and Martin Vaz Archipelago
Atlantic Ocean
Brazil
10°S
30°S
80°W
60°W
40°W
1000
Stereographic Projection WGS 84
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75
150
300
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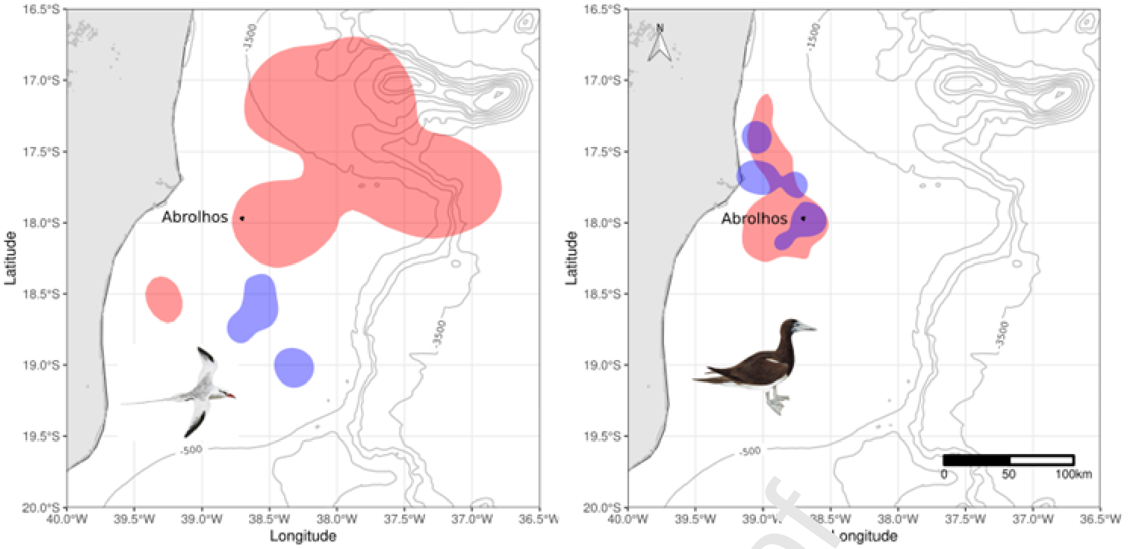
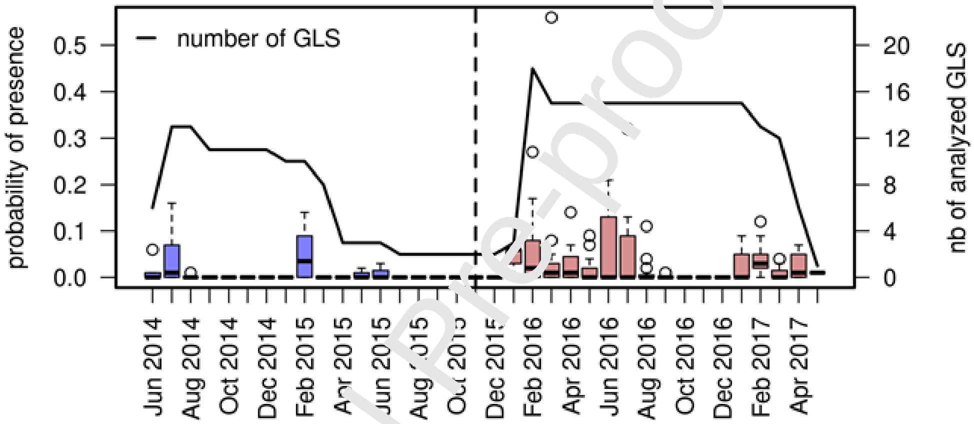
600
km
15°S
20°S
25°S
40°W
35°W
30°W


16.5°S
17.0°S
17.5°S
18.0°S
18.5°S
19.0°S
19.5°S
20.0°S
Latitude
Abrolhos
-1500
-3500
-500
40.0°W
39.5°W
39.0°W
38.5°W
38.0°W
37.5°W
37.0°W
36.5°W
Longitude
N
0
50
100km


number of GLS
probability of presence
0.0
0.1
0.2
0.3
0.4
0.5
nb of analyzed GLS
0
4
8
12
16
20
Jun 2014
Aug 2014
Oct 2014
Dec 2014
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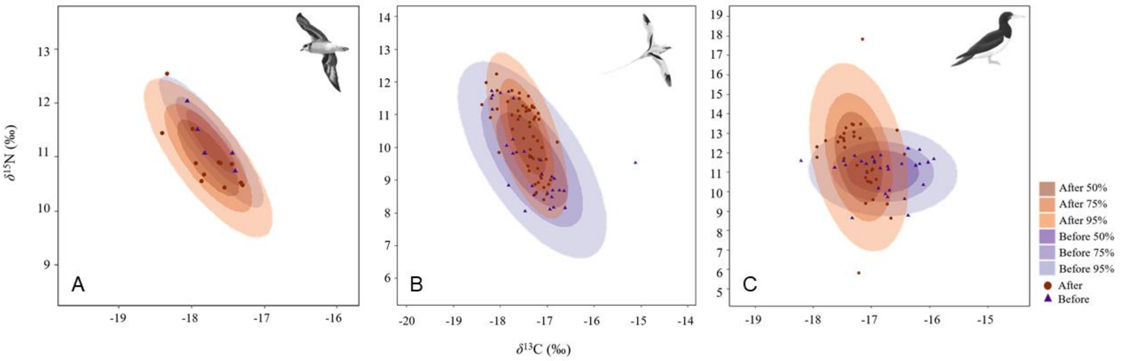
A
B
C
$\delta^{15}N$ (‰)
$\delta^{13}C$ (‰)
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12
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-19
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13
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After 50%
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Before 50%
Before 75%
Before 95%
After
Before

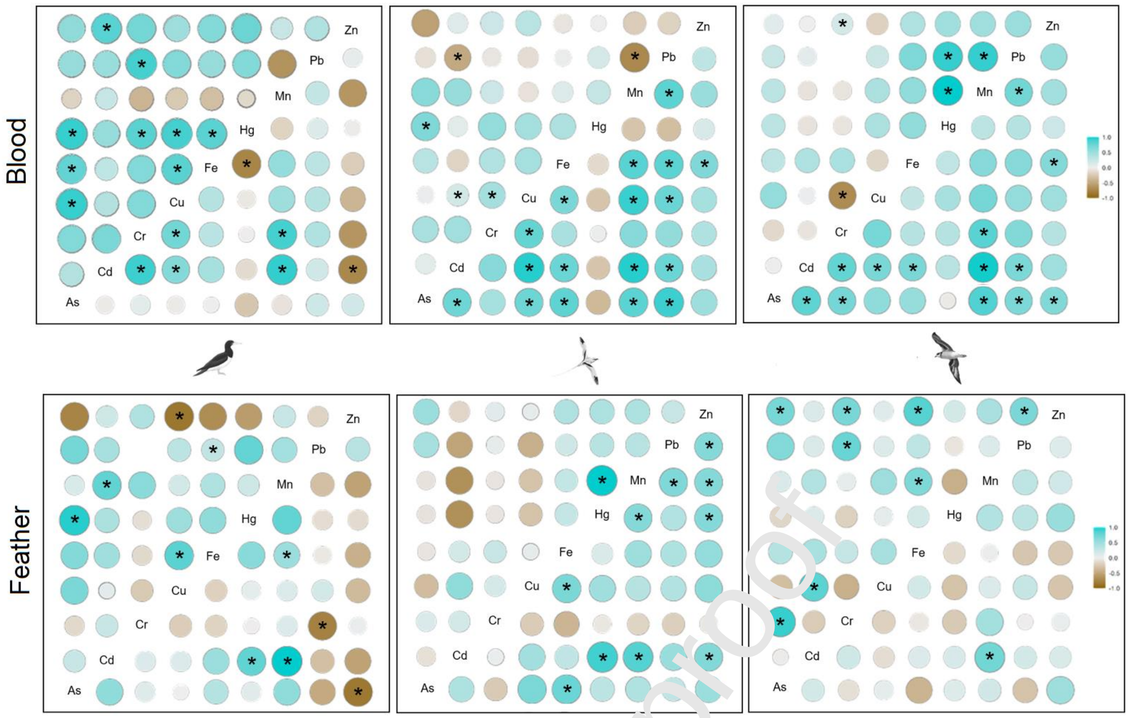

Blood
Feather
Zn
Pb
Mn
Hg
Fe
Cu
Cr
Cd
As
*
1.0
0.5
0.0
-0.5
-1.0

Table 1. Statistics of foraging trips for brown booby *Sula leucogaster* and red-billed tropicbird *Phaethon aethereus* tracked with miniaturized GPS during the breeding period in the Abrolhos archipelago before and after the Fundão dam collapse. Dmax = maximum distance from the colony (km); D = total distance travelled (km); Sin = sinuosity (2D/Dmax); T = trip duration (hours). Foraging areas and overlap were estimated considering 75% of the data. Sample sizes are given in parentheses.

	Brown booby		Red-billed tropicbird	
	Before (n = 3)	After (n = 66)	Before (n = 2)	After (n = 23)
Dmax	22.97 ± 11.34	43.29 ± 28.96	47.26 ± 50.33	133.82 ± 83.76
D	59.75 ± 20.17	119.5 ± 79.69	109.53 ± 121.05	384.72 ± 248.61
Sin	1.42 ± 0.37	1.41 ± 0.30	1.1 ± 0.1	1,41 ± 0.26
T	3.75 ± 0.46	4.68 ± 2.75	3.56 ± 0.17	44.5 ± 34.3
$Area_{75\%}$	0.20	0.38	0.18	2.03
$Overlap_{75\%}$	0.47		0	

Table 2. Stable isotope values from before and after Fundão dam collapse periods for breeding individuals of brown boobies *Sula leucogaster* and red-billed tropicbirds *Phaethon aethereus* from Abrolhos archipelago, and for Trindade petrels *Pterodroma arminjoniana* from Trindade island during the pre-incubation period. Means and standard deviations are shown for each species both for carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopic ratios and differences between periods were calculated by using the Mann-Whitney U test. Estimated isotopic niche area and overlap percentage between before and after periods are considering 50%, 75% and 95% of the data. Sample sizes are given in parenthesis.

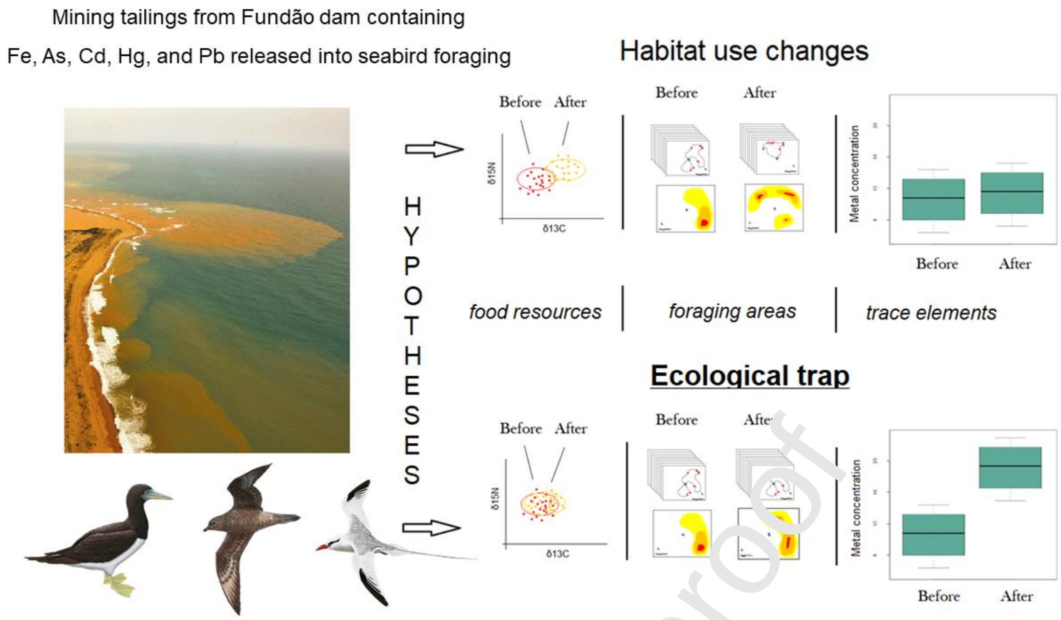
	Brown booby	Red-billed tropicbird	Trindade petrel
$\delta^{13}C_{Before}$	-16.80 ± 0.52 (n=30)	-17.32 ± 0.65 (n=30)	-17.73 ± 0.29 (n=5)
$\delta^{13}C_{After}$	-17.22 ± 0.34 (n=34)	-17.43 ± 0.35 (n=56)	-17.77 ± 0.36 (n=12)
U; *p* (δ^{13}C)	123; 0.05	464.5; 0.98	565.5; <0.01
$\delta^{15}N_{Before}$	11.02 ± 0.93	9.62 ± 1.23	11.28 ± 0.49
$\delta^{15}N_{After}$	11.77 ± 1.98	10.36 ± 1.03	10.98 ± 0.60
U; *p* (δ^{15}N)	91; <0.01	530; 0.35	895.5; 0.73
$Before_{50\%}$	2.1	2.6	0.7
$Before_{75\%}$	4.2	5.3	1.2
$Before_{95\%}$	9.2	11.4	2.3
$After_{50\%}$	2.8	1.2	0.6
$After_{75\%}$	5.7	2.4	1.4
$After_{95\%}$	12.3	5.3	3.0
$Overlap_{50\%}$	0.35	0.76	0.30
$Overlap_{75\%}$	0.44	0.87	0.42
$Overlap_{95\%}$	0.50	0.93	0.50

Table 3. Mean concentrations (mg/kg dry weight) of the essential trace elements chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn), and of the non-essential elements arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) in blood and feather samples of brown bobbies *Sula leucogaster*, red-billed tropicbirds *Phaethon aethereus*, and Trindade petrels *Pterodroma arminjoniana* of before and after Fundão dam colapse. Mann-Whitney U test was used for comparison between periods and significant differences of p value (< 0.05) are bold. Sample sizes are given in parenthesis.

Element	Period	Brown booby		Red-billed tropicbird		Trindade petrel	
		Blood	Feathers	Blood	Feathers	Blood	Feathers
Cr	Before	2.480 (7)	8.280 (6)	2.069 (9)	1.695 (8)	3.043 (6)	3.160 (7)
	After	0.172 (10)	0.972 (10)	0.504 (10)	0.315 (10)	2.857 (10)	0.411 (10)
	p	**0.002**	**0.002**	0.182	**0.0008**	0.958	**0.043**
Cu	Before	12.052 (6)	43.929 (7)	1.723 (8)	4.763 (10)	2.459 (9)	4.294 (9)
	After	0.125 (10)	0.661 (10)	0.634 (10)	0.192 (10)	1.289 (10)	1.436 (10)
	p	**0.014**	**0.0002**	**0.012**	**<0.001**	**0.010**	**0.0007**
Fe	Before	211.601 (7)	392.891 (7)	276.796 (10)	182.017 (10)	378.929 (9)	347.294 (9)
	After	206.338 (10)	40.228 (10)	334.284 (10)	47.527 (10)	405.553 (10)	36.422 (10)
	p	0.887	**0.0001**	1	**<0.001**	0.661	**<0.001**
Mn	Before	7.206 (7)	134.341 (7)	13.446 (10)	37.425 (10)	43.427 (9)	107.202 (9)
	After	4.125 (10)	18.939 (10)	18.862 (10)	13.180 (10)	39.693 (10)	12.979 (10)
	p	**0.025**	**0.0001**	0.218	**0.002**	0.156	**<0.001**
Zn	Before	41.307 (7)	99.899 (7)	6.114 (9)	217.899 (10)	31.673 (8)	248.050 (9)
	After	6.219 (10)	25.445 (10)	5.262 (10)	30.795 (10)	7.723 (10)	12.877 (10)

	p	**0.003**	**0.025**	0.156	**<0.001**	**0.006**	**<0.001**
As	Before	0.394 (7)	19.709 (7)	0.376 (10)	0.504 (10)	0.584 (7)	1.111 (9)
	After	0.490 (10)	2.451 (10)	3.711 (10)	5.036 (10)	7.477 (10)	2.332 (10)
	p	0.315	**0.014**	**0.0003**	**<0.001**	**0.0003**	**0.017**
Cd	Before	0.102 (5)	0.352 (5)	0.080 (6)	0.042 (5)	0.082 (5)	0.116 (5)
	After	0.095 (10)	0.436 (10)	0.449 (10)	0.029 (10)	0.901 (10)	0.250 (10)
	p	0.107	0.514	**0.022**	**0.003**	**0.004**	**0.019**
Hg	Before	0.230 (7)	2.337 (7)	0.249 (10)	0.380 (10)	0.394 (9)	0.419 (9)
	After	0.088 (10)	0.031 (10)	0.091 (10)	0.020 (10)	0.042 (10)	0.238 (10)
	p	0.315	**0.0001**	**0.014**	**<0.001**	**0.0003**	0.156
Pb	Before	0.310 (7)	0.866 (7)	0.276 (10)	0.400 (10)	0.478 (9)	0.408 (9)
	After	0.023 (10)	0.099 (10)	0.763 (10)	0.115 (10)	0.893 (10)	0.246 (10)
	p	**0.004**	**0.0001**	0.089	**0.001**	0.780	0.270

Graphical abstract



Ecological trap for seabirds due to the contamination caused by the Fundão dam collapse, Brazil

Highlights

50 million m^3 of mud with Fe, As, Cd, Hg, Pb released into seabird foraging areas

Seabirds remain using same food resources and foraging areas after the dam collapse

Non-essential elements (e.g. As and Cd) increased in seabird tissues

Essential elements (e.g. Mn and Zn) decreased concentrations in seabird tissues

Poor habitat quality and unchanged use by birds represent an ecological trap.