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Temporal changes in metal and arsenic concentrations in blood and feathers of tropical seabirds after one of the largest environmental disasters associated with mining

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ABSTRACT

Monitoring of contaminant levels in wildlife over time is a tool for assessing the presence and persistence of environmental impacts at ecosystem, community and population levels. Tropical seabirds breeding in the Abrolhos Archipelago, 70 km off the Brazilian coast, forage in areas under the influence of the Doce River discharge. In 2015, the Fundão Dam collapsed and released ca 60 million tons of iron ore tailings into the ocean. In the present study, red-billed tropicbirds *Phaethon aethereus* and brown boobies *Sula leucogaster* breeding in Abrolhos were monitored over four years (2019–2022) for metal (Fe, Mn, Zn, Cu, Cr, Hg, Pb, Cd) and metalloid (As) concentrations in blood and feathers. Over six sampling events, metal (loid) concentrations showed strong temporal variation in both tissues. Overall, feathers showed greater element concentrations than blood, with stronger correlations between elements, especially Mn and the nonessential As, Cd, Hg and Pb. Mn is one of the major chemical markers of the Fundão Dam tailings. Metal (loid) concentrations in the tropical seabirds evaluated were above suggested threshold levels for most nonessential elements (As, Cd and Pb), especially in February 2021, when metal (loid) concentrations peaked in feathers. In this case, values were orders of magnitude higher than those observed in other sampling events. This occurred one year after a major rainy season in the Doce River basin, which increased river discharge of contaminated mud into the ocean, where contaminants are further remobilized by winds and currents, resulting in transference through the marine food web. This finding is consistent to what has been observed for other ecosystem compartments monitored in the region under the influence of the Doce River. Our findings highlight the utility of using tropical seabirds as sentinels of marine pollution, revealing strong temporal patterns in metal (loid) concentrations associated to bottom-up climatic processes.

Author statement

Patricia Gomes Costa: Resources. Guilherme Nunes: Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. Bruno A Linhares: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Adalto Bianchini: Writing – review & editing, Resources, Funding acquisition, Conceptualization. Leandro Bugoni: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. Arthur Bauer: Writing – review &

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1. Introduction

Human-induced impacts alter water and sediment chemical composition in coastal environments and, consequently, in the associated biota (Amora-Nogueira et al., 2023; Islam and Tanaka, 2004; Vikas and Dwarakish, 2015). Due to their high toxicity, elements such as mercury (Hg), lead (Pb), cadmium (Cd) and arsenic (As) are contaminants of great concern in marine ecosystems (Ansari et al., 2003). These elements reach the oceans transported mainly by rivers, and many metals and metalloids are assimilated and accumulated in aquatic organisms (Carravieri et al., 2020; Kolarova and Napiórkowski, 2021). However, few studies have been carried out to understand the temporal dynamics of metal contamination in seabirds (e.g. Cusset et al., 2023), particularly in tropical regions (Ma et al., 2022). Thus, the assessment of potential human-induced effects on metal concentrations in tropical seabirds over time becomes difficult to evaluate, especially in areas subjected to acute or chronic inputs of contaminants.

Recent environmental catastrophes have underscored the urgency of evaluating contaminant dynamics in organisms. Notably, one of the largest environmental disasters linked to mining activities in the globe occurred in eastern Brazil in 2015 (Hatje et al., 2017), when the Fundão Dam collapsed and released about 60 million m^3 of ore tailings into the Doce River (IBAMA, 2015). The toxic mud was composed mostly by iron (Fe) (45,200 ± 2850 $mg.Kg^{-1}$) and manganese (Mn) (433 ± 110 $mg.Kg^{-1}$), but also contained toxic metals and metalloid such as chromium (Cr) (63.9 ± 15.1 $mg.Kg^{-1}$), Pb (20.2 ± 4.6 $mg.Kg^{-1}$), As (~719.07 $ng.g^{-1}$) and Hg (~75 $ng.g^{-1}$) (Queiroz et al., 2018; Segura et al., 2016). In a few days, the tailing sludge reached the Atlantic Ocean (Marta-Almeida et al., 2016). This event altered metal and metalloid concentrations in several environmental compartments in the coastal zone, such as water and sediment in beaches, mangroves and the adjacent continental shelf (Costa et al., 2022; Duarte et al., 2021). Consequently, physiological impact was detected in several groups of organisms along the food chain (RRDM, 2021). Contaminants derived from the contaminated mud also reached the largest reef ecosystem in the South Atlantic Ocean and one of the largest rhodolith beds in the world, the Abrolhos Bank, located about 200 km north of the Doce River mouth (Coimbra et al., 2020; Francini-Filho et al., 2019; Moura et al., 2021). In this context, the high metal (loid) concentrations in ore tailings may have impacted multiple marine organisms across a wide area (Costa et al., 2022), including top predators, such as seabirds (Nunes et al., 2022).

In addition to the high diversity of corals and fishes (Dutra et al., 2005), the Abrolhos Bank is an important foraging area for tropical seabirds breeding in the Abrolhos Archipelago (Nunes et al., 2022). Seabirds are central-place foragers during the breeding period, so nest attendance by adults is interspersed with foraging trips around the colony to feed themselves and their chicks (Schreiber and Burger, 2001). Brown boobies *Sula leucogaster* and red-billed tropicbirds *Phaethon aethereus* were demonstrated to forage around the Abrolhos Archipelago during the chick-rearing period, in areas known to be affected by ore tailings from the Fundão Dam collapse (Nunes et al., 2022). Increases in metal (loid) concentrations in feathers and blood of both species were also reported, comparing samples obtained before and after the disaster (Nunes et al., 2022). Due to the lack of major changes in foraging strategies after the Fundão Dam collapse and the likely decrease in habitat quality due to marine food web contamination, this scenario has been considered an ecological trap for seabirds. Nonetheless, variation of contaminants in seabird tissues over the years after the dam collapse has not been yet evaluated, which would be important for understanding the persistence of the impact on these marine top predators.

Metal and metalloid concentrations in seabirds using this impacted area may vary over time due to variations in climatic and oceanographic processes that influence metal fate and bioavailability. The Doce River drainage basin shows marked rainy (October–March) and dry (April–September) seasons. While the intense rainfall substantially increases the river flow during the rainy season, intense winds and waves in the adjacent continental shelf occur during the dry season (RRDM, 2021). These seasonal changes can remobilize contaminated sediments and suspend them into the water column (Oliveira and Quaresma, 2017; Quaresma et al., 2015), therefore making them available to the biota (Hatje et al., 2017; Magris et al., 2019). Nonetheless, although extreme climatic events could induce occasional peaks in contaminant bioavailability, we could expect a gradual decrease in metal concentrations in seabird blood and feathers after the dam collapse in 2015, due to the potential dilution of the ore tailings in the environment and organisms over time.

In the present study, we evaluated the temporal changes of essential (Fe, Mn, Zn, Cr and Cu) and nonessential (Cd, Hg and Pb) metals and metalloid (As) in the feather and blood of red-billed tropicbirds and brown boobies breeding in the Abrolhos Archipelago. Samples were obtained over four years of monitoring between 2019 and 2022, during both the dry and rainy seasons in the Doce River basin, as determined by the Brazilian government after the dam collapse. Additionally, stable isotope analysis of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in blood samples were used as a proxy to detect possible changes in trophic relationships and habitat use, and thus provide a better understanding on the contamination dynamics in both species. Our study provides one of the few assessments over temporal scales in which metals and metalloid contamination may vary in tropical seabirds influenced by a large environmental disaster.

2. Materials and methods

2.1. Seabird sampling

Brown boobies and red-billed tropicbirds were sampled on six field trips performed in the Abrolhos Archipelago, as part of a monitoring program for impact assessment. Sampling design followed environmental seasonality based on rainfall dynamics in the Doce River basin: February 2019, 2020, 2021, and March 2022 corresponding to the rainy season; August 2021 and September 2022 corresponding to the dry season. Adults of both species, which breed throughout the year, were captured manually or using a handle net on or near their nests. Contour feathers of both species were manually collected, and ~1 mL of blood was obtained from the metatarsal vein with sterile syringe/needle. Blood samples were placed in microtubes and stored at −20 °C, while feather samples were placed in plastic bags and stored at room temperature, until chemical analysis. Bird sex was not discriminated in our analysis to provide a population-level state and to avoid biased results from small sample sizes from asymmetric sex ratios. Bird sampling and manipulation were approved by a federal license (SISBIO 64381, Brasília, DF, Brazil) and the ethics committee of the *Universidade Federal do Rio Grande* (FURG; Rio Grande, RS, Brazil). A total of 393 samples were analyzed for metal (loid) concentrations, where 195 samples (96 blood and 99 feathers) were collected from brown boobies and 198 samples (99 blood and 99 feathers) were collected from red-billed tropicbirds (Tables 1 and 2).

2.2. Metal and metalloid analysis

In order to remove any external contamination, feathers were washed three times with deionized water and then with acetone (Grúz et al., 2019; Solgi et al., 2020; Zebral et al., 2022). Blood and feathers were then dried until constant mass in an oven (45–60 °C) and weighted (dry mass). Dried samples were digested following procedures described by the US Environmental Protection Agency (Method EPA 3052). Samples were digested with 65% ultrapure nitric acid (HNO_3, SupraPur®, Merck) using a microwave sample preparation system (Multiwave 3000

Table 1
Essential metal (Fe, Mn, Zn, Cu and Cr) concentrations (mg.Kg^{-1} dry mass) in blood and feathers of red-billed tropicbirds *Phaethon aethereus* and brown boobies *Sula leucogaster* breeding in the Abrolhos Archipelago, southwestern Atlantic Ocean, over the six sampling field trips (February 2019, 2020, 2021; August 2021, March 2022 and September 2022). Data are expressed as mean ± 1 standard deviation.

Red-billed tropicbirds			**Essential elements**				
Blood	**Season**	***n***	**Fe**	**Mn**	**Zn**	**Cu**	**Cr**
2019	Rainy	10	233.36 ± 71.02	18.86 ± 34.94	5.26 ± 6.79	0.76 ± 1.43	0.5 ± 0.89
2020	Rainy	10	26.25 ± 11.33	10.08 ± 3.19	36.19 ± 18.77	1.56 ± 2.41	0.17 ± 0.10
2021	Rainy	19	26.16 ± 25.27	82.47 ± 72.14	19.82 ± 30.92	4.75 ± 6.45	3.21 ± 3.73
2021	Dry	23	159.44 ± 109.41	0.84 ± 0.70	10.31 ± 7.73	1.29 ± 1.76	1.09 ± 2.06
2022	Rainy	19	118.23 ± 44.37	1.81 ± 1.80	6.91 ± 7.81	0.94 ± 0.48	0.97 ± 0.71
2022	Dry	18	15.89 ± 20.85	5.87 ± 8.87	3.60 ± 3.62	8.28 ± 14.03	2.78 ± 3.50
Grouped		99	104.06 ± 129.59	20.36 ± 45.13	12.37 ± 18.27	3.11 ± 7.03	1.63 ± 2.65
Feathers	**Season**	***n***	**Fe**	**Mn**	**Zn**	**Cu**	**Cr**
2019	Rainy	10	50.13 ± 25.73	13.18 ± 4.04	30.79 ± 26.30	0.26 ± 0.21	0.32 ± 0.19
2020	Rainy	10	25.81 ± 10.84	9.89 ± 2.69	35.53 ± 17.97	2.5 ± 2.22	0.17 ± 0.10
2021	Rainy	20	117.84 ± 101.60	449.9 ± 300.48	58.29 ± 64.28	34.09 ± 33.35	11.78 ± 9.81
2021	Dry	22	20.35 ± 39.94	2.65 ± 1.97	32.91 ± 50.48	0.31 ± 0.34	3.07 ± 3.39
2022	Rainy	20	57.89 ± 45.35	2.1 ± 1.77	13.79 ± 11.20	9.91 ± 4.17	7.66 ± 8.37
2022	Dry	17	42.26 ± 31.27	12.47 ± 4.77	11.08 ± 2.27	22.01 ± 4.39	1.93 ± 0.77
Grouped		99	54.65 ± 64.67	97.33 ± 223.41	30.65 ± 41.99	13.45 ± 20.11	4.96 ± 7.24
Brown boobies							
Blood	**Season**	***n***	**Fe**	**Mn**	**Zn**	**Cu**	**Cr**
2019	Rainy	10	206.34 ± 55.62	4.12 ± 5.40	6.22 ± 4.79	0.19 ± 0.30	0.17 ± 0.26
2020	Rainy	10	50.24 ± 26.87	24.13 ± 8.26	19.13 ± 4.66	3.08 ± 1.30	0.53 ± 0.45
2021	Rainy	20	25.62 ± 16.04	91.61 ± 65.07	11.07 ± 6.24	3.33 ± 4.25	1.3 ± 1.43
2021	Dry	20	199.78 ± 108.83	0.72 ± 0.40	6.89 ± 4.21	0.79 ± 0.60	0.46 ± 0.27
2022	Rainy	19	79.42 ± 83.02	1.98 ± 1.21	3.28 ± 1.74	0.85 ± 0.63	0.77 ± 0.51
2022	Dry	16	5.23 ± 2.06	7.89 ± 7.82	3.54 ± 5.51	4.34 ± 1.76	1.69 ± 1.05
Grouped		96	91.22 ± 102.13	24.14 ± 46.34	7.7 ± 6.69	2.23 ± 2.65	0.88 ± 0.97
Feathers	**Season**	***n***	**Fe**	**Mn**	**Zn**	**Cu**	**Cr**
2019	Rainy	10	40.23 ± 14.53	18.94 ± 5.95	25.45 ± 18.89	0.73 ± 1.10	0.97 ± 1.01
2020	Rainy	10	47.29 ± 25.06	22.69 ± 7.51	195.71 ± 135.67	25.79 ± 11.84	0.49 ± 0.42
2021	Rainy	20	104.16 ± 66.27	438.25 ± 253.67	64.79 ± 81.06	33.33 ± 34.9	11.85 ± 11.84
2021	Dry	20	31.13 ± 34.46	3.68 ± 1.80	59.15 ± 39.17	0.42 ± 0.42	4.22 ± 4.15
2022	Rainy	20	46.61 ± 24.68	2.42 ± 2.20	11.74 ± 6.90	3.68 ± 3.80	3.72 ± 4.08
2022	Dry	19	58.40 ± 82.38	10.94 ± 2.53	11.25 ± 2.57	7.57 ± 2.62	2.17 ± 0.54
Grouped		99	56.8 ± 56.34	96.07 ± 206.09	51.91 ± 78.62	11.81 ± 20.66	4.56 ± 7.00

Microwave Oven, Anton Paar) operating at 80 bar. Digested samples and standard solutions were diluted with high purity deionized water (resistivity of 18 MΩ/cm). Metals (Cd, Cr, Cu, Fe, Hg, Mn, Pb and Zn) and metalloid (As) concentrations were determined following procedures described by the US Environmental Protection Agency (Method EPA 6020A). Digested samples were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS, PlasmaQuant MS Q, Analytik Jena). Metal (loid) 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). Results were expressed as mg.Kg^{-1} dry mass for blood and feathers. Throughout the text, metal (loid) concentrations are included as mean ± standard deviation, except where indicated.

Quality control and assurance procedures for metals and As determinations were based on regular analysis of blanks and spiked matrices, as well as through the evaluation of a fish protein certified reference material for trace metals and other constituents (DORM-5; National Research Council Canada, Canada). Mean (±SD) recovery rates for As, Cd, Cr, Cu, Fe, Hg, Mn, Pb and Zn corresponded to 81.7 ± 2.2, 81.7 ± 2.0, 87.4 ± 2.1, 81.2 ± 3.5, 83.1 ± 14.4, 88.0 ± 8.0, 81.8 ± 6.5, 84.3 ± 7.1, and 81.2 ± 2.6%, respectively. The Limit of Detection (LoD) was three times the standard deviation (SD) of the blank signals (3xSD; n = 7) and the Limit of Quantification (LoQ) was ten times the SD of the blank signals (10xSD; n = 7). The LoQ for the elements analyzed in blood samples were 0.0435, 0.0050, 0.7297, 0.4498, 2.7675, 0.0182, 0.0101, 0.0100, and 0.1737 mg.Kg^{-1} dry mass, respectively. For feathers, they corresponded to 0.0087, 0.0010, 0.1459, 0.0900, 0.5535, 0.0036, 0.0020, 0.0020, and 0.0347 mg.Kg^{-1} dry mass, respectively.

2.3. Stable isotopes analysis

Blood samples were freeze-dried and homogenized. Then, 0.7 mg of blood samples was placed in tin capsules and analyzed for carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotopes using an Isotope Ratio Mass Spectrometer (IRMS, ThermoFisher) coupled to an elemental analyzer (EA Flash 2000 Delta V Advantage), at the *Centro Integrado de Análises* (CIA-FURG). Stable isotope ratios were determined by equation (1):

$$\delta X\ (‰) = (R_{sample}/R_{standard}) - 1 \quad (1)$$

where X is the ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$ and R represents the ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$ of the sample and standard (Peterson and Fry, 1987). Stable isotope abundances are then expressed in delta (δ) values in parts per thousand (‰). Standards applied for carbon and nitrogen were Vienna Pee Dee belemnite and atmospheric air, respectively. Internal laboratory standards cafein, acetinilide and glutamic acid were interspersed between samples. These standards have accuracy of 0.07 (‰) and 0.3 (‰) for carbon and nitrogen, respectively.

2.4. Statistical procedures

Principal component analysis (PCA) using the "FactoMineR" package (Husson et al., 2017) was applied for each species and tissue to identify differences among the sampling field trips and detect elements responsible for segregation. For this, metal (loid) concentration data was standardized. PCA performances were evaluated by computing the percentage variance explained by the first two components (PC1 and PC2) and eigenvalues. Ellipses with 50% of the confidence interval

Table 2
Nonessential metal (Cd, Hg, Pb) and arsenic (As) concentrations (mg.Kg^{-1} dry mass) in blood and feathers of red-billed tropicbirds *Phaethon aethereus* and brown boobies *Sula leucogaster* breeding in the Abrolhos Archipelago, southwestern Atlantic Ocean, over the six sampling field trips (February 2019, 2020, 2021; August 2021, March 2022 and September 2022). Data are expressed as mean ± 1 standard deviation.

Red-billed tropicbirds			**Nonessential elements**			
Blood	**Season**	***n***	**As**	**Cd**	**Hg**	**Pb**
2019	Wet	10	0.92 ± 0.44	0.12 ± 0.05	0.09 ± 0.03	0.02 ± 0.01
2020	Rainy	10	0.54 ± 0.37	0.10 ± 0.04	0.02 ± 0.01	0.05 ± 0.03
2021	Rainy	19	10.16 ± 15.46	0.11 ± 0.10	0.22 ± 0.34	0.37 ± 0.43
2021	Dry	23	0.36 ± 0.31	0.87 ± 0.83	0.18 ± 0.19	0.57 ± 0.56
2022	Rainy	19	2.68 ± 1.02	0.14 ± 0.09	0.04 ± 0.02	1.11 ± 0.64
2022	Dry	18	0.58 ± 0.56	0.12 ± 0.10	0.19 ± 0.17	0.08 ± 0.11
Grouped		99	3.08 ± 7.83	0.33 ± 0.56	0.14 ± 0.20	0.55 ± 0.86
Feathers	**Season**	***n***	**As**	**Cd**	**Hg**	**Pb**
2019	Rainy	10	5.25 ± 3.58	0.29 ± 0.05	0.02 ± 0.01	0.11 ± 0.05
2020	Rainy	10	0.53 ± 0.34	0.09 ± 0.03	0.01 ± 0.01	0.05 ± 0.03
2021	Rainy	20	16.44 ± 15.54	3.82 ± 2.59	3.35 ± 2.47	4.63 ± 4.33
2021	Dry	22	0.41 ± 0.26	0.23 ± 0.14	0.40 ± 0.29	0.17 ± 0.09
2022	Rainy	20	4.76 ± 4.20	1.21 ± 0.99	0.36 ± 0.29	0.71 ± 0.51
2022	Dry	17	0.07 ± 0.02	0.35 ± 0.10	0.22 ± 0.08	0.42 ± 0.21
Grouped		99	4.95 ± 9.47	1.17 ± 1.86	0.89 ± 1.68	1.21 ± 2.61
Brown boobies						
Blood	**Season**	***n***	**As**	**Cd**	**Hg**	**Pb**
2019	Rainy	10	0.49 ± 0.20	0.09 ± 0.11	0.09 ± 0.07	0.02 ± 0.02
2020	Rainy	10	0.41 ± 0.26	0.26 ± 0.22	0.01 ± 0.01	0.03 ± 0.01
2021	Rainy	20	8.98 ± 8.92	0.07 ± 0.06	0.14 ± 0.16	0.19 ± 0.24
2021	Dry	20	0.16 ± 0.09	0.54 ± 0.33	0.11 ± 0.06	0.40 ± 0.27
2022	Rainy	19	1.04 ± 0.35	0.07 ± 0.05	0.57 ± 0.77	0.51 ± 0.55
2022	Dry	16	0.71 ± 0.29	0.10 ± 0.04	0.29 ± 0.12	0.05 ± 0.03
Grouped		96	2.35 ± 5.30	0.20 ± 0.25	0.22 ± 0.40	0.24 ± 0.35
Feathers	**Season**	***n***	**As**	**Cd**	**Hg**	**Pb**
2019	Rainy	10	2.45 ± 0.85	0.44 ± 0.14	0.03 ± 0.01	0.10 ± 0.09
2020	Rainy	10	0.39 ± 0.24	0.25 ± 0.20	0.01 ± 0.01	0.03 ± 0.01
2021	Rainy	20	24.85 ± 30.97	3.61 ± 2.01	3.11 ± 1.49	4.18 ± 2.85
2021	Dry	20	0.56 ± 0.26	0.31 ± 0.14	0.60 ± 0.27	0.18 ± 0.14
2022	Rainy	20	2.29 ± 0.83	0.67 ± 0.25	0.33 ± 0.13	0.46 ± 0.36
2022	Dry	19	0.08 ± 0.15	0.34 ± 0.08	0.63 ± 0.25	0.25 ± 0.07
Grouped		99	5.95 ± 16.77	1.06 ± 1.57	0.94 ± 1.31	1.03 ± 2.04

around centroids were estimated for each group (sampling field trip). Further, the pairwise correlation between elements was tested using the Pearson correlation (Quinn and Keough, 2002) in order to verify relationships among variables. Despite the high positive correlations (>0.85) observed for feather samples regarding nonessential elements (As, Hg, Pb and Cd) and Mn, all variables were kept in the PCA, as we were mostly interested in the potential relationships among contaminants.

To evaluate temporal and interspecific variations in each metal and As concentrations, generalized linear models (GLMs) were used. For this, analyses were performed separately by tissue, using Element Concentrations as response variables and Species, Field Trip, and the interaction Species:Field Trip as explanatory variables. Models were set using Gamma distribution and identity link function, and model assumptions were checked in residual plots (Kinas and Andrade, 2021; Quinn and Keough, 2002). Analysis of deviance tables with chi-square test were set for each GLM to identify significant effects of variables and compute the deviance percentages explained by each variable (Linhares and Bugoni, 2023). Furthermore, contrast analysis were applied with the "emmeans" package to evaluate pairwise differences between sampling campaigns for each species, separately by tissue, and the overall interspecific differences for each element (Lenth, 2023).

Intraspecific temporal differences in stable isotope values of δ^{13}C and δ^{15}N was accessed through Kruskal-Wallis test, and for pairwise-comparison between sampling field trips the Wilcoxon test was used. Isotopic niche estimates were based on standard ellipse areas adjusted for small sample sizes (SEAc), with 95% credible interval using the "SIBER" package (Jackson et al., 2011). The isotopic niche area overlap was estimated using maximum likelihood test (Jackson et al., 2011). All the above procedures on metal (loid) and stable isotope data were performed in R 4.0 (R Core Team, 2021).

3. Results

3.1. Metal and metalloid concentrations in seabird feathers

Table 1 provides metal and metalloid concentrations in seabird feathers. Multivariate results for metal and As concentrations in feathers of tropical seabirds revealed that the first component explained 71.5% of the metal content variance for red-billed tropicbirds (PC1 eigenvalue = 6.4) and 63.6% for the brown booby (PC1 eigenvalue = 5.7) (Fig. 1), with similar temporal patterns observed between species. In feathers of both species, samples collected in February 2021 (rainy season) were associated with high PC1 scores, related to increased concentrations of Fe, Mn, Cr, As, Cd, Hg and Pb. Indeed, apart from Fe and Cr, all these elements showed positive correlations among each other in both species, with correlation coefficients above 0.8, thus revealing simultaneous increases over time (Fig. S1). For red-billed tropicbirds, samples collected in March 2022 (rainy season) also had high PC1 values. For brown boobies, samples collected in February 2020 (rainy season) were distinguished with high PC2 values, associated to high values of Zn and Cu. In general, PCA results suggest that the other sampling field trips exhibited lower and more constant element concentrations.

GLM revealed that time (Field Trip) was the strongest explanatory variable for element concentrations in feathers of tropical seabirds, explaining a large proportion of deviance in data (Tables S1 and S2).

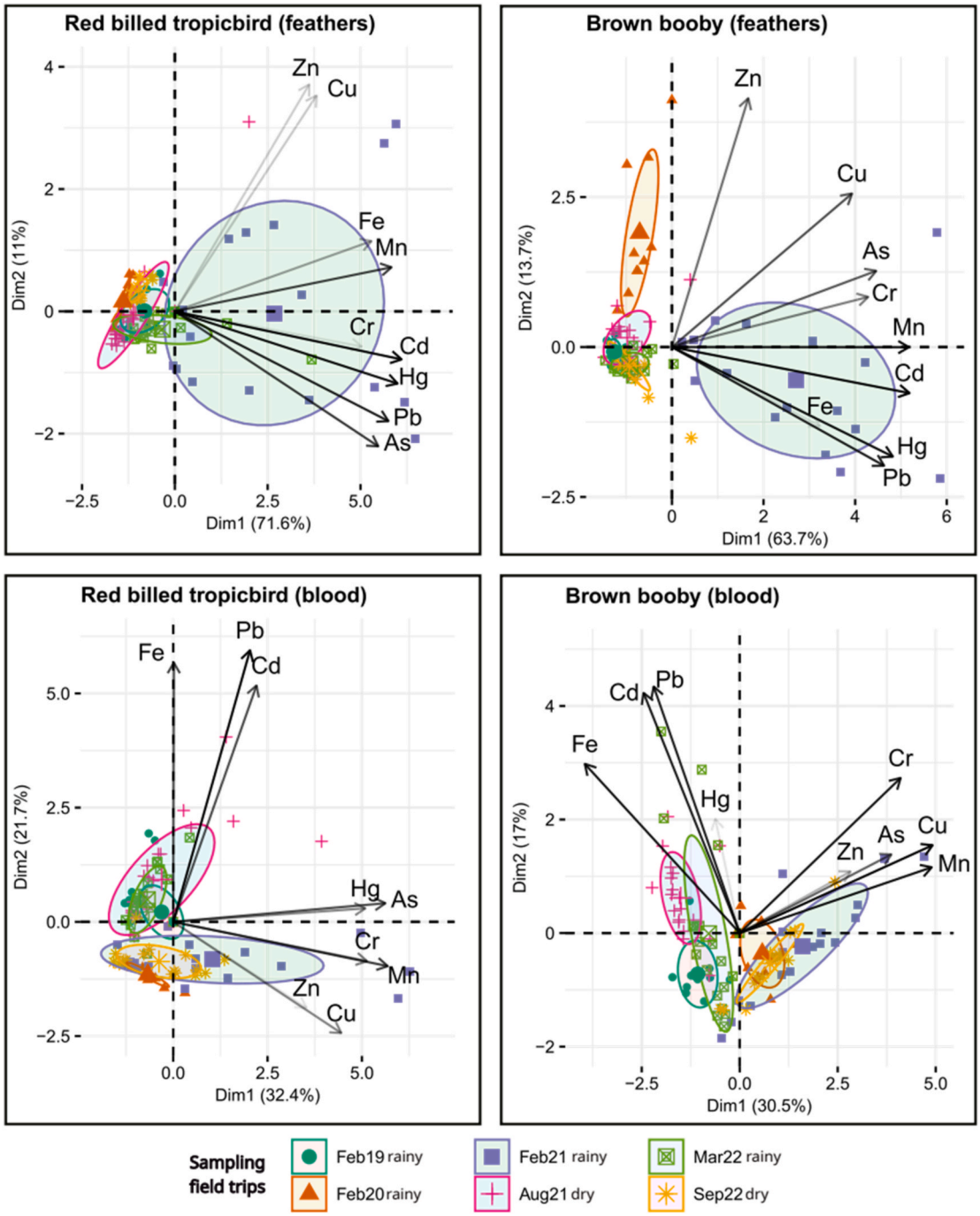

Fig. 1. Principal component analysis showing intraspecific variation in metal (loid) concentrations in feathers (upper pannels) and blood (lower pannels) of brown boobies *Sula leucogaster* (right pannles) and redbilled tropicbirds *Phaethon aethereus* (left pannels) from Abrolhos Archipelago, southwestern Atlantic Ocean. Ellipses represent the 75% confidence intervals around the group centroid of each sampling year. Arrows represent coefficients of the metal (loid) concentrations oriented along the first and second components.

Field Trip explained 26.5 and 42.6% of deviance for Fe and Zn, respectively, and 87.6% of deviance for Hg and 92.2% for Mn. The variable Species was significant ($p < 0.01$) only for Zn, for which it explained 5.4% of deviance in data. The interaction Species:Field Trip was significant for As, Cd, Cu, Hg and Zn, explaining up to 8.6% deviance for Cu. During the whole sampling period, all elements, except Zn, showed peaked concentrations in feathers of both species in February 2021 (Figs. 2 and 3), a level significantly greater ($p < 0.01$) than those obtained for samples collected in all other field trips for Mn, Cd, Hg and Pb for both species, and for As in brown boobies (Tables S3 and S4). For Cd, Cr, Hg, Mn and Pb, concentrations of samples collected in the first two field trips were low in comparison to those collected in most field trips (Figs. 2 and 3). Similarly, for Zn and Fe, few pairwise comparisons were significant for element concentrations in feathers (Tables S3 and S4). Furthermore, for feathers, the only significant difference between species, averaged among field trips, was observed for Zn, with higher values being found in brown boobies ($p = 0.003$).

3.2. Metal and metalloid concentrations in seabird blood

Table 1 provides metal and metalloid concentrations in seabird blood. PCA results for metal and As concentrations in blood of tropical

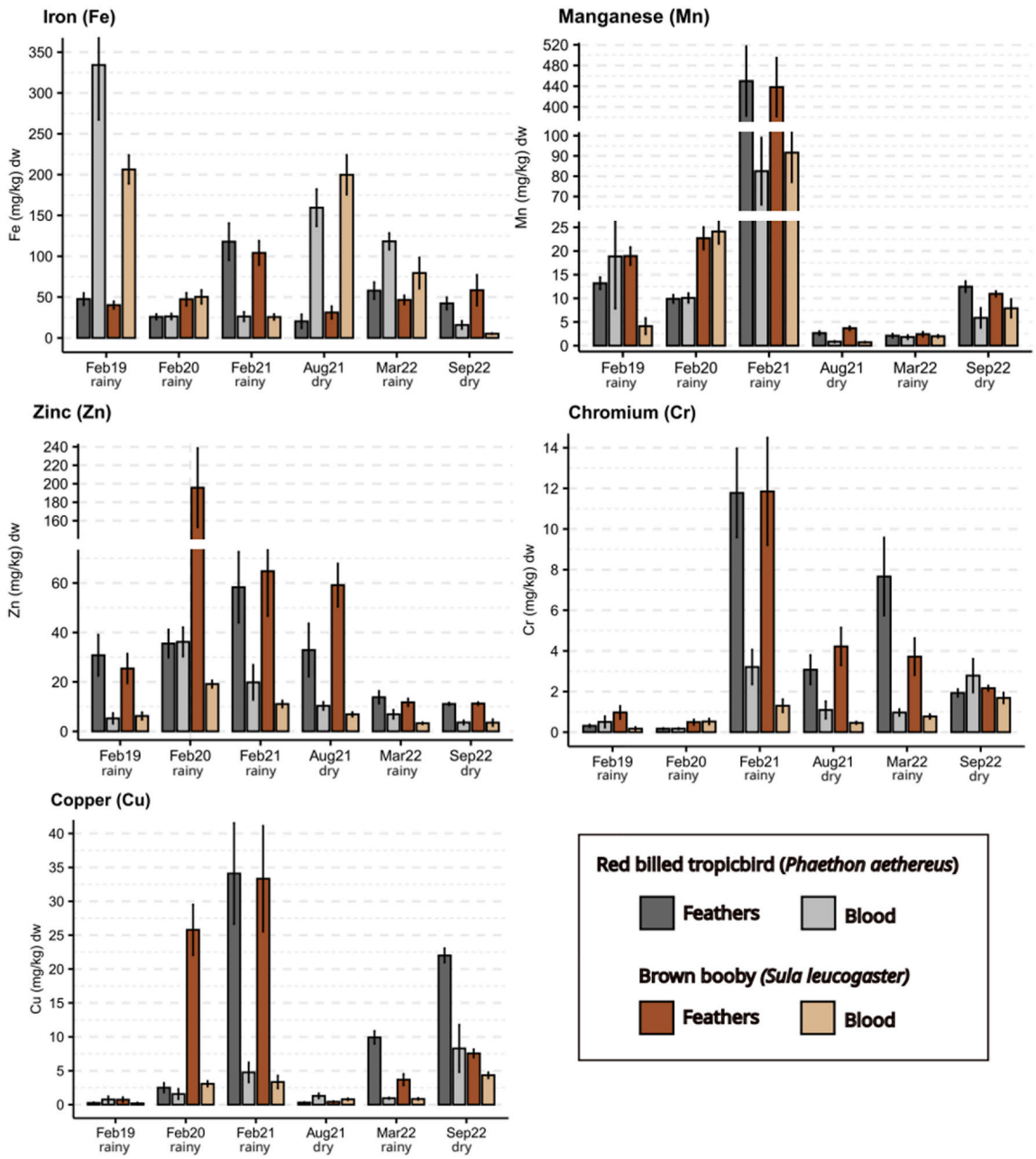

Fig. 2. Temporal variation in essential metals (Fe, Mn, Zn, Cr and Cu) in blood and feathers of red-billed tropicbirds *Phaethon aethereus* and brown boobies *Sula leucogaster* sampled in the Abrolhos Archipelago, Brazil. Bars represent means and standard errors. Note that the Y axis is not continuous for Zn and Mn.

seabirds revealed lower explanatory performance than for feathers, with the first component explaining 30–32% of the variance for red-billed tropicbirds and brown boobies (PC1 eigenvalue = 2.9 and 2.8, respectively). For blood of both species, temporal patterns were more diffuse, but samples collected in February 2021 (rainy season) were still associated with higher PC1 scores, related to increased concentrations of Mn and As (Figs. 1–3). Higher PC2 scores were related to increased concentrations of Fe, Cd and Pb for both species, and occurred mainly for samples collected in August 2021. Relationship among element concentrations in blood was weaker than for feathers, with no correlation coefficient higher than 0.85 detected (Fig. S1).

GLMs had lower explanatory performance for blood in relation to feathers, but for all elements the variable Field Trip was significant ($p < 0.01$) and explained from 25% of deviance for Hg, up to 65% for As and 73% for Mn (Tables S1 and S2). Explanatory performance was only higher in blood than feathers for Fe, with Field Trip explaining 59% of deviance for blood. The variable Species was significant ($p < 0.01$) only for Zn, with Field Trip explaining 5.4% of data deviance. The interaction Species:Field Trip was significant for As, Cr, Cd, Hg, Mn and Pb, and explained up to 20% of data deviance for Hg and 14% for Pb. Pairwise comparisons between sampling field trips were significant for blood, especially regarding the concentrations of Fe, Mn and the concentrations of the nonessential elements As, Cd, Hg and Pb for both seabird species (Tables S3 and S4). Between species, difference was significant ($p < 0.01$) for Cd, Cr, Hg and Pb concentrations, with greater values of Cd, Cr and Pb in the blood of red-billed tropicbirds, and greater values of Hg in the blood of brown boobies.

3.3. Intra- and interspecific variation of stable isotopes values

A total of 355 blood samples were used for the stable isotopes analysis. Stable isotope values of $\delta^{13}C$ (Kruskal-Wallis, chi-squared =

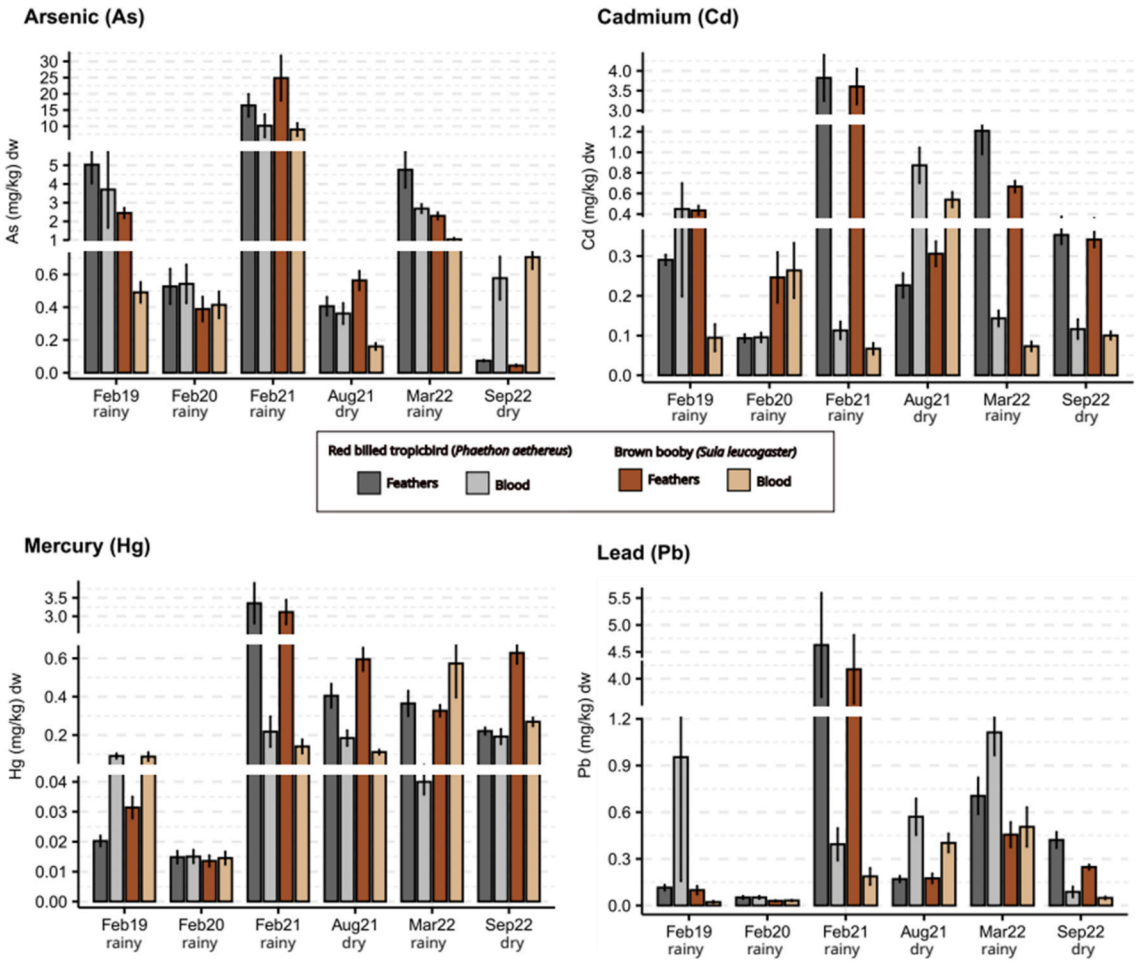

Fig. 3. Temporal variation in nonessential metals (Cd, Hg and Pb) and arsenic (As) in blood and feathers of red-billed tropicbirds *Phaethon aethereus* and brown boobies *Sula leucogaster* sampled in the Abrolhos Archipelago, Brazil. Bars represent means and standard errors. Note that the Y axis is not continuous.

Table 3
Stable isotopes values (δ^{13}C and δ^{15}N, in ‰) of brown boobies *Sula leucogaster* and red-billed tropicbirds *Phaethon aethereus* from Abrolhos Archipelago, southwestern Atlantic Ocean. SEA_c = standard ellipse areas adjusted for small sample sizes; sd = standard deviation.

Species/Year	Season	*n*	δ^{13}C (‰)		δ^{15}N (‰)		SEA_c
			Mean	sd	Mean	sd	
Brown boobies							
2019	Rainy	12	−17.12	0.48	10.29	0.85	1.18
2020	Rainy	20	−17.39	0.30	12.60	2.01	2.00
2021	Rainy	20	−17.32	0.29	9.41	1.35	1.27
	Dry	20	−18.20	0.41	11.76	0.76	0.99
2022	Rainy	20	−18.50	0.44	10.9	0.44	0.56
	Dry	20	−17.79	0.21	12.26	0.49	0.33
Red-billed tropicbirds							
2019	Rainy	25	−17.35	0.41	9.97	1.02	1.20
2020	Rainy	26	−17.51	0.32	11.13	0.45	0.40
2021	Rainy	16	−17.46	0.16	9.19	0.96	0.51
	Dry	30	−18.30	0.43	9.98	0.89	1.17
2022	Rainy	19	−18.28	0.36	8.72	1.24	1.01
	Dry	17	−17.71	0.31	9.95	0.93	0.78

75.65; df = 5; $p < 0.01$) and δ^{15}N (Kruskal-Wallis, chi-squared = 71.78; df = 5; $p < 0.01$) in blood of brown boobies varied significantly across sampling field trips. The post hoc Wilcoxon test identified significant difference in δ^{13}C among all sampling field trips for brown boobies, except between 2020 and 2021 rainy seasons (Table S5). Such differences correspond to a maximum of 1.3‰ in the δ^{13}C mean values between the sampled groups (Table 3). Significant differences in δ^{15}N values among all sampling field trips were identified for brown boobies, except between 2020 and 2021 rainy seasons (Wilcoxon, $p = 0.06$), and between 2020 and 2022 rainy seasons (Wilcoxon, $p = 0.05$) (Table S5). The highest δ^{15}N mean value was observed in 2020 rainy season (12.60 ± 2.01‰) and more ^{15}N-depleted samples in the 2021 rainy season (9.41 ± 1.35‰) (Table 3).

For red-billed tropicbirds, significant differences between sampling field trips were found for both δ^{13}C (Kruskal-Wallis, chi-squared = 78.55; df = 5; $p < 0.01$) and δ^{15}N values (Kruskal-Wallis, chi-squared = 57.22; df = 5; $p < 0.01$) over the sampling period. Mean δ^{13}C values varied between −18.30 ± 0.43‰ and −17.35 ± 0.41‰ (Table 3). Significant differences in δ^{13}C values were detected in all sampling field trips (Wilcoxon, $p < 0.04$) (Table S5). Mean δ^{15}N values of red-billed tropicbirds ranged from 8.72 ± 1.24 to 11.13 ± 0.45‰ (Table 3). The δ^{15}N values of samples collected in 2020 rainy season significantly differed from all other groups of samples (Wilcoxon, $p < 0.01$) (Table S5).

The widest isotopic niche widths (SEAc) for brown boobies were recorded in the 2020 rainy season (2.00‰^{2}), while for red-billed tropicbirds it was estimated for 2019 rainy season (1.20‰^{2}; Table 3; Fig. 4). For brown boobies, the niche width seems to decrease over time (Table 3). Based on pairwise comparisons using maximum likelihood test, high temporal isotopic niche overlaps were estimated throughout the sampling period for both species (Fig. 4; Table 4). The higher niche overlaps of brown boobies were recorded between the 2022 and 2021 dry seasons, as well as the 2022 dry and 2020 rainy seasons, for which

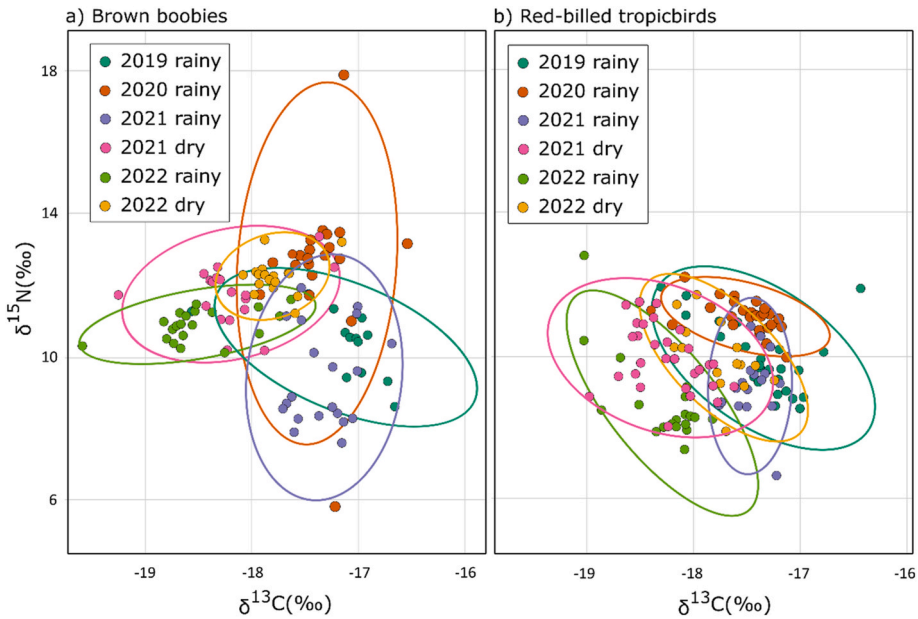

Fig. 4. Standard ellipse areas adjusted for small sample sizes (SEAc; 95% confidence limit) of brown boobies *Sula leucogaster* (a) and red-billed tropicbirds *Phaethon aethereus* (b) from Abrolhos Archipelago, southwestern Atlantic Ocean.

Table 4
Intraspecific and interspecific isotopic niche overlap (%) of brown boobies *Sula leucogaster* and red-billed tropicbirds *Phaethon aethereus* from the Abrolhos Archipelago, southwestern Atlantic Ocean. Values refer to the overlap of the area of group A (rows) by group B (columns). Dry (d) and rainy (r) seasons are indicated after sampling year.

		Brown boobies						Red-billed tropicbirds					
		2019r	2020r	2021d	2021r	2022d	2022r	2019r	2020r	2021d	2021r	2022d	2022r
Brown boobies	2019r		61.4	29.1	60.0	15.8	17.7	77.2					
	2020r	36.3		22.8	42.3	14.8	8.1		19.0				
	2021d	34.6	45.9		20.3	33.4	45.7			49.6			
	2021r	56.0	66.8	15.9		7.4	7.1				40.3		
	2022d	56.1	89.4	100	28.1		33.0					35.5	
	2022r	37.2	28.7	80.5	15.9	19.4							43.6
Red-billed tropicbirds	2019r	78.5							33.5	38.5	34.0	57.4	8.4
	2020r		94.6					100		36.2	32.5	57.8	0
	2021d			42.0				39.5	12.4		21.4	45.7	56.5
	2021r				100			80.2	25.7	49.3		77.8	18.8
	2022d					15.2		88.9	30.0	69.2	51.2		20.8
	2022r						24.4	10.0	0	65.9	9.55	16.0	

the overlapped areas reached 100% and 89.4%, respectively (Table 4). For red-billed tropicbirds, the isotopic niche width of 2019 rainy season was the widest, and highly overlapped with other sampling periods, such as the 2020 rainy (overlap niche area = 100%), 2022 dry (88.9%) and 2021 rainy (80.2%) seasons (Table 4).

Interspecific isotopic niche overlap estimations were performed for each sampling field trip separately and also showed relatively high overlap in several cases (Table 4). Isotopic niches of brown boobies were highly overlapped with isotopic niches of red-billed tropicbirds during 2021 rainy (overlap niche area = 100%), 2020 rainy (94.6%) and 2019 rainy (78.5%) seasons (Table 4). On the other hand, niches of red-billed tropicbirds overlapped with brown booby niches mainly during the 2019 rainy (overlap niche area = 77.2%) and the 2021 dry (49.6%) seasons (Table 4; Fig. 4).

4. Discussion

In the present study, temporal changes in bioaccumulation patterns of eight metals and one metalloid were observed in the blood and feathers of two tropical seabirds foraging in the marine area impacted by the Fundão Dam failure over four years. Our results suggest the occurrence of acute contamination events, demonstrated by the peak in values of all nonessential elements (As, Hg, Cd, Pb) analyzed in seabird feathers collected in February 2021. This occurred one year after a major rainy season (2020) in the Doce River basin that increased river discharge and matter transport, likely remobilizing contaminated sediments from the Fundão Dam failure into the ocean (RRDM, 2021). Indeed, our findings in seabird tissues are consistent with patterns found in metal concentrations and/or biomarker responses of several ecosystem compartments monitored after the dam failure, such as seawater, beach sediments, marine zooplankton, corals, shrimps, fishes, beach invertebrates and estuarine birds (Costa et al., 2022; Marques et al., 2022; RRDM, 2021; Vieira et al., 2022). The combination of these findings, from plankton to seabirds, raise concerns regarding the whole-ecosystem impacts even six years after the dam collapse, highlighting the need for the continued monitoring of toxicological impacts in the aquatic biota.

For both feathers and blood of seabirds, the influence of temporal changes on metal (loid) concentrations was stronger than interspecific differences, despite the differences in foraging ecology and at-sea distributions of boobies and tropicbirds (Mancini et al., 2014; Nunes et al., 2022). In body feathers, a concise temporal trend for the concentrations

of Fe, Mn and nonessential elements (As, Cd, Hg and Pb) was observed, revealing bottom-up processes influencing metal (loid) bioaccumulation in both seabird species monitored. Variation in Mn concentration was highly correlated to the concentration of nonessential elements in feathers over time. Since Mn was shown to be the second most abundant element in ore tailings from the Fundão Dam failure (Queiroz et al., 2018; Segura et al., 2016), the overall correlation between the concentration of Mn with those of nonessential elements may suggest the association of acute contamination events in seabirds to the dam failure in 2015. In turn, Cr, Cu, Fe and Zn concentrations varied more independently in feathers, with a lower influence of different sampling field trips, suggesting the metabolic regulation of the levels of these essential elements. It is worth noting that Fe is the only element with higher concentrations in blood than feathers, which further supports the involvement of metabolic regulation mechanisms, given that metals have high chemical affinity to feather proteins (Burger and Gochfeld, 2001).

Circulating blood levels of metal (loid)s exhibited more diffuse relationships among elements over time. Nonetheless, the PCA also revealed that blood samples collected in the 2021 rainy season had higher concentrations of some essential elements (i.e. Mn, Zn, Cu, Cr) and As, while other elements (i.e. Fe, Cd and Pb) characterized the second component of the PCA matrix and were associated with higher concentrations in samples collected in the subsequent field trip (August 2021). Circulating blood levels may be related to recent exposure or internal organ remobilization of metal (loid)s during specific metabolic periods such as fasting or breeding (Burger and Gochfeld, 2001; Furness, 1993), thus suggesting more nuanced variations than those observed in body feathers, which reflect metal body burden for a period of ca. 4 weeks (Burger and Gochfeld, 2001).

Differences in food habits and habitat use are among the main factors that promote interspecific differences in metal (loid) concentrations in marine organisms, including seabirds (Michelutti et al., 2010; Moura et al., 2018). The present study showed a relatively high isotopic niche overlap between the studied species and within species over time. Notwithstanding, although the brown booby and red-billed tropicbird colonies are sympatric in Abrolhos, their foraging areas differ (Nunes et al., 2022). While the brown booby uses shallower areas near the shoreline, red-billed tropicbird foraging range is wider along the Abrolhos Bank and the continental shelf slope. Such differences in habitat use can be associated with different food resources exposed to different pollutant levels. These ecological differences may explain, at least in part, the differences between the concentrations of metal (loids) observed between species monitored in the present study. The high isotopic niche overlap suggests similar isotopic baselines through space and time and therefore suggests that tropical seabirds are under similar bottom-up oceanographic processes, which helps to explain the similar patterns in metal (loid) concentrations over time and the absence of consistent interspecific differences.

Among birds, seabirds are known to be particularly tolerant to high levels of metals (Beyer and Meador, 2011). Nevertheless, seabirds have already been shown to be impacted by pollutants, such as the observed eggshell thinning associated with DDT pollution (Sparling, 2016). Negative effects caused by Hg in birds include reproductive output reduction, negative effects on immune, neurological and endocrine function, and behavior alterations (Whitney and Cristol, 2018). For example, decline in bird populations was associated to Hg exposure for long periods (Braune et al., 2006). In brown boobies sampled in Rio de Janeiro state, southward of Abrolhos and the Doce River, and in an area highly influenced by oil industry activities and large river discharges, Bighetti et al. (2021) reported Hg concentrations in feathers of juvenile and adult brown boobies of 1.65 ± 0.79 mg.Kg^{-1} d.w. and 2.68 ± 0.78 mg.Kg^{-1} d.w., respectively. In the present study, only the Hg values observed in feathers collected in 2021 were higher than those reported by Bighetti et al. (2021). In the Doce River and nearby estuaries, Zebral et al. (2022) reported values of Hg in estuarine birds sampled in 2018 and 2019, which were generally lower than those reported here, with the exception of birds from Aracruz (6.0 ± 1.98 mg.Kg^{-1}). Proposed thresholds for adverse effects in birds for Hg are 1–3 mg.Kg^{-1} in blood (Eagles-Smith et al., 2008; Evers et al., 2008) and 5.0 mg.Kg^{-1} in feathers (Burger and Gochfeld, 2001; Eisler, 1987). All Hg concentrations reported in the present study were within this range, thus adverse effects from Hg contamination solely are unlikely to occur.

Nonetheless, for Pb, suggested threshold values for adverse effects in birds are 0.2–0.5 mg.Kg^{-1} for blood (Blus et al., 1993; Franson and Pain, 2011; Sanderson, 1986) and 4 mg.Kg^{-1} for feathers (Burger and Gochfeld, 2001). Remarkably, values found here, in the blood of both seabird species monitored, were generally greater than this threshold for samples collected in most field trips, reaching up to 1.11 ± 0.64 mg.Kg^{-1} in red-billed tropicbirds collected in the 2022 rainy season. For the case of feathers, levels above the proposed threshold were only found in samples collected in the 2021 rainy season (4.63 ± 4.33 mg.Kg^{-1} for red-billed tropicbirds). Furthermore, Zebral et al. (2022) studied bird species feeding in the Doce River Estuary and reported Pb levels in blood that were very similar to those found in the present study. Additionally, those authors reported Pb concentrations in feathers that were as high as 1.5 mg.Kg^{-1}, a contamination level fairly lower than those found in the present study during the peak period. Together, these findings could suggest potential adverse effects in tropical seabirds associated with Pb contamination.

Regarding Cd in circulating blood, mean values reached 0.87 ± 0.83 mg.Kg^{-1} in red-billed tropicbirds during the 2021 dry period, being above the suggested levels for natural exposure (0.26 mg.Kg^{-1}) (Fenstad et al., 2017; Wayland and Scheuhammer, 2011). In feathers, suggested toxicity threshold for birds is 2 mg.Kg^{-1} (Burger and Gochfeld, 2009; Furness, 1993). Mean values reported in the present study for samples of red-billed tropicbirds and brown boobies collected in the 2021 rainy season were ca. 1.5 mg.Kg$^{-1,}$ above the toxicity threshold of 3.6–3.8 mg.Kg^{-1}. Remarkably, peak mean values of Cd for both feathers and blood of tropical seabirds in Abrolhos were consistently higher than observed from birds captured in the Doce River and nearby estuaries (Zebral et al., 2022). Sublethal effects of Cd in birds include growth retardation, anemia and testicular damage (Eisler, 1985). In mallard *Anas platyrhynchos* ducklings, altered blood chemistry and severe kidney lesions were developed after the supply of 20 ppm dietary Cd for 12 weeks (Cain et al., 1983), but an increase in avoidance behaviors was observed in young American black ducks (*Anas rubripes*) after parents were fed with only 4 ppm dietary Cd for four months before egg laying. Although potential effects of Cd contamination in tropical seabirds from Abrolhos were not assessed, Cd values reported here during the peak concentration event raise concerns on potential harmful effect on seabirds.

The highest concentrations of As in blood and feather samples were detected in samples collected in 2021. In feathers of brown boobies (24.85 mg.Kg^{-1}), the observed As concentrations are comparable to those found in feathers of a passerine bird, the great tit *Parus major* (23.35 mg.Kg^{-1}) from highly polluted terrestrial areas in Belgium (Janssens et al., 2001). Brown boobies stranded along the Rio de Janeiro coast (eastern Brazil) showed As concentrations of 2.20 ± 0.44 mg.Kg^{-1} and 2.03 ± 0.40 mg.Kg^{-1} in liver and muscle samples, respectively (Moura et al., 2018). Some studies have shown that As concentrations in liver are higher than those found in bird blood (Albert et al., 2008; Pendleton et al., 1995). In the present study, mean As concentrations in brown boobies and red-billed tropicbirds blood samples collected in 2021 are over four times higher than those detected in brown boobies liver from Rio de Janeiro (Moura et al., 2018). Furthermore, Sánchez-Virosta et al. (2015) suggested that polluted sites would present values lower than 10 mg.Kg$^{-1,}$ while Laine et al. (2021) showed that great tits exposed to As during early life stages may have fitness affected through changes in DNA methylation. Other effects observed in birds include the reduction of food consumption, decrease in egg production and body mass, as well as liver damage (Sánchez-Virosta et al., 2015). Therefore, the elevated levels of As found in seabirds monitored in the

present study are alarming, due to potential deleterious effects of this metalloid on birds.

Moreover, high Mn values were detected in blood and feathers in samples of both species collected in the rainy season of 2021. Remarkably, Mn concentrations were more than 400 times higher than those recorded in feathers of brown boobies from Rio de Janeiro (Padilha et al., 2018). For the best of our knowledge, the levels reported for Mn herein are among the highest reported for birds worldwide (e.g. Barbieri et al., 2010; Burger et al., 2008; Burger and Gochfeld, 2000; Durkalec et al., 2022). This suggests a potential influence of the contaminated sediment originated from the Fundão Dam, for which Mn may be used as a marker of the dam mud, given that this event caused increased levels of this element in several organisms (Costa et al., 2022), including other bird species (Zebral et al., 2022). Indeed, leaching tests and toxicological bioassays performed indicated that tailings and contaminated soils can pose risk of cytotoxicity and cause cellular DNA damage associated with the high potential of Al, As, Fe and Mn from the Fundão Dam tailings into the water (Segura et al., 2016). Although Mn is an essential element, high concentrations of this element has already been shown to negatively affect growth and behavior of the European herring gull *Larus argentatus* chicks (Burger and Gochfeld, 1995).

The potential event of acute contamination observed in 2021 in tropical seabirds from Abrolhos is supported by the consistently increased concentrations of all nonessential elements (As, Hg, Cd and Pb) simultaneously in seabird blood and feather. Mean values above threshold levels were reported for all these elements for both tissues during this period, pointing to a potential cumulative synergistic effect. The time of detection in seabird feathers suggests an effect of much intense raining period recorded in 2020 in the Doce River basin, which resulted in increased river discharge into the ocean (RRDM, 2021). Results from the Aquatic Biodiversity Monitoring Program (PMBA) obtained after the Fundão Dam failure indicated high metal concentrations in marine zooplankton in samples collected in the 2020 rainy season, suggesting an immediate response, and increased biomarker response levels in samples collected in the 2021 rainy season (Marques et al., 2022; RRDM, 2021). Marine fish, shrimps and corals from Abrolhos also showed increased biomarker responses in samples collected in the 2021 rainy season and, interestingly, estuarine birds from Doce River and nearby rivers also showed increased values at this period (RRDM, 2021; Zebral et al., 2022), showing a similar response to that observed for seabirds sampled in Abrolhos. All these evidences point to a bottom-up climatically-driven recontamination event that affected the entire river and marine ecosystems around the Doce River influence zone, thus suggesting the persistent impact from the huge mining disaster occurred in 2015.

After an acute impact, meteorological events may lead to remobilization of contaminants, raising their bioavailability and resulting in recontamination in the long-term (Hatje et al., 2017; Magris et al., 2019). Consequently, this chronic pollution phase can represent a high contamination risk for marine organisms and its effects are still poorly studied. Although some studies show the effects of high concentrations of individual metal (loid)s on the health of birds exposed, the synergistic effects of these pollutants are still poorly understood at population levels (Ma et al., 2022). Consequences could be deleterious at the population level in the short or medium term, especially for populations with low genetic diversity, as is the case for brown boobies (Nunes and Bugoni, 2018) and red-billed tropicbirds (Nunes et al., 2017) breeding in Abrolhos, the latter of which is categorized as 'Endangered' by the Brazil Environmental Ministry (MMA, 2022). This therefore highlights the importance of monitoring contaminant levels in seabird tissues (blood and feathers) as an effective non-destructive tool to measure temporal fluctuations in contaminants in marine food webs in response to anthropogenic sources. Here, feathers showed a stronger temporal pattern than blood, showing a clear response about one year after a major discharge of the Doce River to the ocean. This likely relates to feathers representing contaminant incorporation during the period of synthesis (ca. 4 weeks) as well as having chemical affinity to metals (Burger and Gochfeld, 2001), while blood circulating levels may be more sensitive to individual condition (e.g. recent food intake, breeding status). Moreover, we also show that Mn, a potential marker of the Fundão ore tailings, was correlated to As, Hg, Cd and Pb, suggesting the association of these major contaminants to tailings. Seabirds were therefore shown to incorporate contaminants up to six years after a major mining disaster, even breeding ca. 200 km away from the pollution source (Doce River estuary) and feeding offshore, highlighting whole-ecosystem impacts reaching marine apex predators.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118240.

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