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Mercury concentrations, habitat and trophic position of *Antimora rostrata* and *Macrourus holotrachys* from South Georgia (Southern Ocean)

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ABSTRACT

Mercury (Hg) is a neurotoxic element that can harm marine wildlife. Hg can reach the Southern Ocean through atmospheric and oceanic currents. However, data on Hg in Southern Ocean deep-sea fishes remain scarce. Our study assessed the influence of biological and ecological factors on Hg bioaccumulation in two deep-sea species, blue antimora (*Antimora rostrata*) and bigeye grenadier (*Macrourus holotrachys*), inhabiting the South Georgia region. Specifically, we aimed to: 1) analyse the habitat and trophic position of both species; 2) understand how Hg concentrations vary between tissues (muscle, brain, liver and gills); 3) evaluate how biological (length and weight) and ecological characteristics (trophic position ($\delta^{15}N$) and habitat ($\delta^{13}C$)) influence Hg concentrations. Muscle tissue had the highest Hg concentrations in both species, while the liver in *A. rostrata* and gills in *M. holotrachys* had the lowest. Overall, *A. rostrata* exhibited lower Hg concentrations (51.0 ± 9.0) than *M. holotrachys* (62.0 ± 11.0). No significant relationships were found between Hg concentrations and length, weight nor trophic position of *A. rostrata*. In contrast, *M. holotrachys* showed a positive relationship between Hg concentrations and habitat in all tissues, whereas for length and weight this positive relationship was observed in most tissues except the brain. *A. rostrata* is a pelagic feeder, whereas *M. holotrachys* mostly feeds near the sea bottom, highlighting how feeding strategy and habitat influence Hg bioaccumulation. It also reveals unexpected patterns of Hg distribution among tissues, particularly in the brain, where *M. holotrachys* exhibited one of the highest Hg concentrations.

1. Introduction

The Southern Ocean ecosystem is under several global threats, including the continuous influx of anthropogenic contaminants (Cossa et al., 2011; Constable et al., 2014; Szopińska et al., 2017). From these, mercury (Hg) is considered one of the most dangerous neurotoxic elements to wildlife (Miranda et al., 2007; Mieiro et al., 2009; Chu et al., 2019; Teixeira et al., 2020). Hg has a great dispersion capacity, enabling it to reach all regions of the globe, including the Southern Ocean (Lamborg et al., 2014). Among the different forms of Hg, methylmercury (MeHg), its main organic form in biota, is considered the most toxic to living organisms, due to its high liposolubility and high affinity with

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proteins (Miranda et al., 2007), bioaccumulating throughout the life of organisms (Polak-Juszczak, 2012), and biomagnifying along marine food webs including in the Southern Ocean (Gray, 2002; Polak-Juszczak, 2012; Seco et al., 2021). Therefore, long-lived top predators usually contain high concentrations of Hg (McIntyre and Beauchamp, 2007; Cherel et al., 2018; Seco et al., 2021). Hg accumulation in organisms depends on several biological and ecological factors such as length, age, sex, trophic position and feeding habitat (Havelková et al., 2008). Furthermore, tissue composition also influences the accumulation pattern of marine organisms, with previous studies showing significant differences in Hg concentrations across tissues of the same individual (Łuczyńska et al., 2016; Lopes-Santos et al., 2025). Therefore, a thorough understanding of the biology and ecology of marine species, including in the Southern Ocean, is important to understand Hg concentrations in marine food webs.

Studying inter-tissue Hg concentrations helps to understand bioaccumulation patterns and detoxification processes, as tissues accumulate Hg at varying rates (Polak-Juszczak, 2018). It can also serve as an environmental and ecological indicator, as variations between tissues may reflect different exposure pathways, feeding behaviours, and environmental contamination levels (Mieiro et al., 2012). Additionally, it helps reveal species-specific metabolism, since different species process and store Hg differently (Mieiro et al., 2012; Polak-Juszczak, 2018).

Within the Southern Ocean, South Georgia is considered one of the most productive regions due to its cold and nutrient-rich waters (Atkinson et al., 2001; Murphy et al., 2013). These waters support the development of large zooplankton biomass and provide habitat for vast colonies of top predators, such as seals and seabirds (Murphy et al., 2007). Additionally, it is considered a highly important region for the commercial fishing of Antarctic krill (*Euphausia superba*) and the longline fishery for Patagonian toothfish (*Dissostichus eleginoides*) (Atkinson et al., 2001; Collins et al., 2010).

The blue antimora (*Antimora rostrata*) and the bigeye grenadier (*Macrourus holotrachys*) are two common species in the Southern Ocean deep-sea (Gon et al., 2021), commonly caught as bycatch in South Georgia toothfish fisheries (Collins et al., 2010; Hollyman et al., 2022). They are present in the diet of several top predators, such as the Patagonian toothfish, seals and albatrosses (Morley et al., 2004; Xavier et al., 2004; Stevens et al., 2014; Queirós et al., 2024). Despite some similarities, these fish species present distinct biological and ecological characteristics: *A. rostrata* (Family: Moridae) is a cosmopolitan species that is found across all oceans, from shallow to deep waters (Cohen et al., 1990). In the Southern Ocean, *A. rostrata* can be found in the Scotia Sea, Ross Sea, Amundsen Sea and Weddell Seas (Orlov et al., 2020). It is a bathypelagic species, inhabiting between 350 and 3000 m (Cohen et al., 1990), slow-growing and long-lived species and can reach more than 60 cm in total length (Cohen et al., 1990). Additionally, *A. rostrata* presents a sexual dimorphism with females being larger than males (Horn and Sutton, 2015).

Macrourus holotrachys (Family: Macrouridae) is the most abundant macrourid species in many sub-Antarctic island's bycatches (McMillan et al., 2012; Romanelli, 2017). In contrast to *A. rostrata*, its distribution is limited to the Patagonian shelf and to the Southern Ocean, with its abundance decreasing further south (Hanchet et al., 2008; McMillan et al., 2012). It is a bathy-demersal fish species, being found between 200 and > 2000 m depth (Cohen et al., 1990; Laptikhovsky, 2005; Pinkerton et al., 2012). As adults, individuals of *M. holotrachys* can reach over 80 cm in total length and can be found living close to the seafloor, and present life-history traits of a deep-sea species (e.g. long lifespan and late maturation) (Morley et al., 2004; Laptikhovsky, 2005).

According to FishBase (Froese and Pauly, 2025), *A. rostrata* occupies a mid-trophic position (δ^{15}N: 3.6 ± 0.47) and feed mainly on mesopelagic and benthopelagic invertebrates, such as crustaceans and cephalopods, although small fishes are also part of its diet. In contrast, *M. holotrachys* is positioned slightly higher in the food web (δ^{15}N: 3.7 ± 0.64), reflecting its benthic feed habits, and preys predominantly on benthic invertebrates and small demersal fishes.

While information on the ecology of *M. holotrachys* in the Southern Ocean is limited, less is known about the ecology of *A. rostrata*. Filling this gap of scientific knowledge is crucial due to its importance as a prey species for top predators and as an important bycatch in toothfish fisheries (Horn and Sutton, 2015; Ñacari et al., 2022).

Despite their ecological importance and potential role as a Hg pathway to top predators in the Southern Ocean, only one study reported Hg concentrations in *A. rostrata* in the Southern Ocean (Hanchet et al., 2012), while no studies exist for *M. holotrachys*. Hg concentrations in *A. rostrata* muscle caught on the Ross Sea continental slope averaged 0.19 μg g^{-1} dw, ranging from 0. 04 to 0.68 μg g^{-1} dw (Hanchet et al., 2012). Furthermore, this study found that Hg concentrations increased with fish length, and were influenced by the location, with fish found further south exhibited lower Hg concentrations (Hanchet et al., 2012). Despite this study, major gaps remain regarding how Hg concentrations in *A. rostrata* are influenced by its biology and ecology, including in other Antarctic regions (other than the Ross Sea), as well as how these are distributed across the different tissues. Carbon stable isotopes (δ^{13}C) helps identify feeding habitats and primary productivity sources, distinguishing between coastal and offshore environments or pelagic and benthic regimes (Cherel and Hobson, 2007; Stowasser et al., 2012). Furthermore, stable nitrogen isotope analysis (δ^{15}N) provides a good insight into the biomagnification pattern of contaminants in a food web by determining the trophic position of species (Cabana and Rasmussen, 1994; Stowasser et al., 2012; Chouvelon et al., 2014). Within this context, this study aims to study the habitat, trophic position and Hg concentrations in *A. rostrata* and *M. holotrachys* in South Georgia (Southern Ocean). In detail, we i) investigate the feeding habitat and trophic ecology of both species; ii) examine Hg accumulation across different tissues (muscle, brain, liver and gills) in both species; iii) investigate which biological (i.e. length and weight) and ecological (i.e. habitat and trophic position) factors influence Hg bioaccumulation in these species. To evaluate which ecological factors influence the Hg concentrations in both species, stable isotopes of δ^{13}C and δ^{15}N were analysed in the muscle to determine the habitat and trophic ecology.

2. Materials and methods

2.1. Data collection

Individuals of *A. rostrata* ($n = 23$) and *M. holotrachys* ($n = 22$) were collected in June 2020 at South Georgia ((Commission for the Conservation of Antarctic Marine Living Resources) (CCAMLR) sub-Area 48.3) (Fig. 1) aboard the *FV Nordic Prince* during the longline Patagonian toothfish fishing season. It is important to note that samples were not randomly collected but to create a length gradient to ensure a range of individuals were represented in the analysis.

Total length (± 1 cm), standard length (SL) (± 1 cm), weight (± 0.05 Kg), sex and maturity stage (following Kock and Kellermann, 1991) were recorded for each individual of both species. After measurements, samples of muscle, brain, liver and gills were collected and preserved in individual plastic bags at −30 °C. In the laboratory, samples were freeze dried for 72 h at −50 °C and cut in to small pieces using stainless steel scissors.

2.2. Stable isotope analyses

Stable isotope analysis of δ^{13}C and δ^{15}N were performed on the muscle to allow comparisons with previous studies. Furthermore, the muscle provides a stable and representative isotopic signature of the fish's diet as it has a relatively low turnover rate, reflecting the diet over a longer time period than metabolically active tissues such as the liver.

Prior to analyses, between 22 and 28 mg of muscle samples were weighed in an identified glass tube and delipidated using three successive rinses with cyclohexane following Chouvelon et al. (2011). Briefly,

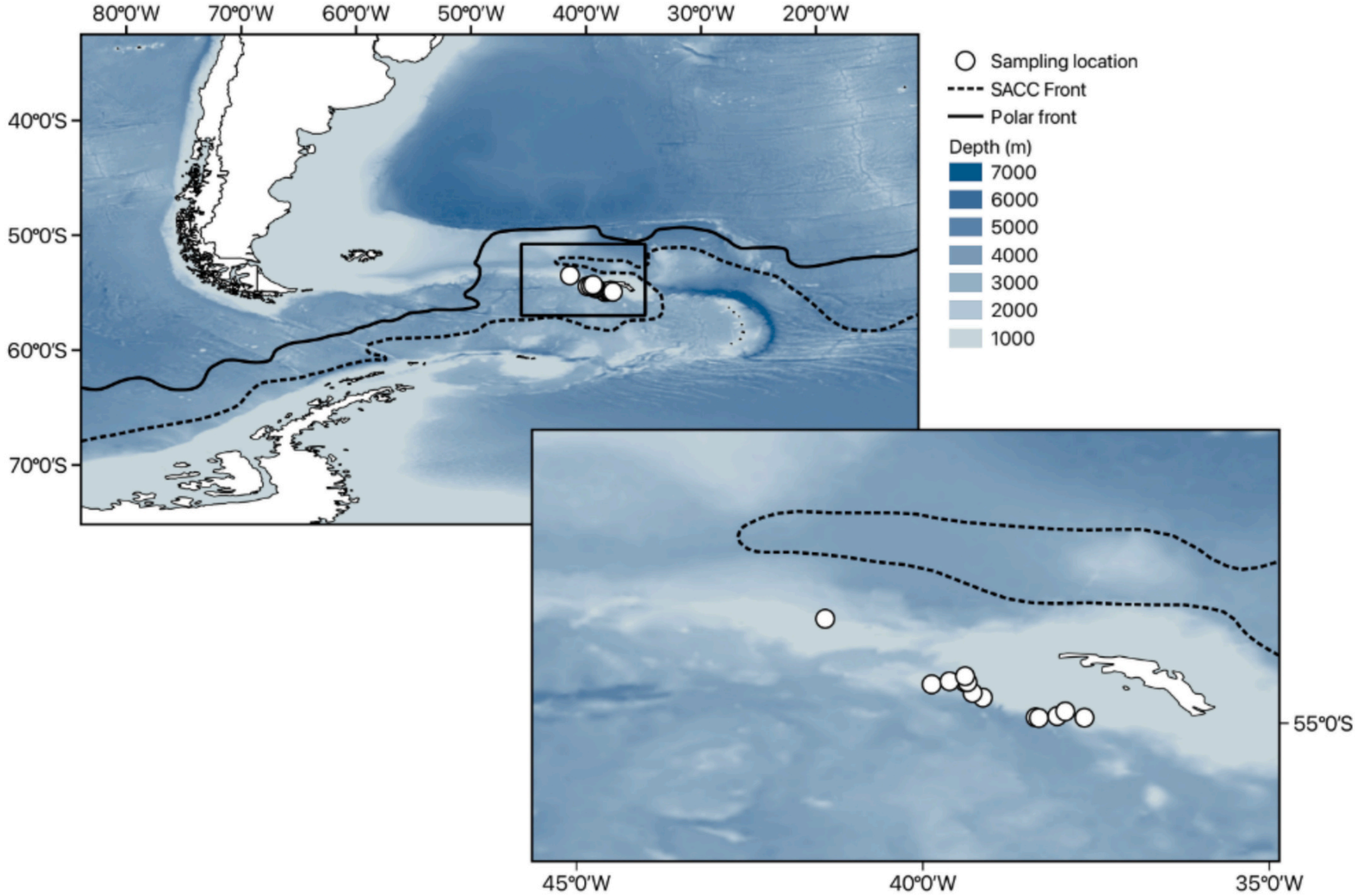

Fig. 1. Map of the study area. White dots represent the sampling locations. Solid line represent the Polar Front (PF) and the dotted line represent the Southern Boundary of the Antarctic Circumpolar Current (SBACC).

glass tubes were shaken for 10 min at approximately 1000 rpm with 4 ml of cyclohexane and then centrifuged for 5 min at 4500 rpm. The supernatant containing the lipids was discarded. After delipidation, all samples were dried overnight in an oven at 45 °C. Delipidation was performed because the presence of lipids influences δ^{13}C values and different species have different lipid contents. Therefore, delipidation allows the comparison between individuals and species with different lipid content. After drying, between 0.2 and 0.4 mg of muscle was weighed in a tin capsule using a Mettler Toledo microbalance. Carbon and nitrogen stable isotope values were measured using a Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS) coupled to an elemental analyzer (Thermo Scientific EA Flash®). Isotope data were calculated using the following equation:

$$\delta^{13}\text{C or } \delta^{15}\text{N (‰)} = \left(\left(\text{R}_{\text{sample}}/\text{R}_{\text{standard}}\right) - 1\right) \times 1000$$

where R is ^{13}C/^{12}C or ^{15}N/^{14}N. Isotopic results are presented in delta notation (δ in *per mil*, ‰) relative to Vienna PeeDee Belemnite and atmospheric nitrogen (N_2) for δ^{13}C and δ^{15}N, respectively. Quality control was assessed using two certified reference materials: USGS-61 (caffeine) and USGS-63 (caffeine). The analytical precision was <0.04 ‰ for δ^{13}C and < 0.06 ‰ δ^{15}N.

2.3. Mercury analyses

Hg analyses were performed on all tissues (muscle, brain, liver and gills). Concentrations of total Hg (hereafter Hg) were determined by atomic absorption spectrophotometry with thermal decomposition and gold amalgamation using an Advanced Mercury Analyzer (AMA) LECO® 254 (Costley et al., 2000) with a limit detection of 0.01 ng. Analytical quality control was performed using the certified reference materials DORM-4 ($n = 10$; fish protein Hg = 0.41 μg g^{-1}) with a recovery of 96.0 ± 7.8 % and TORT-3 ($n = 11$; lobster hepatopancreas Hg = 0.29 μg g^{-1}) with a recovery of 95.9 ± 9.3 %. Hg concentrations were further expressed in μg g^{-1} relative to the dry weight.

2.4. Data analyses

All statistical analyses were performed using GraphPad Prism 8 and considering alpha at 0.05. The normality of all study variables was first tested using the Shapiro-Wilk test. δ^{13}C and δ^{15}N values for both species followed a normal distribution ($p > 0.05$) and were therefore treated as parametric variables. For Hg concentrations, muscle and brain tissues of *A. rostrata* followed a normal distribution ($p = 0.49$ and $p = 0.08$, respectively), while gills and liver ($p = 0.05$ and $p = 0.04$, respectively), and all tissues of *M. holotrachys* ($p < 0.0001$) did not follow a normal distribution. Accordingly, parametric tests were applied to δ^{13}C and δ^{15}N values, whereas non-parametric tests were used for most Hg data.

For stable isotope analyses, a *t*-test was performed to compare the δ^{13}C and δ^{15}N values between the two species. Furthermore, a relationship between the biological variables (standard length and weight) and δ^{15}N values and also between the biological variables and δ^{13}C values, were conducted to get some information about the bioaccumulation patterns and habitat use, respectively, for both species.

For comparisons of Hg concentrations across tissues within each species, a Friedman test was applied because the four tissues were measured in the same individuals, thus representing repeated and paired measurements. When significant results were obtained, a Nemenyi post hoc test was used to identify differences between tissues. To compare Hg concentrations between the two species for each tissue, a Mann-Whitney tests were performed. To test Hg bioaccumulation in these species, we modeled the length/weight–Hg relationship using a Lognormal approach, fitting a Gaussian linear model on the log scale: $\log(\text{Hg}) = \alpha + \beta\log(\text{SL or Weight}) + \varepsilon,\ \ \varepsilon \sim N(0, \sigma 2)$, where $\alpha\alpha$ is the intercept and β is the allometric exponent. Assumptions were checked on the log scale. These statistical analyses were performed in R (version 4.5.1; R Core Team, 2025). Finally, a linear regression was performed for each species to test relationships between Hg concentration and the δ^{15}N values in the muscle.

3. Results

3.1. Habitat use and trophic position of *A. rostrata* and *M. holotrachys*

Standard length of *A. rostrata* ranged from 32 to 62 cm and weight from 0.34 to 1.34 kg, while *M. holotrachys* had a standard length ranging from 40 to 82 cm and a weight ranging between 0.40 and 2.80 kg (Table 1).

Significant differences were found in δ^{13}C and δ^{15}N values between the two species (δ^{13}C: $t = 9.36, p < 0.0001$; δ^{15}N: $t = 13.90, p < 0.0001$), with *A. rostrata* presenting lower δ^{13}C (1.74 ‰) and δ^{15}N (2.52 ‰) values than *M. holotrachys* (Fig. 2; Table 1). No significant relationships were found between standard length and both δ^{13}C ($p = 0.072$) or δ^{15}N values ($p = 0.676$) in *A. rostrata*, as well as no significant relation with weight (δ^{13}C: $p = 0.073$; δ^{15}N: $p = 0.544$). Regarding *M. holotrachys*, a significant relationship was found between standard length and δ^{13}C values ($p = 0.021$; $r^2 = 0.239$; $\delta^{13}\text{C} = 0.03205\text{SL} - 22.93$) and between weight and δ^{13}C values ($p = 0.026$; $r^2 = 0.223$; $\delta^{13}\text{C} = 0.4867\ \text{W} - 21.61$). No relationship was found between standard length or weight and δ^{15}N values ($p = 0.159$ and $p = 0.137$, respectively) in *M. holotrachys*.

3.2. Inter-tissue specific Hg accumulation in *A. rostrata* and *M. holotrachys*

Hg concentrations in the tissues of *A. rostrata* decreased in the following order: muscle > brain > gills > liver (Table 1). Significant differences were found for Hg concentrations in *A. rostrata* between tissues ($p < 0.0001$), with multiple comparison test showing significant differences between all tissues (muscle/gills; muscle/liver; brain/liver: $p < 0.0001$; brain/gills: $p < 0.05$), except muscle/brain ($p = 0.1520$) and gills/liver ($p = 0.090$) (Fig. 3).

Regarding *M. holotrachys*, Hg concentrations in the tissues decreased in the following order: muscle > brain > liver > gills (Table 1). Significant differences were also found for Hg concentrations in *M. holotrachys* tissues ($p < 0.0001$), with multiple comparison test showing significant differences between all tissues (muscle/gills and muscle/liver: $p < 0.0001$; brain/gills: $p = 0.0008$; brain/liver: $p = 0.0003$), except muscle/brain ($p = 0.7743$) and gills/liver ($p > 0.9952$) (Fig. 3).

Significant differences were found for Hg concentrations between all tissues of the two studied species (muscle: $U = 64$; $p < 0.0001$; brain: $U = 80$; $p < 0.0001$; liver: $U = 27$; $p < 0.0001$; gills: $U = 75$; $p < 0.0001$). Hg concentrations in *A. rostrata* tissues were lower than concentrations in *M. holotrachys* tissues, i.e. 2-fold in muscle, 3-fold lower in the brain, 9-fold in liver and 4-fold in gills (Table 1).

3.3. Hg bioaccumulation in relation to biological factors in *A. rostrata* and *M. holotrachys*

No significant relationships were found between Hg concentration and either standard length or weight in any tissue of *A. rostrata*. In contrast, *M. holotrachys* exhibited significant positive relationships between Hg concentrations and both standard length and weight in most tissues,except for the brain, which showed no significant relationships with either variable (Table 2).

No significant relationship was found between Hg concentrations in the different tissues and the δ^{15}N values in both species (*A. rostrata*: muscle: $p = 0.259$; brain: $p = 0.962$; liver: $p = 0.958$; gills: $p = 0.063$; *M. holotrachys*: muscle: $p = 0.132$; brain: $p = 0.056$; liver: $p = 0.219$; gills: $p = 0.070$).

4. Discussion

To the best of our knowledge, this is the first study assessing Hg concentrations in *M. holotrachys* in the South Georgia. Using stable isotopes and Hg analysis, we found that *A. rostrata* occupies a lower trophic position and forages more in the pelagic environment than *M. holotrachys* which is a demersal feeder, resulting in consistently lower Hg concentrations. Only *M. holotrachys* showed length-related Hg accumulation, likely reflecting age-related bioaccumulation and potential dietary shifts with growth. These finding highlight the role of species-specific ecology in shaping contaminant exposure in deep-sea environments.

A. rostrata and *M. holotrachys* presented a limited range of lengths, with all individuals exceeding 32 cm and 40 cm, respectively, that suggest the sampled specimens were predominantly adults. This limited length variation may influence their ecological characteristics (habitat use, feeding behaviour, trophic position) and Hg bioaccumulation patterns observed in our study.

4.1. Habitat use and trophic position of *A. rostrata* and *M. holotrachys*

Our results, suggest that, despite captured in the same region, *A. rostrata* and *M. holotrachys* use different habitats. Lower δ^{13}C values of *A. rostrata* suggest that this species forage more in pelagic environments, whereas *M. holotrachys* is more associated with benthic habitats (Newsome et al., 2007). This result is supported by previous studies showing that *A. rostrata* is a bathypelagic species strongly connected to the copepod-based pelagic food web (Cohen et al., 1990; Stowasser et al., 2009), contrary to *M. holotrachys* which is a bathy-demersal species living closer to the seafloor and feeds essentially in ostracods, isopods, amphipods, decapods and polychaetes (Cohen et al., 1990; Laptikhovsky, 2005; Ñacari et al., 2022).

However, our results contrast with a previous study by Ñacari et al. (2023) in the Southeastern Pacific Ocean with *A. rostrata* exhibiting a more demersal foraging strategy ($\delta^{13}\text{C} = -18.9 \pm 0.2$ ‰) compared to *M. holotrachys* ($\delta^{13}\text{C} = -19.7 \pm 1.6$ ‰). These differences may be correlated to both geographic variation and/or body length differences between the two studies. Additionally, *A. rostrata* and *M. holotrachys*

Table 1

Number (overall and per sex), standard length, weight, mercury (Hg) concentrations in the analysed tissues and stable isotopic values of δ^{13}C and δ^{15}N in the muscle of *Antimora rostrata* and *Macrourus holotrachys* from South Georgia. Values are mean ± standard deviation (minimum - maximum). ♀ Females; ♂ Males.

Species	n			Standard length (cm)	Weight (kg)	Hg (μg g^{-1} dw)				δ^{13}C (‰)	δ^{15}N (‰)
	Total	♀	♂			Muscle	Brain	Liver	Gills		
Antimora rostrata	23	20	3	51.0 ± 9.0 (32.0–62.0)	1.4 ± 0.7 (0.2–3.1)	0.7 ± 0.2 (0.3–1.3)	0.6 ± 0.2 (0.2–1.2)	0.1 ± 0.1 (0.1–0.3)	0.2 ± 0.1 (0.1–0.6)	−22.6 ± 0.5 (−23.4 - -21.5)	10.5 ± 0.5 (9.5–11.6)
Macrourus holotrachys	22	17	5	62.0 ± 11.0 (40.0–82.0)	1.4 ± 0.7 (0.4–2.8)	1.8 ± 1.8 (0.7–9.2)	1.8 ± 2.0 (0.3–9.5)	1.5 ± 3.9 (0.2–18.7)	1.0 ± 1.4 (0.1–6.6)	−20.9 ± 0.7 (−22.4 - -19.4)	13.0 ± 0.7 (12.0–11.4)

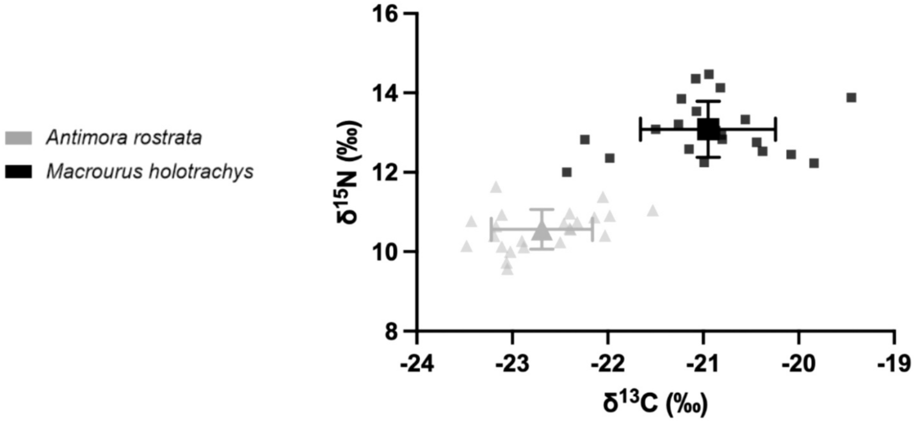

Fig. 2. δ^{13}C and δ^{15}N values in the muscle of *Antimora rostrata* ($n = 23$) and *Macrourus holotrachys* ($n = 22$) from South Georgia. Mean ± standard deviation.

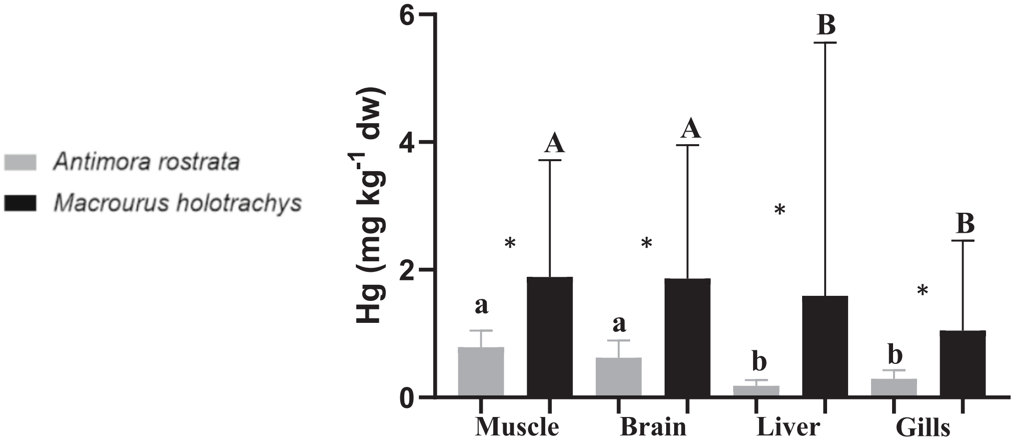

Fig. 3. Mercury concentrations (Mean ± 1 SD, μg g^{-1} dw) in different tissues (Muscle, Brain, Liver and Gills) of *Antimora rostrata* and *Macrourus holotrachys*. Different lowercase (for *Antimora rostrata*) and uppercase (for *Macrourus holotrachys*) letters above bars indicate significant differences among tissues in each species (Friedman test with Nemenyi post hoc test, $p < 0.05$). * between bars indicate differences between the same tissue in both species (Mann-Whitney test, $p < 0.0001$).

analysed in our study were, on average, larger (51.0 ± 9.0 and 62.0 ± 11.0 cm, respectively) than those reported by Ñacari et al. (2023) (48.9 ± 7.2 and 56.5 ± 6.3 cm, respectively). Environmental factors such as depth distribution, prey availability, and carbon sources differ across locations, potentially influencing the δ^{13}C signature of these species (Rodríguez-Malagón et al., 2021).

Regarding δ^{15}N values, our results showed that *A. rostrata* occupies a lower trophic position than *M. holotrachys*. Considering a trophic enrichment factor of 3.4 ‰ per trophic position, our results suggest that *A. rostrata* is positioned ≈0.75 trophic position lower than *M. holotrachys* in the South Georgia food web (Minagawa and Wada, 1984; Post, 2002). This pattern in consistent with Queirós et al. (2025), where they identified *A. rostrata* occupying the 4th trophic level and *M. holotrachys* the 5th trophic level reinforcing the distinct δ^{15}N values observed in our study. Studies of the diet of adult *A. rostrata* showed that they are opportunistic scavengers and mainly pelagic feeders, presenting a varied diet based on several taxonomic groups, although fish and squid make up the majority of their prey (Wenner and Musick, 1977; Mauchline and Gordon, 1986; Deng et al., 2011; Reid et al., 2013; Stowasser et al., 2009). In contrast, studies of the diet of adult *M. holotrachys* showed that they are mainly demersal feeders, feeding near the bottom, presenting a wide variety of vertebrates and invertebrates such as benthic and benthopelagic crustaceans, e.g. *Thymops birsteini*, *Notocrangon* sp., and benthopelagic fish, e.g. *Muraenolepis microps* and *Psilodraco breviceps* (McLellan, 1977; Morley et al., 2004; Laptikhovsky, 2005). Aside from the different diet and feeding strategies, the differences found in δ^{15}N values between the two species may also be attributed to the fact that benthic food webs are typically longer than pelagic food webs (Queirós et al., 2025). In longer food webs, energy assimilation losses are greater, requiring higher predators to consume more prey to get the same energy input. This not only reduces population stability but also increases the biomagnification of contaminants through the food web (Post, 2002b; Queirós et al., 2025).

According to FishBase (Froese and Pauly, 2025), the trophic positionsof *A. rostrata* (δ^{15}N: 3.6 ± 0.47) and *M. holotrachys* (δ^{15}N: 3.7 ± 0.64), estimated from food items, are very similar. These values are consistent with our stable isotope results, which revealed close but distinct δ^{15}N values. The similarity in trophic positions reported by FishBase also suggests that length-related differences, particularly in *M. holotrachys*, may play an important role in explaining the stronger length-Hg relationships observed in this species. Larger individuals may consume prey of higher trophic positions within the benthic food web, enhancing bioaccumulation patterns. In contrast, the more pelagic feeding behaviour of *A. rostrata* may result in a less pronounced relationship between size and Hg concentration.

Our results suggests that for *M. holotrachys*, length may influence δ^{13}C isotopic signature, possibly due to an ontogenetic shift in habitat use, where larger individuals may forage in different and/or deeper habitats or consume different prey. In contrast, the absence of a relation between length and δ^{13}C values may suggest that *A. rostrata* does not undergo a similar ontogenetic shift in habitat as it grows. Nonetheless, we need to be cautious as an ontogenetic shift in habitat may occur

Table 2

Summary of statistical relationships between mercury (Hg) concentrations and biological variables (standard length and weight) in different tissues (muscle, brain, liver, gills) of *Antimora rostrata* and *Macrourus holotrachys*.

Species	Tissue	Biological variable	*p*-value	r^2	Equation
Antimora rostrata	Muscle	SL	0.253	0.062	Hg = 0.11840 · SLˆ0.466
		Weight	0.311	0.049	Hg = 0.72805 · Wˆ0.108
	Brain	SL	0.165	0.094	Hg = 0.03474 · SLˆ0.713
		Weight	0.218	0.075	Hg = 0.55817 · Wˆ0.165
	Liver	SL	0.093	0.128	Hg = 0.00443 · SLˆ0.915
		Weight	0.15	0.096	Hg = 0.15652 · Wˆ0.206
	Gills	SL	0.397	0.034	Hg = 0.04439 · SLˆ0.453
		Weight	0.466	0.026	Hg = 0.25918 · Wˆ0.101
Macrourus holotrachys	Muscle	SL	0.029	0.216	Hg = 0.00288 · SLˆ1.522
		Weight	0.041	0.193	Hg = 1.370 · Wˆ0.467
	Brain	SL	0.105	0.132	Hg = 0.00156 · SLˆ1.638
		Weight	0.155	0.103	Hg = 1.191 · Wˆ0.466
	Liver	SL	0.014	0.265	Hg = 3.85e-06 · SLˆ2.943
		Weight	0.03	0.214	Hg = 0.58664 · Wˆ0.860
	Gills	SL	0.021	0.238	Hg = 4.19e-05 · SLˆ2.359
		Weight	0.028	0.22	Hg = 0.59399 · Wˆ0.737

before the fish reach the 32 cm in length. The lack of a relationship between length and $\delta^{15}N$ values in both species, suggests that these species may not change their trophic position throughout the studied life period. Similar to *A. rostrata* for $\delta^{13}C$ values, these results should be carefully analysed as ontogenetic shifts in diet, and consequently in trophic position, may occur earlier in the life cycle. This is supported by previous diet studies in *M. holotrachys* that showed that smaller individuals typically prey on smaller and different organisms, with dietary shifts life cycleas they grow and move to deeper habitats (Morley et al., 2004; Laptikhovsky, 2005; Pinkerton et al., 2012, 2013; Moore et al., 2022). Further studies are needed to fully understand the trophic ecology of *A. rostrata* in South Georgia.

4.2. Inter-tissue specific Hg accumulation in A. rostrata and M. holotrachys

The muscle was the tissue with the highest Hg concentrations in both species. Higher Hg concentrations in the muscle are linked to the affinity of Hg for thiols of the cysteine of proteins composing the muscle, leading to its preferential accumulation in this tissue in fish (Havelková et al., 2008). The muscle as the main tissue accumulating Hg was also observed for other fish species worldwide such as bonnethead (*Sphyrna tiburo*) and silky shark (*Carcharhinus falciformis*) (O'Bryhim et al., 2017), bird beak dogfish (*Deania calcea*) and smooth lanternshark (*Etmopterus pusillus*) (Teixeira et al., 2020) in the Atlantic Ocean, and the Atlantic cod (*Gadus morhua* L.) (Amlund et al., 2007). From an ecological perspective, the higher Hg accumulation in the muscle plays a significant role in food webs, as it highlights the potential for biomagnification through trophic position. As muscle is a key tissue for energy storage and is normally the largest tissue by mass of the animal, it has a big impact on the Hg burden that is transferred along the food web (from prey to predator). This underscores the importance of understanding Hg dynamics in tissues to assess the ecological risks posed by Hg exposure across food webs.

An unexpected result was the mercury concentrations in the brain, which were comparable to those in the muscle. The brain was the second most contaminated tissue in both species, which was surprising, as it typically considered one of the tissue with the lowest mercury accumulation. The higher Hg bioaccumulation in the brain may indicate that these species may experience significant neurological challenges, among other potential toxic effect of MeHg. These species could face impaired cognitive function, affecting their foraging capacities, predator avoidance, and overall survival (Weis and Candelmo, 2012). Additionally, Hg exposure may disrupt immunity, reproductive processes and potentially affecting population dynamics in the region, with long-term ecological consequences (Crump and Trudeau, 2009; Bera et al., 2022). Due to its critical role in organisms, marine organisms have evolved mechanisms to protect and prevent high concentrations of contaminants in the brain (Rouleau et al., 1999; Manceau et al., 2021). However, previous studies also found high concentrations of Hg in the brain of zebrafish (*Danio rerio*) raised in aquaria and in the golden mullet (*Liza aurata*) captured in Ria de Aveiro estuaries (Gonzalez et al., 2005; Mieiro et al., 2009). These studies found that MeHg is capable of crossing the blood-brain barrier by passive diffusion and by actively neutral amino acid transport systems due to its structural mimicry of methionine and the MeHg-cysteine complex (Gonzalez et al., 2005; Mieiro et al., 2009). It is possible that this mimicry process is present in our studied species, however, future studies will be necessary to understand the Hg bioaccumulation in the brain of *A. rostrata* and *M. holotrachys*.

Another possible explanation is based on a previous study that suggests that higher concentrations may still occur because of detoxification processes, particularly the sequestration of Hg as mercury-selenium complexes (HgSe) or Hg-selenocysteine complexes (Manceau et al., 2021).

Surprisingly, the liver, which is a tissue responsible for storage, redistribution, detoxification of Hg in vertebrates (Maršálek et al., 2007; Seco et al., 2020; Yamashita et al., 2005), presents the lowest Hg concentrations in *A. rostrata* and the second lowest in *M. holotrachys*. Rather than indicating rapid excretion, this pattern may reflect effective detoxification mechanisms that convert MeHg into less toxic forms, such as HgSe which are then sequestered and retained in other tissues or excreted at a later stage.

Studies in other vertebrates, including birds and mammals, have shown that detoxification often results in long-term storage rather than elimination, particularly in the form of insoluble compounds like tiemannite (mercury selenide granules) (Kojadinovic et al., 2007; Lailson-Brito et al., 2012). Although fewer studies exist for fish, emerging evidence suggests that similar processes may occur, with detoxification leading to internal sequestration rather than direct elimination (Siscar et al., 2014).

In *M. holotrachys*, the gills presented the lowest Hg concentrations among all studied tissues. The gills are usually responsible for the intake of some waterborne contaminants in fish (Marrone et al., 2021). While the gills are a primary site for the uptake of waterborne contaminants in fish (Marrone et al., 2021), their relatively low Hg content suggests that they do not serve as a major site of mercury accumulation. Instead, as observed in other species, most Hg is likely incorporated through dietary exposure and subsequently stored in internal tissues such as muscle and liver (Gonzalez et al., 2005; Hall et al., 1997).

Our results showed that *A. rostrata* presented lower Hg concentrations in all tissues compared to *M. holotrachys*. This difference was expected and can be explained either by the lower trophic position or the more pelagic distribution of *A. rostrata* in relation to *M. holotrachys*. However, the absence of relationship between Hg concentrations and $\delta^{15}N$ values suggests that biomagnification may not be the primary factor driving these differences, but the habitat use, as benthic food webs are generally enriched in Hg (Li et al., 2022).

4.3. Hg bioaccumulation and inferences on Hg biomagnification

Surprisingly, no relationships were found between either length or weight and Hg concentrations in *A. rostrata*. This may be explained by its feeding behaviour, i.e. an opportunistic scavenger (Reid et al., 2013). Therefore, *A. rostrata* may not present an ontogenetic shift in the diet which could lead to the absence of visible bioaccumulation if Hg incorporation decreases while growth continues, due to a tissue dilution effect (Sánchez-Hernández et al., 2019). It may also be related to habitat use and detoxification mechanisms. In contrast, Hg concentrations were positively related to the length and weight in most tissues of *M. holotrachys*, with the exception of the brain, where no significant relationships were observed. The largest and heaviest individual exhibiting the highest Hg concentration. This positive relationship could be explained by changes to higher trophic-level prey as it grows, leading to increased Hg bioaccumulation, with this pattern being reinforced by its benthic habitat. The absence of length- or weight-related patterns in the brain may reflect physiological regulation mechanisms, such as detoxification or protection of neural tissues.

The absence of a significant relationship between Hg concentration and δ^{15}N in both species could be explained by various ecological and physiological factors. In *A. rostrata*'s case, its opportunistic scavenging behaviour and association with the pelagic food web, could result in highly variable Hg exposure. Since scavenged prey may originate from different trophic positions and habitats, Hg accumulation may be influenced more by prey availability than by trophic position. In *M. holotrachys*, despite its association with demersal food web, where Hg concentrations are usually higher, the lack of correlation with δ^{15}N suggests that other factors, such as habitat use and physiological processes, i.e. Hg detoxification or excretion rates, may play a major role in determining Hg concentrations.

In terms of biomagnification, considering the Trophic Magnification Slope (TMS) equation proposed by Seco et al. (2021) for the pelagic food web in the Scotia Sea ($Hg = 0.2782 \times \delta^{15}\text{N} - 3.0960$), we expected an average Hg concentration of approximately 0.85 $\mu\text{g g}^{-1}$ dw for *A. rostrata*. Indeed, this value is similar to those measured here (0.79 ± 0.26 $\mu\text{g g}^{-1}$ dw), indicating that the biomagnification factor of this species fits in the pelagic food web of the Scotia Sea. In contrast, the expected Hg concentration for *M. holotrachys* would be of 1.72 $\mu\text{g g}^{-1}$ dw, which is slightly lower than our results (1.89 ± 1.83 $\mu\text{g g}^{-1}$ dw) and roughly twice as high as the of *A. rostrata*, suggesting that the Hg biomagnification factor of this species differs from those in the pelagic food web of this ecosystem. This was expected considering that this species is associated to the benthic food web (discussed above; Morley et al., 2004; Ñacari et al., 2022). However, we must be cautious as the standard deviation is relatively high and includes the expected value of Hg following this TMS (Seco et al., 2021). Further studies are needed to confirm this hypothesis.

5. Conclusion

In this study, we analysed stable isotopes of δ^{13}C and δ^{15}N in the muscle and Hg concentrations in 4 tissues (muscle, brain, liver and gills) of two Southern Ocean deep-sea fish species that, despite their important ecological role, remain poorly studied. Our results indicated that *A. rostrata* forage in the pelagic zone while *M. holotrachys* has a stronger association to the benthic habitat. Unexpectedly, high Hg concentrations were found in the brain in both species, challenging conventional assumptions about contamination patterns among tissues and raising the question of the neurotoxic effects and the detoxification processes involved to cope with potential damages due to MeHg. This suggests a potential vulnerability to Hg accumulation in this tissue in both species, possibly due to complex interactions with the blood-brain barrier and metabolic processes. Additionally, the contrasting Hg concentrations between tissues and species hint at differential dietary habits and possible detoxification mechanisms. However, it is worth highlighting that only adult individuals were analysed in this study. Future studies should also consider juvenile individuals to have a greater understanding of their patterns of accumulation along their life cycle. Overall, our study underscores the importance of further research into the ecological dynamics and contamination risks associated with these species.

CRediT authorship contribution statement

Diana Vaz: Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José P. Queirós:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **José C. Xavier:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Formal analysis, Conceptualization. **Paco Bustamante:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **José Abreu:** Writing – review & editing, Visualization, Validation, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Eduarda Pereira:** Writing – review & editing, Methodology. **Philip R. Hollyman:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Conceptualization. **João P. Coelho:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **José Seco:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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