# Tissue distribution and trophic magnification of trace elements in typical marine mammals in Bohai and north Yellow Seas

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## Abstract

A total of 20 stranded spotted seals (*Phoca largha*) and 9 stranded minke whales (*Balaenoptera acutorostrata acutorostrata*) were collected from Liaodong Bay and the northern part of the Yellow Sea to investigate the tissue distribution (liver, kidney, heart, lung, and muscle), risk, and trophic magnification of 13 trace elements (TEs, Hg, As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Se, Sn, V, Zn). The 13 TEs were all detected in all spotted seal and minke whale tissue samples, with mean concentrations ranging from 0.041-136.3 mg/kg dry weight (dw) and 0.022 to 152.6 mg/kg dw, respectively. Zn was the dominant contaminant in all tissues for both spotted seals and minke whales. There was tissue-specific distribution of TEs in both marine mammals, and the TEs tended to accumulate in internal organs. Significant positive correlations were found in the body length of the spotted seals and minke whales among some of the TEs, especially for Cd in the internal organs. Gender-dependent distribution of the TEs was not obtained for the spotted seal. Ecological risk evaluation for spotted seals and minke whales suggested that greater concern should be given to Hg, As, and Se. Based on the TE concentrations detected in this study and trophic levels determined by stable carbon and nitrogen isotopes, trophic level-associated biodilution was obtained for As, Cd, Co, Cu, Mn, Pb, Se, Sn, and V in the spotted seal, while Zn displayed a significant biomagnification trend with increasing trophic levels. In the case of the minke whale, As, Cd, Co, Mn, Pb, Se, and V displayed significant biomagnification trends with increasing trophic levels.

**Keywords**: spotted seal; minke whale; trace elements; trophic magnification; tissue distribution; risk evaluation

## 1 Introduction

Marine mammals such as cetaceans and pinnipeds are often considered sentinel species as their health and population changes can act as an indicator of the current or potential negative effects on the marine ecosystem (Hazen et al., 2019; Maxwell et al., 2013). Cetaceans and pinnipeds play an important role in maintaining the structure, composition, and function of marine ecosystems (Sanganyado et al., 2021). They regulate the spatiotemporal flow of mass and energy in the ocean and archive in their fat deposits critical trophic data from multiple spatiotemporal scales (Hazen et al., 2019). In addition, cetaceans and pinnipeds are long-term inhabitants of marine environments and long-lived apex predators which makes them susceptible to environmental threats such as marine pollution (Desforges et al., 2016). Therefore, understanding the impact of marine pollution on cetaceans and pinnipeds is important since a decline in their health and population may disrupt critical ecosystem functions and services of marine ecosystems.

Spotted seals (*Phoca largha*) and mink whales (*Balaenoptera acutorostrata acutorostrata*) are typical marine mammals that inhabit tropical, temperate, and polar regions (Burns, 2009; Risch et al., 2019). Spotted seals inhabit ice floes during the breeding season and open ocean or shores in the summer season. In contrast, mink whales breed throughout the year and do not have clear seasonal migration patterns like other baleen whales. Juvenile spotted seals feed on krill and crustaceans while adults feed on small schooling fish such as arctic cod, capelin, and herring (Burns, 2009). However, mink whales are opportunistic feeders that eat crustaceans, krill, plankton, and small schooling fish (Risch et al., 2019). The International Union for Conservation of Nature’s Red List of Threatened Species ranked spotted seals and mink whales as least concern, meaning they were at a low risk of extinction (IUCN, 2020). However, in China, spotted seals and mink whales are considered class-I protected animals because of increasing threats from climate change, habitat loss, poaching, noise, traffic, and marine pollution(Wang et al., 2021).

The Bohai and northern Yellow Seas in China are important habitats of spotted seals and mink whales. Of the eight known breeding grounds of spotted seals worldwide, Liaodong Bay, in northern parts of Bohai Sea, is the southmost and has hundreds of adults raising their cubs there during winter seasons (Hu et al., 2013; Wu et al., 2022). However, the Bohai Sea has several offshore oil platforms that often contribute to the discharge of anthropogenic pollutants in the ocean (Wang et al., 2022). High median concentrations of trace elements such as Cr (27.07 mg $kg^{-1}$), Cu (10.35 mg $kg^{-1}$), Zn (38.90 mg $kg^{-1}$), Pb (21.16 mg $kg^{-1}$), and As (9.78 mg $kg^{-1}$) were found in sediments from Liaodong Bay (Wang et al., 2020). Additional studies demonstrated that these trace elements accumulated in clams (Liu et al., 2020), oysters (Liu et al., 2021), and fish (Guo et al., 2016).

In spotted seals, Cd (0.09-2.18 mg $kg^{-1}$), Hg (0.10-2.62 mg $kg^{-1}$), and As (0.01-0.13 mg $kg^{-1}$) were found in the liver and Cd (7.76 mg $kg^{-1}$) and Hg (0.90 mg $kg^{-1}$) were found in the kidneys (Dehn et al., 2006a). Dehn et al. (2006) found that trace elements (TEs) had higher concentrations in the liver, lower in the muscle, and sex had no significant effect on TE distribution. The biomagnification factors of Hg were found to be higher than 1 in the liver and kidney of spotted seals, as well as those for renal Cd, indicating biomagnification of these two TEs in the internal organs in spotted seals. A recent study found that As, Hg, Se, Cd, and Pb widely occur in the meat of minke whales from the Northeast Atlantic Ocean, with concentrations ranging from 0.002 to 0.65 mg/kg wet weight, and Cd levels were found to increase with increasing body length (Maage et al., 2017). Hence, spotted seals and minke whales may accumulate TEs through the surrounding environment or food chain due to their long lifespan and high trophic level. However, there is a knowledge gap on the trophic magnification of TEs in spotted seals and minke whales and their food webs. Therefore, the objectives of this study were 1) to investigate the tissue distribution of TEs in spotted seals and minke whales, 2) to evaluate the risk of TEs on spotted seals and minke whales, and 3) to characterize the trophic magnification of TEs in the food web of spotted seals and minke whales. To the best of our knowledge, this is the first systemic study on the tissue distribution and trophic magnification of TEs in both spotted seals and minke whales, which could expand our knowledge on TE trophic transfer in marine mammals and their food chains.

## 2 Materials and Methods

### *2.1 Chemicals and reagents*

The TE standards were purchased from Perkin Elmer (PerkinElmer, USA). Rhodium (Rh) was purchased from O2Si (Charleston, SC, USA) and was used as an internal standard to overcome the matrix effect during detection. Nitric acid and hydrogen peroxide were UPS grade and were purchased from Jinrui (Suzhou Crystal Clear Chemical Co., Ltd, Suzhou, China). Certified reference material (CRM) TMQC0005 (BBS27) (salmon) was obtained from the National CRM Center of China. Milli-Q water was used throughout the study.

### *2.2 Sample collection and preparations*

A total of 20 individual stranded spotted seals and 9 stranded minke whales from Liaodong Bay and the northern part of the Yellow Sea were investigated in this study. Spotted seals and minke whales were collected from 2015 to 2020. Muscle, kidney, liver, heart, and lung samples were collected from stranded individual samples, while the prey items of marine mammals were collected between 2016 and 2017 in the same area

(38°28'8.86″ - 38°58'33.81″ N, 120°31'26.58 - 122°17'50.02″ E). The biological information of the collected samples was recorded according to the national standard method of China: Specifications for oceanographic survey - Part 6: Marine biological survey (GB/T 12763.6-2007, in Chinese). The biological information of the investigated marine mammals is given in Table S1 in the Supplementary materials (SM). The spotted seals and minke whales collected in Liaodong Bay, China, were authorized under the Ministry of Agriculture and Rural Affairs of the People's Republic of China, permit number: 1376. This study was conducted under a permit issued by the Liaoning Fisheries Administration Bureau, Liaoning Province, China (approval number: LSYXFZ20111105).

Approximately 0.3 g of the freeze-dried marine mammal tissue sample or food web sample was digested using 2 ml $H_2O_2$ and 5 ml $HNO_3$ by a microwave digestion system (YiYao, TOPEX 40, China) and then reconstituted in 10 mL with Milli-Q water. Before analysis, the samples were filtered with a 0.22 μm syringe-driven filter.

### *2.3 Trace elements analysis*

Analysis of TEs was performed according to the method described by Liu et al. (2018). Briefly, As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Se, Sn, V, and Zn were analyzed using ICP–MS (PerkinElmer, NEXION 300X, USA). Standard mode (STD) was applied to analyze Cd, Pb, and Sn, while As, Co, Cr, Cu, Mn, Ni, Se, V and Zn were determined by kinetic energy discrimination mode (KED). Hg was analyzed using an atomic fluorescence spectrometer (JiTian, AFS-921, China). The settings of ICP–MS were as follows: RF power 1200 W, plasma gas (argon) flow rate 15 L/min, nebulizer gas flow rate 0.94 L/min, analog stage voltage -1900 V, pulse stage voltage 950 V, scan mode peak hoping, MCA channels 1, dwell time 50 ms, integration time 1000 ms, and readings were taken as triplicates. The main parameters for the atomic fluorescence spectrometer were a lamp current of 30 mA, photomultiplier tube voltage of 270 V, reading time of 7 s, and delay time of 0.5 s.

### *2.4 Trophic level determination*

Stable carbon and nitrogen isotopes of the selected marine mammals and other organisms were detected using an isotope ratio mass spectrometer (Delta V Advantage, Thermo, USA) in our previous study (Tian et al., 2018), and the results and abbreviations are shown in Table S2 in the SM. Trophic levels (TL) were calculated using the following equation (Sham et al., 2020), and the results are given in Table S2:

$$TL_{consumer} = 2 + (\delta^{15}N_{consumer} - \delta^{15}N_{baseline})/TEF$$

where $\delta^{15}N_{consumer}$ is the $\delta^{15}N$ value of the investigated organisms in this study (Table S2), $\delta^{15}N_{baseline}$ is the $\delta^{15}N$ value of adductor muscle of Chlamys farreri, 5.8‰, and TEF is the trophic enrichment factor, 3.4‰.

### *2.5 Trophic magnification factor calculation*

The following formulas were used to calculate the trophic magnification factor (TMF) of the TEs in the marine food web (Sham et al., 2020):

$$Log_{10}[TE] = a + b \times TL$$

$$TMF = 10^{b}$$

where [TE] is the concentration of the element in the prey item and muscle of the spotted seal or minke whale (mg/kg dw); TL is the trophic level; and b is the slope of the regression equation.

### 2.6 Risk assessment

The molar ratio of Se/Hg was calculated using the following formula:

$$Se/Hg = (C_{Se}/78.96)/(C_{Hg}/200.59)$$

where $C_{Se}$ and $C_{Hg}$ are Se and Hg concentrations in the same tissue, and 78.96 and 200.59 are the atomic weights of Hg and Se, respectively. For risk evaluation, the reference dose (RfD) and toxicity reference value (TRV)-based risk quotient (RQ) were employed in this study, and the maximum allowable concentration (MAC) was calculated using the formulas below (Hung et al., 2004):

$$MAC_{RfD} \text{ or } MAC_{TRV} = (RfD \text{ or } TRV \times BW \times AT)/(IR \times FI \times EF \times ED)$$

$$RQ = C_{TEs}/ MAC_{RfD} \text{ or } MAC_{TRV}$$

Where BW is body weight of spotted seal or minke whale, 100 or 3000 kg in this study; AT represents average time, 14600 days (365 day/year × 40 years) for spotted seal and 18250 (365 day/year × 50 years) for minke whale, respectively; IR is ingestion rate, 5 and 150 kg/day (5% of body weight), respectively for spotted seal and minke whale; FI is fraction ingested from pollution source, 0.9; EF is exposure frequency, 365 day/year; ED is exposure duration, 40 and 50 years, respectively for spotted seal and minke whale. The RfD values were cited from the USEPA in the Integrated Risk Information System (http://www.epa.gov/iris). The TRV values used in this study were calculated by the no observable adverse effect level (NOAEL) obtained on test mammals (rat, mouse, and mink) reported by Sample et al (1996) and were calculated using the following formula (Hung et al., 2004):

$$TRV = NOAEL_t \times (BW_t/BW_r)^{0.25}$$

where $NOAEL_t$ is the NOAEL for the test mammal; $BW_t$ is the body weight for the test mammal; and $BW_r$ is the body weight for the spotted seal or minke whale in this study. The parameters used for risk evaluation in the current study are given in Tables S3 and S4 in the SM, and the calculated $MAC_{RfD}$ and $MAC_{TRV}$ are shown in Tables S3 and S4 in the SM.

### *2.7 Quality control and quality assurance*

Procedural and reagent blank samples were performed throughout the study. Zn and manganese Mn were found in both procedural and reagent blanks but accounted for less than 0.05% of the lowest acquired data in this study and thus could be negligible. The results in this study were not blank corrected. Satisfactory recoveries were obtained for the CRM samples, with TE recoveries ranging from 91.1% to 114.7% (Table S5). Two standard solutions (0.5 $\mu g\ L^{-1}$ for Hg and 5 $\mu g\ L^{-1}$ for the remaining TEs) were analyzed with each batch of 20 samples. The accuracy and precision of the instrumental analysis were reported as recoveries, and the relative standard deviations are shown in Table S6 and ranged from 93.7% to 103.7% and from 2.7% to 6.5%, respectively.

### *2.8 Statistical analysis*

Statistical analysis was performed using SPSS 21.0. Descriptive statistics and box charts were used to characterize the levels of TEs in the marine mammals and food web samples. Data sets of TE concentrations were normally distributed when natural logarithm transformed (Kolmogorov–Smirnov test), and ln-transformed data were used in the parametric statistical analysis. Briefly, a Pearson correlation model was employed to analyze potential relationships among various parameters. Independent samples t tests and LSD tests were applied to analyze the difference in TE levels in different tissues. Statistical tests were considered significant when $p < 0.05$.

# 3 Results and Discussion

## 3.1 *Tissue distribution of the selected TEs*

### *3.1.1 Spotted seal*

The statistical concentrations of the TEs in different tissues (muscle, kidney, liver, heart, and lung) of the 20 selected spotted seals are shown in Fig. 1, and detailed information is given in Tables S7 to S11 in the SM. Briefly, the selected 13 TEs were detected in all spotted seal tissues with mean concentrations of 0.041-136.3 mg/kg dw. The levels of Co were the lowest with mean concentrations ranging from 0.018 to 0.077 mg/kg dw; in contrast, Zn was the predominant element in all five tissues, with mean concentrations up to 173.9 mg/kg dw in the liver. Generally, a tissue-specific distribution of TEs was found; TEs tended to accumulate in internal organs, and the total TE concentrations in the five tissues from highest to lowest were in the order of liver > kidney > heart > muscle > lung. In the case of specific TEs, pulmonary As and Zn were significantly lower (LSD, $p < 0.05$) than those in the other tissues, while renal Pb and Cd were significantly higher (LSD, $p < 0.05$) than those in the other tissues. Hepatic, renal and cardiac Co, Cu, Mn and Se were significantly higher (LSD, $p < 0.05$) than those in the muscle, while hepatic and renal V displayed higher levels (LSD, $p < 0.05$) than those in the muscle. However, muscular Cr was significantly higher (LSD, $p < 0.05$) than those in the liver and kidney, while muscular Ni displayed higher levels (LSD, $p < 0.05$) than that in the liver. Similar distribution trends were found in different tissues in spotted seals for Cd and Hg (Dehn et al., 2006b, 2006a). However, Cu was mainly found in the internal organs of the spotted seals in this study, while Cu accumulated in the muscle of the spotted seals from Alaska (Dehn et al., 2005). Overall, only two studies reported TE levels in spotted seals, and wet weight-based concentrations were used in previous studies; therefore, they could not be compared with the data from this study and merit further study.

### *3.1.2 Minke whale*

The levels of the TEs in different tissues (muscle, kidney, liver, heart, and lung) of the selected 9 minke whale are given in Fig. 2, and detailed information is displayed in Tables S7 to S11 in the SM. Similar to spotted seals, 13 selected TEs were detected in all mink whales with concentrations ranging from 0.003 to 242.7 mg/kg dw. Muscular V concentrations (0.036 mg/kg dw) were the lowest, while Zn (48.05-152.6 mg/kg dw) was the predominant element in all five tissues. There was tissue-specific distribution with TEs preferentially accumulating in internal organs. The total TE concentrations tissues in ascending order was liver > kidney > heart > lung > muscle. In terms of specific TEs, hepatic, renal and cardiac As, Co, Cu, Se and Zn were significantly higher (LSD, $p < 0.05$) than those in the muscle, while muscular Cd, Mn and V were significantly lower (LSD, $p < 0.05$) than those in the kidney and liver. However, Hg, Cr, Ni, Pb and Sn did not show a significant distribution in the investigated tissues from the selected minke whale. The mean concentrations of Mn, Zn, Cu, Pb, and Co in the liver of the minke whale in this study were comparable to those from the Antarctic; however, hepatic Cd and Hg were orders of magnitude lower than those from the Antarctic (Honda et al., 1987).

## ***3.2 Differences in TE accumulation with different body lengths and sexes***

### *3.2.1 Spotted seal*

Briefly, some TE concentrations showed significant positive correlations with the body length of the spotted seals, including muscular Cd (Pearson correlation coefficient (PCC)

= 0.503, p = 0.028), renal Hg (PCC = 0.569, p = 0.017), renal Cd (PCC = 0.840, p = 0.000), hepatic Cd (PCC = 0.677, p = 0.003), hepatic Se (PCC = 0.551, p = 0.022), hepatic V (PCC = 0.487, p = 0.047), pulmonary Cd (PCC = 0.644, p = 0.005), and pulmonary Se (PCC = 0.612, p = 0.009), but significant negative correlations were observed among muscular Cu (PCC = -0.750, p = 0.000), renal Cu (PCC = -0.506, p = 0.038), hepatic Cu (PCC = -0.521, p = 0.032) and body length. No significant correlations were found among the investigated TE levels of the five spotted seal tissues and sex.

### *3.2.2 Minke whale*

Similar to spotted seals, some TE concentrations exhibited significant positive correlations with body length of the minke whales, including muscular As (PCC = 0.712, p = 0.048), hepatic Cr (PCC = 0.873, p = 0.023), cardiac Cd (PCC = 0.758, p = 0.029), cardiac Se (PCC = 0.713, p = 0.047), cardiac Sn (PCC = 0.743, p = 0.035), pulmonary Hg (PCC = 0.891, p = 0.003), pulmonary As (PCC = 0.804, p = 0.016), pulmonary Cd (PCC = 0.800, p = 0.017), pulmonary Co (PCC = 0.713, p = 0.047), and pulmonary Mn (PCC = 0.817, p = 0.013). Due to the small number of individual male minke whales (only two specimens), the correlation between gender and TE levels of the minke whale was not analyzed. Overall, the negative correlation coefficients of TE levels with body length could be partially explained by biodilution as a result of animal growth, while the positive correlation coefficients of TE levels with body length suggested that the rate of bioaccumulation of TEs was faster than that of biodilution (Zhang et al., 2017).

## ***3.3 Risk assessment***

The RQ values of the investigated TEs were calculated for the spotted seals and minke whales based on $MAC_{RfD}$ and $MAC_{TRV}$ described above in two exposure scenarios (50th and 95th represent average and high exposure scenarios), and the results are given in

Table 1. Generally, the RfD-based RQ values were higher than those for TRV-based RQ values for both spotted seal and minke whales, largely because RfD is used for human health evaluation and stricter than those from toxicological studies on mammals. In spotted seals, more than half of the $\mathrm{MAC}_{\mathrm{RfD}}$-based RQ values exceeded 1, including Hg, As, Cr, Cu, Se, and Zn. The highest risk was observed in the two exposure scenarios, indicating potential toxicological risk to spotted seals. Greater concern should be given to Hg, As, and Se because $\mathrm{MAC}_{\mathrm{TRV}}$-based RQ values exceeded 1 in average and high-exposure scenarios. Similar to the spotted seals, the RQ values based on $\mathrm{MAC}_{\mathrm{RfD}}$ of Hg, As, Cd, Cr, Cu, Se, and Zn in mink whales exceeded 1, suggesting potential toxicological risk to minke whales. Among them, As was the primary pollutant. In the case of $\mathrm{MAC}_{\mathrm{TRV}}$-based RQ values, Hg, As, and Se exhibited potential risk to minke whales in both average and high exposure scenarios and merits more attention.

It should be noted that As exists mainly in organic form in marine mammals and organisms and is relatively nontoxic (Kubota et al., 2003); therefore, the risk might be overestimated for both spotted seals and minke whales. Cd can influence the immune system and reproduction and cause cancer (Shankar et al., 2021; Zwolak, 2020). The source of Cd in marine mammals is from both land-based and offshore discharges (Fraga et al., 2018), and this study found that Cd accumulation in some tissues was significantly positively related to the body length of the investigated spotted seals and minke whales, especially in internal organs, and the $\mathrm{MAC}_{\mathrm{RfD}}$-based RQs of Cd exceeded 1. Therefore, the health risk of Cd to spotted seals and minke whales is worth noting and needs further study. In the case of essential elements Cu and Zn, these two element concentrations in all of the investigated tissues of spotted seals and minke whales were within the acceptance ranges (12-120 mg/kg dw for Cu and 80-400 mg/kg dw for Zn) (Hung et al., 2007, 2004), suggesting that the investigated spotted seals and minke whales are basically healthy. Trivalent Cr is an essential element for mammals, but hexavalent Cr is toxic to biology and is found to cause tissue damage, irritative lesions of the skin and respiratory tract and cell-mediated allergic reactions. Some hexavalent chromium compounds also induce tumors. However, most Cr in marine animals is trivalent and usually does not pose a health risk to consumers (Yılmaz et al., 2017). Therefore, the risk of Cr to minke whales might be overestimated, and more studies should be conducted to illustrate the chemical speciation of Cr in minke whales. Se is necessary for organism growth, and the levels of Se in the current study were far lower than the essential limitation (120 mg/kg dw) (Law, 1996); hence, the risk of Se to the spotted seal and minke whale mainly belongs to chronic selenosis, which might result in feed intake reduction, growth retardation, liver cirrhosis, and even induce genotoxicity, embryotoxicity, immunotoxicity, and cytotoxicity (Lv et al., 2021). Therefore, further study should be conducted to identify which risk would be posed by long-term accumulation of Se in spotted seals and minke whales. Hg, As, and Cd have attracted more attention due to their high toxicity at low concentrations; however, Se has antioxidant properties that play a special detoxification mechanism to these pollutants, including competing binding sites, formatting nontoxic complexes, and activating the Nrf2 pathway (Zwolak, 2020), especially for Hg. Previous studies have documented that a molar ratio of Se/Hg less than 1 indicated an exposure risk posed by Hg (Berry and Ralston, 2008). Overall, the molar ratios of Se/Hg in all of the tissues of the investigated spotted seals and minke whales were larger than 1, indicating that Se could largely counteract the harmful effects of Hg in these two marine mammals. However, based on the current study, $MAC_{TRV}$-based RQ values of Hg for the two marine mammals exceeded 1, which indicated that the investigated spotted seals and minke whales have potential risk exposure to Hg and needs further attention.

### *3.4 Trophic magnification of TEs*

The concentrations of the TEs in food webs of the spotted seal and minke whale were reported in our previous study (Tian et al., 2021), and the average concentrations of the TEs in each class of prey are given in Table S12 in the SM. The TMF values of TEs from the food web of spotted seals and minke whales investigated in this study are shown in Table 2. Only muscular TE levels were used to calculate TMFs in this study to minimize the effects of different TE levels on different tissues, especially for internal organs, because some TEs, such as Pb and Cd, are mainly stored in the liver and kidney (Hu et al., 2021). For spotted seals, based on the current study, trophic level-associated biodilution was obtained for As, Cd, Co, Cu, Mn, Pb, Se, Sn, and V, while Zn displayed a significant biomagnification trend with increasing trophic levels. However, Hg, Cr, and Ni did not exhibit obvious trophic transfer trends. In the case of the minke whale, As, Cd, Co, Mn, Pb, Se, and V displayed significant biomagnification trends with increasing trophic levels, while the other investigated TEs did not exhibit obvious trophic transfer trends.

Both biodilution and biomagnification of As with increasing trophic levels were found in previous studies (Trevizani et al., 2018), but As biodilution was the primary process in aquatic food webs and presented a biodilution trend in global marine food webs (Sun et al., 2020). However, organic As, which readily biomagnifies than the inorganic As, is often the predominant form in marine organism. Therefore, As might be readily biomagnified by minke whales since they have broader diet different kinds of diets compared to spotted seals (Du et al., 2021). A recent study documented that environmental (e.g., latitude and temperature) and ecological factors (e.g., trophic structure composition) can substantially influence the biomagnification process of As and Se. In addition to the level of bioaccumulated concentration, biomagnification depends on the biology, ecology and physiology of the organisms (Córdoba-Tovar et al., 2022). Cu and Mn can be excreted by high trophic level species efficiently and are regulated by homeostasis, which might partially explain the results of biodilution of Cu and Mn in spotted seal obtained in the current study (Hu et al., 2021). Trophic transfer of Cd in aquatic food chains is controversial, and trophic transfer of Cd in marine food webs was observed in a previous study, with biodilution in higher trophic organisms and biomagnification in lower trophic organisms, which was in line with this study (Espejo et al., 2018). Pb is known to be transferred inefficiently through marine food webs, probably because its form presented in aquatic organisms is difficult to absorb (Nfon et al., 2009). Therefore, biodilution might occur with the growth of marine mammals, such as spotted seals in this study. Trophic transfer of Co and V and their transfer mechanisms have rarely been reported by previous studies and need further study. Although we have found trophic magnification of Zn, there is much debate on whether Zn can be transferred at the trophic level and needs further study (Hu et al., 2021). Based on the current study, different trophic transfers of most TEs were found, which might be partially explained by the different dietary habits and physical structures of these two marine mammals. The spotted seal has only one stomach, while the minke whale has three stomachs. As filter feeders, minke whales mainly prey on large zooplankton (65%), small pelagic fishes (30%), and miscellaneous fishes (5%) and occupy a lower trophic level than spotted seals (Pauly et al., 1998). In contrast, the main food source of spotted seals is fish. They like to prey on pelagic and mesopelagic fishes, as well as cephalopods and shrimp (Tian et al., 2018). In general, trophic biomagnification or biodilution of TEs in marine food webs is affected by various factors, such as food web length and environmental and biological factors, and hence inconsistent results might be obtained, even for the same predator (Córdoba-Tovar et al., 2022).

## 4 Conclusions

Thirteen TEs were 100% detected in all of the investigated tissues of 20 stranded spotted seals and 9 stranded minke whales, and the TEs tended to accumulate in internal organs, especially the liver and kidney. Body length can affect the accumulation of TEs in the two marine mammals, and both positive and negative effects have been observed. However, the TE levels displayed insignificant sex-specific differences. More than half of the investigated TEs posed health risks to the two marine mammals based on the current study, especially for Hg, As, and Se. Therefore, long-term monitoring of TEs is required to discover the adverse effects of TEs on marine mammals in depth. Trophic transfer of TEs was evaluated for the first time for spotted seals and minke whales. For the spotted seal in this study, As, Cu, Mn, Ni, Pb, and V underwent biodilution, while Zn underwent biomagnification. In the case of the minke whale, As, Cd, Co, Mn, Pb, Se, and V undergo biomagnification. The rest of the TEs underwent no obvious biodilution or biomagnification for either spotted seal or minke whale.

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**Table 1**. The risk quotient (RQ) of halogenated organic contaminant calculated at $50^{th}$ and $95^{th}$ percentile.

**Table 2.** Trophic magnification factor (TMF) for the investigated trace elements of the two marine mammals.

**Figure 1**. Nonparametric probability distribution of the TEs levels and molar ratio of Se/Hg in the tissues of the spotted seals (the top and bottom of each box represent 75th and 25th percentiles, respectively; the top and bottom of each whisker represent 5th and 95th percentile, respectively; line across inside of each box represents median; the small square represents the mean value, and diamond beyond whiskers means outliers).

**Figure 2**. Nonparametric probability distribution of the TEs levels and molar ratio of Se/Hg in the tissues of the minke whales (the top and bottom of each box represent 75th and 25th percentiles, respectively; the top and bottom of each whisker represent $5^{th}$ and $95^{th}$ percentile, respectively; line across inside of each box represents median; the small square represents the mean value, and diamond beyond whiskers means outliers).