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The role of tropical small-scale fisheries in trace element delivery for a Small Island Developing State community, the Seychelles

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ABSTRACT

The concentrations of 13 trace elements were determined in 1032 muscles of 54 small-scale fisheries species collected from the Seychelles waters between 2013 and 2019. Overall, profiles were dominated by zinc (Zn) > arsenic (As) > iron (Fe) > copper (Cu) > selenium (Se), with the spiny lobsters, spanner crab and octopus exhibiting the highest levels of As, Cu and Zn while fish had higher Fe concentrations. Both taxonomy-dependent processes and ecological factors explained the interspecific differences of trace element profiles observed. A benefit-risk assessment revealed that crustaceans and cephalopods were good sources of Cu and Zn. One portion of any fish could provide 30–100 % of daily Se needs, and one portion of demersal and pelagic teleost fish could bring 5–20 % of Cu, Fe and Zn needs, especially for young adult and adult women. Finally, our analysis showed that there was very low health risks associated with small-scale fisheries consumption for the Seychelles population.

1. Introduction

Seafood consumption plays a major role in a healthy and balanced diet, providing numerous essential macro- and micronutrients to human body (Weichselbaum et al., 2013). Well-known for its content in essential fatty acids like long chain omega-3, seafood also provide important levels of essential trace elements such as copper (Cu), iron (Fe), selenium (Se) and zinc (Zn), which are co-factors of many proteins and enzymes (Weichselbaum et al., 2013). Selenoproteins, containing the organic form of Se – selenocysteine –, are also known to have a protective effect against mercury (Hg), due their binding affinity with each other (Ralston et al., 2016, 2007). As a consequence, nutrient-rich seafood is thought to be critical in promoting global food security and healthy diets (Béné et al., 2015), and could have the largest impact of all foods in the fight against micronutrient deficiency (Hicks et al., 2019).

Although the most common essential trace elements-related nutritional problems are associated with low intakes and thus mineral deficiency, problems can also arise from too high intakes resulting in trace element toxicity (Goldhaber, 2003). Indeed, the essentiality of a trace element for human metabolism depends on the dose, with some essential trace elements having narrow concentration ranges for which they are neither in deficiency or in excess (Zoroddu et al., 2019). In addition, seafood contains significant levels of non-essential trace elements, like cadmium (Cd), Hg and lead (Pb), which are toxic even at low concentrations and can thus have adverse effects on human health (Mudgal et al., 2010). Children and pregnant women are particularly vulnerable to Hg exposure, as pre- and post-natal exposure to non-essential trace elements like Hg can alter the nervous and cognitive development (Mahaffey, 2004). In order to better understand nutritional intakes, it is thus crucial to increase our knowledge on essential and non-essential trace element contents in seafood.

Documenting the nutritional quality of seafood items, especially from small-scale fisheries, is of high importance in Small Island Developing States (SIDS) like the Seychelles (Western Indian Ocean). One of the particularities of SIDS is their high reliance on marine resources for local subsistence and for their economy, due to their small land size (i.e.,

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limited terrestrial resources), insularity and remoteness (Briguglio, 1995). As a consequence, small-scale fisheries resources are the main source of proteins and micronutrients for local populations of SIDS (Hicks et al., 2019). With an Exclusive Economic Zone (EEZ) of 1.37 million km^2 constituting 99.7 % ocean, Seychelles has one of the highest rate of marine fish consumption in the world (57 kg·person^{-1}·year^{-1}) (World Bank, 2017). The analysis of 14 trace elements in 13 species of oceanic pelagic fish caught by the industrial and semi-industrial fisheries from the Seychelles EEZ revealed that they are good sources of Fe, Se and Zn, and that their consumption is associated with low exposure risks with regards to Cd, Hg and Pb (Bodin et al., 2017; Hollanda et al., 2017). Robinson and Shroff (2020) also showed a low Hg exposure risk for the Seychelles population through the consumption of 16 reef-associated fish species commonly caught by the artisanal fisheries. However, there is still a lack of data on the full trace element profile in the vast majority of species that are exploited, particularly in demersal and benthic reef-associated species, which constitute a significant part of the seafood diet of SIDS populations like Seychelles (Robinson et al., 2020).

Trace element concentrations in marine organisms depend on several physiological processes that can be species-, age-, or size-dependent (e.g., Bustamante et al., 1998; Kojadinovic et al., 2007; Metian et al., 2008), and ecological factors such as habitat and diet (e.g., Bodin et al., 2013; Chouvelon et al., 2017; Le Croizier et al., 2016; Metian et al., 2013). In a context of global change that can affect both the physiology and ecology of marine species (Beaugrand and Kirby, 2018; Little et al., 2020), anthropogenic modifications of ecosystems could indirectly affect the levels of essential and non-essential trace elements in marine species (Robinson et al., 2022). Assessing the influence of physiological and ecological factors on species-specific trace element concentrations is thus needed to appreciate the changes in mineral availability for fisheries resources, and consequently in future micronutrient supply and contaminant exposure for SIDS populations.

Our study aimed to assess the benefit and risk associated with the consumption of a wide range of marine species exploited by the Seychelles small-scale fisheries, and to identify species' taxonomic and ecological traits influencing trace element intake for the Seychelles communities. The specific objectives were to (i) report on the concentrations of six essential (i.e., cobalt – Co, Cu, Fe, manganese – Mn, Se, and Zn), three potentially essential (i.e., arsenic – As, chromium – Cr, nickel – Ni) and four non-essential trace elements (i.e., silver – Ag, Cd, Hg, Pb) in the edible part (muscles) of 54 nearshore and offshore tropical fisheries species, (ii) investigate the effects of taxonomy and trophic ecology (i.e., vertical habitat, diet and trophic position) on trace element profiles measured in the studied species and (iii) assess the benefit and risk related to small-scale fisheries species consumption for the Seychelles population.

2. Material and methods

2.1. Sample collection and preparation

A total of 1032 individuals from 54 marine species, including one cephalopod, four crustaceans, seven sharks and 42 teleost fish, were collected from the Seychelles waters during 2013–2019 (Table S1). Nearshore species (n = 51) were caught on the Mahé Plateau, where most of the artisanal fishing grounds are located (Robinson et al., 2006, 2020), and offshore species (n = 3) were caught around the Mahé Plateau (Fig. 1). After their capture, all organisms were measured (mantle and total lengths for octopus, cephalothorax length for crustaceans, lower jaw-fork length for swordfish, fork length and total length for other fish species), weighted, and a piece of the edible part was collected from the mantle for octopus, tail for crustaceans, and dorsal muscle for fish and immediately stored at −80 °C. Samples were then freeze-dried during 72 h and ground to powder before trace element and stable isotope analyses. The percentage of moisture was determined

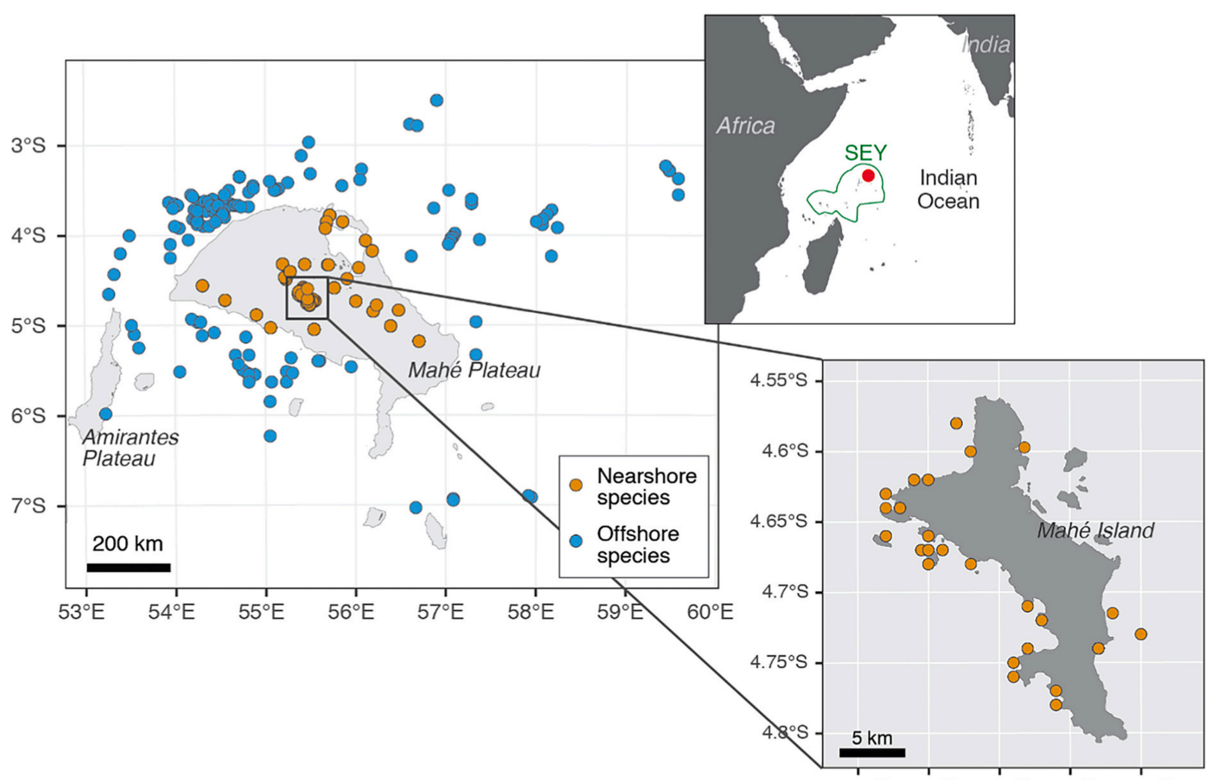

Fig. 1. Fishing locations of the 54 marine species on and around the Mahé Plateau, Seychelles (Western Indian Ocean). Red point indicates the location of the Mahé Plateau within the Seychelles economic exclusive zone. SEY = Seychelles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

gravimetrically as the difference between wet and dry masses of samples after freeze-drying. The mean analytical variability of the method was <1 %.

2.2. Trace element analysis

Dry samples were analysed for the concentrations of 13 trace elements. Except for Hg, all trace elements were analysed by induced coupled plasma (ICP) at the LIENSs laboratory (France), using a Varian Vista-Pro ICP coupled with optical emission spectrometry and a ThermoFisherScientific X-Series II ICP coupled with mass spectrometry. Aliquots of 90–200 mg were microwave digested with 6 ml 67–70 % of nitric acid and 2 ml 34–37 % of hydrochloric acid. Seven control samples (five Certified Reference Materials, CRMs, and two blanks) treated and analysed in the same way as the samples were included in each analytical batch. CRMs were fish homogenate IAEA 407, tuna fish flesh homogenate IAEA 436, scallop (*Pecten maximus*) IAEA 452, marine tropical clam (*Gafrarium tumidum*) IAEA-461, dogfish liver DOLT-5 (National Research Council Canada) and lobster hepatopancreas TORT-3 (National Research Council Canada). Mean recovery rates in CRMs ranged from 74 to 128 %, and detection frequencies (i.e., number of data above limit of quantification, LOQ) in samples ranged from 10 to 100 % (Table S2).

Hg was analysed in aliquots of 2–10 mg by atomic absorption spectrophotometry with a Direct Mercury Analyser (Milestone DMA 80) at the SFA facility (Seychelles) or an Advanced Mercury Analyser (Altec AMA 254) at the LIENSs laboratory (France). Hg determination involves progressive heating to 750 °C to burn the matrix and evaporate the metal, which is further collected on a gold amalgamator. Hg is then liberated by heating at 950 °C, and measured by atomic absorption spectrophotometry. Hg concentrations were validated by the analysis of CRM DOLT-5 whose masses were adjusted to represent the same amount of Hg as the samples. CRMs were analysed every 10 samples, according to the same conditions as the samples. Blanks were also analysed at the beginning of each set of samples, and the LOQ of the Hg analysers was 0.1 ng.

All trace element concentrations were converted from dry weight to wet weight (ww) by using the percentage of moisture determined in this study. When not available, a mean moisture percentage of 75 % was used (Table S1).

2.3. Stable isotope analysis

Stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) were analysed on dry samples at the LIENSs laboratory (France). Removal of lipids and urea before the C and N isotope analysis is recommended to avoid biased results due to lipids being more depleted in ^{13}C than other tissue components and to urea being more depleted in ^{15}N (Li et al., 2016; Logan et al., 2008; Post et al., 2007). In this study, spiny lobsters characterised by a low fat content in the tail muscle (mean of 0.74 ± 0.14 % wet weight; Sabino et al., 2021), were analysed directly for stable isotopes (bulk $\delta^{13}C$ and $\delta^{15}N$ values), while $\delta^{13}C$ corresponded to lipid-normalised values for all other species, and $\delta^{15}N$ corresponded to urea-normalised values for shark species.

2.3.1. Lipid-normalisation methods

Except for swordfish, lipids were chemically removed prior to stable isotope analysis. For each sample, between 10 and 12 mg of powdered sample was placed in a glass tube with 4 ml of cyclohexane. The tubes were then agitated during 10 min at room temperature and centrifuged during 5 min at 4500 rpm before removal of extraction solvent. Agitation, centrifugation and solvent-removal steps were repeated three times before putting tubes for drying in an oven at 45 °C overnight. For swordfish, known for their particularly high muscle fat content (26.2 ± 18.9 % dw, Bodin et al., 2017), a mathematical lipid-correction was applied on the measured bulk $\delta^{13}C$ values. Indeed, lipid-removal in fatty tissues can affect $\delta^{15}N$ values due to contact with the extraction solvent during an extended period of time (Sotiropoulos et al., 2004). For this, we used the equation:

$$\delta^{13}C_{corr} = [(D \times C{:}N_{bulk} + a)/(C{:}N_{bulk} + b)] + \delta^{13}C_{bulk}, \tag{1}$$

with $C{:}N_{bulk}$ and $\delta^{13}C_{bulk}$ corresponding to the carbon to nitrogen (C:N) ratio and carbon isotope ($\delta^{13}C$) value measured in the sample, respectively (Logan et al., 2008), and with $D = 7.05$, $a = -22.4$ and $b = -0.44$.

2.3.2. Urea-removal

Urea was removed in muscle tissue samples from all analysed shark species using deionised water (Li et al., 2016). For this, after lipid-removal, 1 ml of deionised water was added in each tube containing the samples, and tubes were then vortexed during 30 s. Samples were left in deionised water for 24 h before centrifugation (5 min at 5000 rpm) and removal of rinsing water with a pipette. These steps were repeated three times before freeze-drying the samples during 24 h prior to stable isotope analysis.

2.3.3. Isotopic ratio mass spectrometry analysis

Between 0.2 and 0.5 mg of sample was weighed in tin capsules. The samples were analysed by continuous flow on a Thermo Scientific Flash 2000 elemental analyser coupled to a Delta V Plus interface mass spectrometer. International isotopic standards of known $\delta^{13}C$ and $\delta^{15}N$ were used: USGS-61 and USGS-62. Results are expressed in the δ unit notation as deviations from standards (Vienna Pee Dee Belemnite for $\delta^{13}C$ and atmospheric nitrogen for $\delta^{15}N$) following the formula: $\delta^{13}C$ or $\delta^{15}N = [(R_{sample}/R_{standard}) - 1] \times 1000$, where R is $^{13}C/^{12}C$ or $^{15}N/^{14}N$, respectively. Measurement errors (SD) of stable isotopes, calculated on all measured values of $\delta^{13}C$ and $\delta^{15}N$ in isotopic reference materials, were <0.10 ‰ for both the nitrogen and carbon isotope measurements. For each sample, the C:N ratio was calculated, and never exceeded 3.5 proving that reserve lipids were adequately removed, or that there was no need of lipid removal or normalisation (Post et al., 2007).

2.4. Benefit-risk assessment

Essential trace element supply was assessed by estimating the contribution of one serving to the age-, sex- and status-specific recommended daily intakes (RDIs) set by the American Food and Nutrition Board of the Institute of Medicine (NIH, 2019a) (Table S3). Calculations were made for all NIH-categories, i.e. 2–3 years old, 4–8 years old, 9–13 years old, 14–18 years old, 19+ years old, pregnant women and lactating women. The following equation was used to calculate the percentage of contribution to RDI for each sampled individual of each species:

$$\%RDI = ([TE] \times \text{portion weight}) \times 100/RDI \tag{2}$$

with [TE], the concentration ($\mu g \cdot g^{-1}$ ww) of the considered trace element; portion weight, the weight (g) of the portion for the considered category; and RDI, the recommended daily intake ($\mu \cdot d^{-1}$) for the considered trace element.

The risks associated with too high intake of essential trace elements and with non-essential trace element exposure were assessed by estimating the number of servings before reaching the age-, sex- and status-specific provisional tolerable intakes (PTIs) set by the American Food and Nutrition Board of the Institute of Medicine (NIH, 2019b), and by the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011, 2021), respectively (Table S3). Calculations were made for all NIH-categories and for each sampled individual of each species with the equation:

$$\text{Number of servings} = PTI/([TE]^{*}\text{portion weight}) \tag{3}$$

with PTI, the daily provisional tolerable intake ($\mu \cdot d^{-1}$) for the considered trace element; [TE], the concentration ($\mu g \cdot g^{-1}$ ww) of the considered trace element; and portion weight, the weight (g) of the portion for the considered category.

For each element, the calculated RDIs and PTIs were then summarised into three main categories representing the most vulnerable populations in terms of either trace element deficiency or exposure: children (C) = 2–13 years old, young adults (YA) = 14–18 years old, and adult women (A) = 19+ years old, including pregnant and lactating women. All parameters used in Eqs. (2) and (3) are presented in Table S3.

To take into account the interaction ability of Se with Hg in the benefit/risk assessment, the molar ratio of Hg above Se (MHg:MSe) and the Health Benefit Value of Se (HBVSe) were calculated according to the following equations (Ralston et al., 2016, 2007):

$$\text{MHg:MSe} = (\text{CHg}/\text{MHg})/(\text{CSe}/\text{MSe}) \tag{4}$$

$$\text{HBVSe} = [(\text{Mse} - \text{MHg})/\text{MSe}] \times (\text{MSe} + \text{MHg}) \tag{5}$$

Considering that Se and Hg bind in a molar ratio of 1:1 in human tissues (Ralston et al., 2007), the concentration of theoretically available Se after interaction with Hg was estimated using the following equation:

$$\text{Concentration of theoretically available Se} = (\text{MSe} - \text{MHg}) \times \text{MSe} \tag{6}$$

For each species, contribution to RDI and number of servings necessary to reach PTI associated to concentrations of theoretically available Se were calculated using the method described above (Eqs. (2) and (3)).

No reference values of RDI and PTI exist for potentially essential trace elements. However, with regards to As, the contribution of one serving was estimated for to the “adult women” only using the adult-specific RDI of 12 $\mu g \cdot d^{-1}$ proposed by (Nielsen, 1991). Moreover, the concentration of inorganic As (iAs), the main non-essential and toxic forms of As (Sharma and Sohn, 2009), was estimated for all species using the proportions of iAs in seafood calculated by Uneyama et al. (2007) (i.e., 4.4 % in fish and 2.2 % in crustaceans).

2.5. Assessment of the effects of physiology and trophic ecology on trace element profiles

Only trace elements for which the detection frequency was above 70 % were selected, and data < LOQ were substituted with values drawn randomly from the range]0;LOQ[. Species were grouped according to their trace element profiles by using hierarchical cluster analysis (Ward's clustering method) on their scaled mean trace element concentrations. Trace element concentrations and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) values were compared among determined groups by using Kruskal-Wallis followed by Dunn post hoc tests. Finally, we looked at the composition of

Table 1

Concentrations (mean ± SD, $\mu g \cdot g^{-1}$ ww) of the 13 trace elements measured in the muscle of 16 families collected from the Seychelles EEZ. iAs corresponds to concentrations of inorganic As estimated from its proportions in seafood (Uneyama et al., 2007). Concentrations (mean ± SD, $\mu g \cdot g^{-1}$ ww) per species are given in Table S4. LOQ = limit of quantification.

Group family	Essential						Potentially essential			Non-essential				
	Co	Cu	Fe	Mn	Se	Zn	As	Cr	Ni	Ag	Cd	Hg	Pb	Estimated iAs
Cephalopods														
Octopodidae	0.003 ± 0.000	1.12 ± 0.34	1.9 ± 1.0	0.09 ± 0.02	0.27 ± 0.05	19.3 ± 2.5	26.1 ± 5.9	0.11 ± 0.06	0.03 ± 0.01	<LOQ	0.02 ± 0.01	0.01 ± 0.01	0.003 ± 0.001	1.10 ± 0.25
Crustaceans														
Palinuridae	0.005 ± 0.002	9.89 ± 4.22	2.5 ± 1.5	0.09 ± 0.04	0.29 ± 0.12	29.2 ± 7.7	45.3 ± 20.7	0.14 ± 0.14	0.07 ± 0.06	0.017 ± 0.030	0.07 ± 0.13	0.03 ± 0.02	0.022 ± 0.073	1.00 ± 0.46
Raninidae	0.009 ± 0.003	7.21 ± 3.29	1.0 ± 0.1	0.04 ± 0.01	0.55 ± 0.09	43.5 ± 4.2	50.5 ± 12.0	<LOQ	0.08 ± 0.03	0.039 ± 0.011	0.44 ± 0.24	0.03 ± 0.00	0.003 ± 0.001	1.11 ± 0.26
Teleost fish														
Mullidae	0.004 ± 0.001	0.32 ± 0.06	2.9 ± 1.3	0.09 ± 0.04	0.44 ± 0.07	4.2 ± 0.8	6.2 ± 4.1	0.13 ± 0.10	0.07 ± 0.04	<LOQ	0.01 ± 0.00	0.03 ± 0.02	0.004 ± 0.001	0.26 ± 0.17
Scaridae	0.005 ± 0.002	0.42 ± 0.06	1.6 ± 0.3	0.11 ± 0.05	0.39 ± 0.16	4.0 ± 0.9	1.3 ± 1.0	0.05 ± 0.03	0.02 ± 0.01	<LOQ	0.01 ± 0.01	0.01 ± 0.00	0.007 ± 0.003	0.06 ± 0.04
Siganidae	0.029 ± 0.039	0.44 ± 0.13	2.7 ± 1.0	0.08 ± 0.08	0.20 ± 0.08	4.0 ± 1.3	0.2 ± 0.1	0.14 ± 0.09	0.16 ± 0.18	0.005	0.04 ± 0.05	0.00 ± 0.00	0.005 ± 0.002	0.01 ± 0.00
Acanthuridae	0.011 ± 0.008	0.38 ± 0.07	3.3 ± 1.4	0.05 ± 0.02	0.42 ± 0.17	4.9 ± 1.8	2.0 ± 2.4	0.11 ± 0.05	0.11 ± 0.12	<LOQ	0.02 ± 0.01	0.02 ± 0.01	0.004 ± 0.000	0.08 ± 0.10
Carangidae	0.009 ± 0.010	0.53 ± 0.19	6.9 ± 4.0	0.09 ± 0.04	0.58 ± 0.22	6.5 ± 1.8	0.9 ± 0.5	0.31 ± 0.22	0.14 ± 0.13	0.042 ± 0.054	0.02 ± 0.03	0.28 ± 0.29	0.009 ± 0.012	0.04 ± 0.02
Lethrinidae	0.005 ± 0.005	0.44 ± 0.12	4.3 ± 3.4	0.06 ± 0.06	0.81 ± 0.39	4.5 ± 1.2	2.6 ± 1.8	0.28 ± 0.28	0.08 ± 0.08	0.031 ± 0.030	0.02 ± 0.03	0.26 ± 0.15	0.009 ± 0.017	0.11 ± 0.07
Lutjanidae	0.006 ± 0.006	0.40 ± 0.15	3.8 ± 3.0	0.06 ± 0.05	0.60 ± 0.14	4.8 ± 1.5	2.5 ± 1.5	0.36 ± 0.37	0.09 ± 0.15	0.028 ± 0.020	0.02 ± 0.03	0.19 ± 0.17	0.013 ± 0.017	0.10 ± 0.06
Serranidae	0.013 ± 0.024	0.33 ± 0.16	3.7 ± 3.0	0.06 ± 0.04	0.57 ± 0.12	5.1 ± 2.0	1.0 ± 1.7	0.28 ± 0.33	0.08 ± 0.10	0.038 ± 0.044	0.01 ± 0.01	0.12 ± 0.10	0.024 ± 0.044	0.04 ± 0.07
Sphyraenidae	0.005 ± 0.002	0.38 ± 0.21	4.8 ± 2.3	0.11 ± 0.09	0.49 ± 0.10	5.0 ± 1.4	1.0 ± 0.5	0.41 ± 0.23	0.05 ± 0.03	<LOQ	0.02 ± 0.05	0.25 ± 0.14	0.003 ± 0.001	0.04 ± 0.02
Scombridae	0.007 ± 0.005	0.65 ± 0.18	7.2 ± 3.4	0.08 ± 0.03	0.76 ± 0.36	7.2 ± 2.6	1.1 ± 0.8	0.15 ± 0.13	0.04 ± 0.03	<LOQ	0.03 ± 0.04	0.19 ± 0.25	0.004 ± 0.002	0.05 ± 0.03
Xiphiidae	0.005 ± 0.002	0.43 ± 0.34	3.8 ± 3.7	0.04 ± 0.03	0.74 ± 0.28	9.1 ± 4.6	0.7 ± 0.3	0.16 ± 0.16	0.03 ± 0.03	0.003 ± 0.000	0.05 ± 0.04	0.74 ± 0.44	0.045 ± 0.097	0.03 ± 0.01
Sharks														
Carcharhinidae	0.004	0.34 ± 0.09	2.3 ± 1.3	0.10 ± 0.02	0.67 ± 0.33	5.4 ± 1.8	4.3 ± 2.3	0.08 ± 0.06	0.02 ± 0.00	<LOQ	0.00 ± 0.00	0.44 ± 0.27	0.005 ± 0.001	0.18 ± 0.10
Sphyrnidae	0.010 ± 0.009	0.34 ± 0.04	1.8 ± 0.5	0.19 ± 0.05	1.23 ± 0.51	5.3 ± 2.1	5.7 ± 1.9	0.05 ± 0.01	0.02 ± 0.01	<LOQ	0.00	0.50 ± 0.12	0.005 ± 0.004	0.24 ± 0.08

each group in terms of functional group, habitat type and feeding mode (Table S1). All data treatment were performed under R 3.5.2 software (R Core Team, 2018).

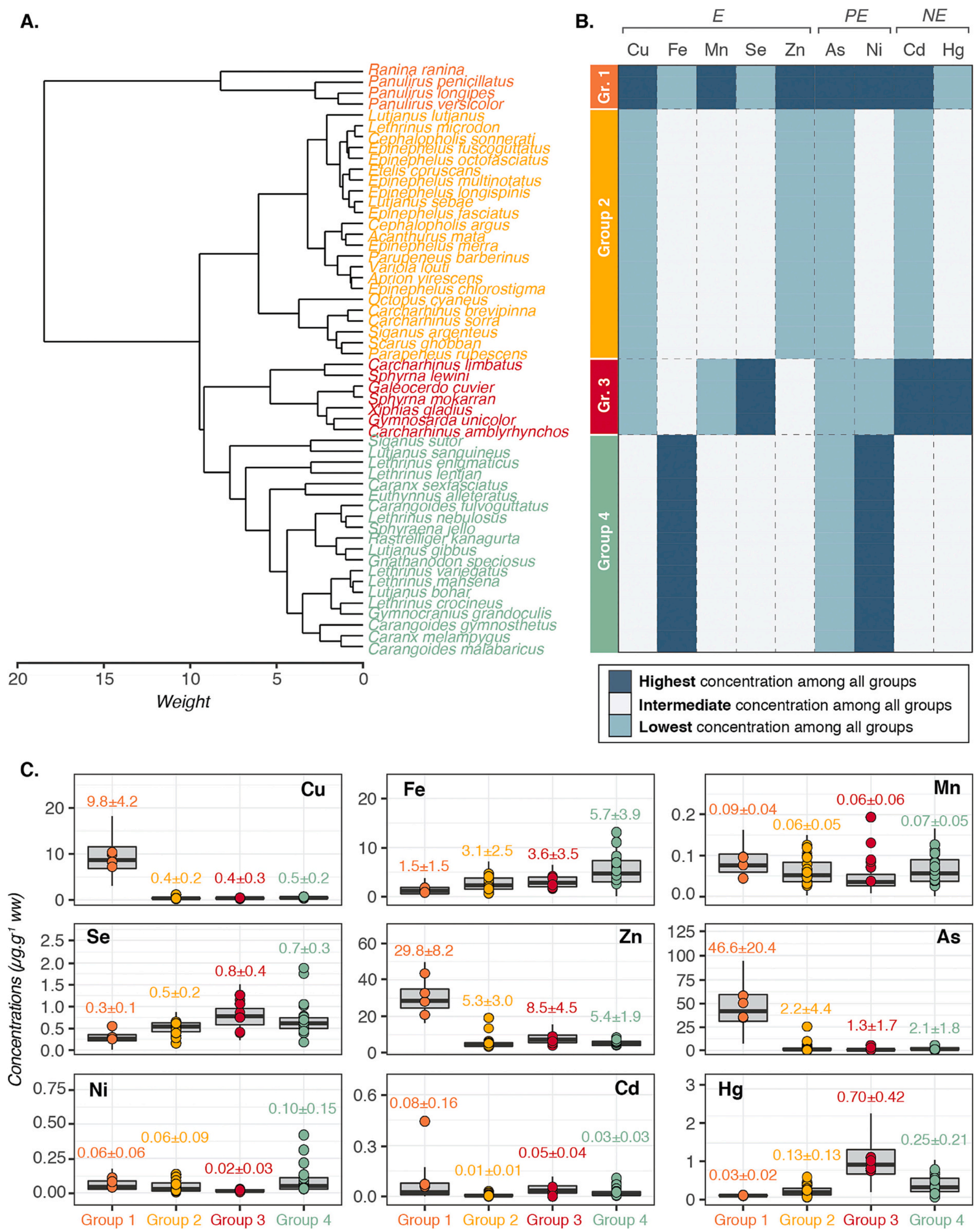

Fig. 2. Groups inferred from cluster analysis of mean trace element concentrations in Seychelles marine species (A), and their trace element profiles (B) and concentrations (C) in each group. Points represent the mean concentration for each species in the group, and the value (mean ± SD) in each group is indicated above each boxplot in the corresponding colour (C). E = essential, PE = potentially essential, NE = non-essential. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Essential, potentially essential and non-essential trace element concentrations

Overall, essential and potentially essential trace element profiles in Seychelles marine species were dominated by Zn > As > Fe > Cu > Se (Tables 1 and S4). Co, Cr, Mn and Ni concentrations were low, with mean concentrations below 1 $\mu g \cdot g^{-1}$ ww. The highest As, Cu and Zn concentrations were observed in decapod crustaceans (*Panulirus* sp. and *Ranina ranina*) followed by the cephalopod *Octopus cyanea*. Fe concentrations were higher in fish compared to the other groups, and in particular in scombrids and carangids with the species *Euthynnus alletteratus* and *Carangoides gymnostethus* exhibiting the highest values, respectively. The highest Se concentrations were observed in teleost fish and sharks, i.e. sphyrnids > lethrinids ≈ scombrids ≈ xiphiids (swordfish) > carcharhinids.

Among non-essential trace elements, Ag and Pb concentrations were very low, with mean concentrations below 0.05 $\mu g \cdot g^{-1}$ ww (Tables 1 and S4). Cd exhibited low levels (<0.1 $\mu g \cdot g^{-1}$ ww) in all species, except in the spanner crab (*R. ranina*) with mean Cd concentrations of 0.44 $\mu g \cdot g^{-1}$ ww. Finally, the highest Hg concentrations were measured in teleost fish and sharks, i.e. xiphiids (swordfish) > sphyrnids > carcharhinids > carangids.

3.2. Clustering on species' trace element profiles and composition of inferred groups

Four groups were inferred by the hierarchical cluster analysis of mean trace element concentrations in Seychelles marine species (Fig. 2A). Among all groups, group 1 and group 3 had the highest mean concentrations of Cd (Dunn test, $p < 0.001$) and group 1 and group 4 had the highest mean Ni concentrations ($p = 0.001$ between groups 1 and 2, $p < 0.001$ for all other comparisons) (Fig. 2B, C). Groups 2 and 3 had the lowest mean Cu concentrations ($p < 0.001$). Group 1 also had the highest mean As, Cu, Mn and Zn concentrations (all $p < 0.001$), and the lowest mean Hg, Fe and Se concentrations (all $p < 0.001$). Group 3 also had the highest mean Hg and Se concentrations (both $p < 0.001$) while having the lowest mean Ni and Mn concentrations (both $p < 0.001$). Group 4 also had the highest mean Fe concentration ($p < 0.001$). Finally, group 2 also had the lowest mean Cd ($p < 0.001$) and mean Zn ($p = 0.001$ with group 2, $p < 0.001$ with all other groups) concentrations.

Group 1 was composed only of benthic crustaceans (Fig. 3). Groups 2 and 4 were mainly composed of demersal teleost fish (but group 2 includes the octopus), and group 3 was composed only of pelagic species, including pelagic-neritic and pelagic-oceanic shark, and teleost fish species. There was no clear clustering among species' habitat type or feeding mode. Indeed, for most habitat types and feeding modes, a given type or mode could be found in at least two groups.

Group 1 had a higher mean $\delta^{13}C$ value than the three other groups ($p < 0.001$) (Fig. 4). Group 3 had the highest mean $\delta^{15}N$ value ($p < 0.001$), while group 1 had the lowest mean $\delta^{15}N$ value ($p < 0.001$) (Fig. 4).

3.3. Contribution of Seychelles small-scale fisheries to recommended intakes

One portion of any of the studied fish species (teleosts and sharks) provided between 35 and >100 % of Se RDI, between 1 and 20 % of Cu, Fe and Zn RDIs, and <1.5 % of Mn RDI to all population categories (Table S5). Little tunny, *Euthynnus alletteratus*, was the species that contributed the most to all essential trace elements' daily needs (i.e., >10 % of Cu, Fe and Zn, >100 % of Se and >0.6 % of Mn RDIs). For three demersal (i.e., *Caranx sexfasciatus*, *Carangoides gymnostethus*, *Lutjanus lutjanus*) and four pelagic-neritic (Teleots: *Euthynnus alletteratus*, *Rastrelliger kanagurta*, *Xiphias gladius*; Sharks: *Carcharhinus limbatus*) species, a portion could deliver >10 % of Zn RDI for one or more population

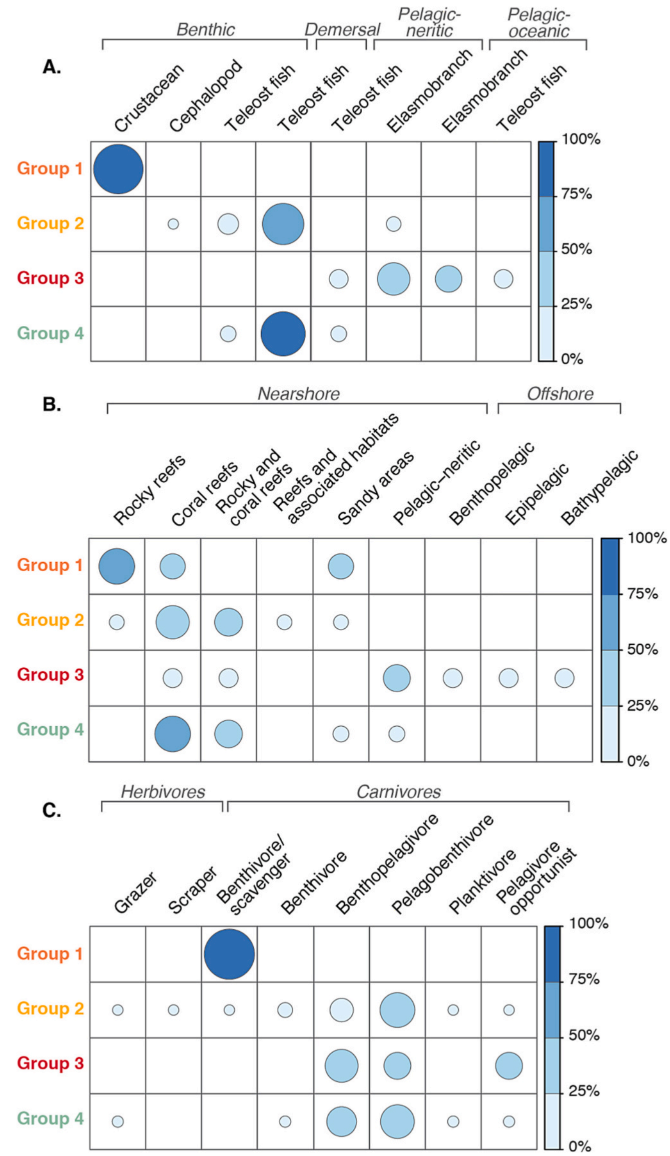

Fig. 3. Compositions of groups inferred from mean trace element concentrations in Seychelles marine species in terms of functional group (A), habitat type (B) and feeding mode (C). Circles' colour intensity and size are proportional to the percentage of each functional group, habitat type or feeding mode in each trace element profile group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

categories. For four demersal (i.e., *Lethrinus lentjan*, *Lutjanus gibbus*, *Lutjanus lutjanus*) and two pelagic-neritic (*Rastrelliger kanagurta*, *Euthynnus alletteratus*) species, a portion provided >10 % of Cu RDI to one or more population categories. The species that showed the highest contribution to Fe RDI (i.e., >10 % per daily portion) were the bigeye trevally (*Carans sexfasciatus*) and the little tunny. With the exception of the two rabbitfish (*Siganus argenteus* and *S. sutor*), one portion of any of the studied fish species provided >70 % of Se RDI, including 36 of them that provided >100 % of Se RDI.

One portion of any of the crustacean and cephalopod species provided between 59 and >100 % of Se RDI, between 15 and >100 % of Cu RDI, and between 25 and 62 % of Zn RDI to all population categories, but <3 % and 0.7 % of Fe and Mn RDIs, respectively (Table S5). The spiny lobsters *Panulirus* sp., and the spanner crab *Rania ranina*, in particular, provided >100 % of Cu RDI to all categories, against 15–20 % for the big blue octopus *Octopus cyanea*. The spanner crab was the species that contributed the most to Se and Zn RDIs (>100 and >56 %

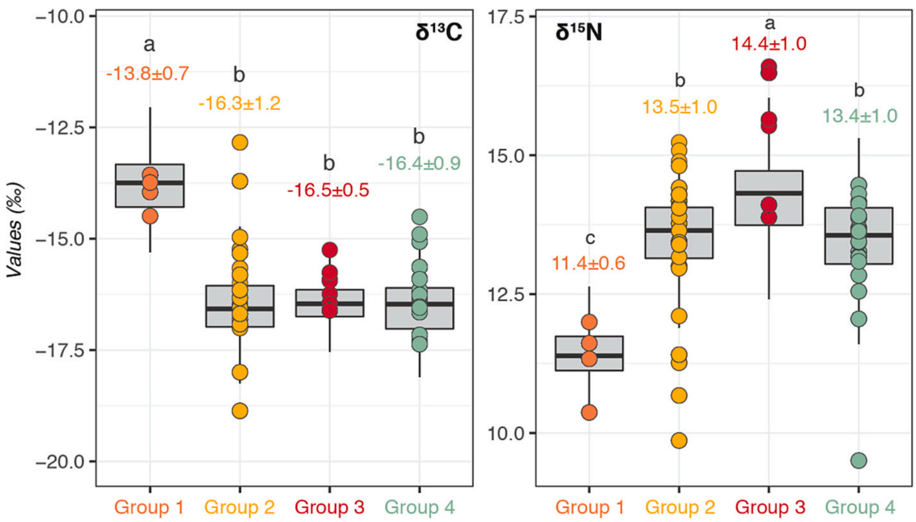

Fig. 4. $\delta^{13}C$ and $\delta^{15}N$ values (‰) measured in the muscle of Seychelles marine species in each group determined from trace element profiles. Points represent the mean value for each species present in the group, and the value (mean ± SD) in each group is indicated above each boxplot in the corresponding colour. A different letter indicates a significant difference between groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for all population categories, respectively) compared to other crustacean and cephalopod species.

Finally, one portion of any of the 54 studied species contributed to >100 % of adult women As RDI when using the adult-specific RDI of 12 $\mu g \cdot d^{-1}$ proposed by Nielsen (1991).

3.4. *Number of daily servings of Seychelles small-scale fisheries to reach provisional recommended intakes*

The number of daily servings of any of the studied species before reaching Cu, Fe, Mn and Zn PTIs was high (≥4) for all population categories (Table S6). For Cd, the number of daily servings before reaching PTI was ≥3 for all population categories, except for the pink ear emperor (*Lethrinus lentjan*: two daily servings for children and young adults) and the spanner crab (one daily serving for children and young adults, and two daily serving for adult women). For Se, the number of daily servings before reaching PTI was ≥3 for all population categories, except for two lethrinids (one daily serving for *Lethrinus enigmaticus* and *L. lentjan*) and two sharks (two daily servings for *Carcharhinus limbatus*, *Sphyrna lewini*) (Table S6). Same results were obtained when dietary intake calculations were made using the fraction of Se that remains available after taking into account its interaction with Hg and estimated for each studied individual (Table S7). With regards to Hg, only 17 of the 54 studied species had a number of daily servings before reaching PTI ≥ 3 for all population categories, whereas the number of servings was one or two for 30 species (Table S6). Moreover, four species appeared to be unsafe (number of servings = 0) for all population categories and three more species for children and young adults only (Table S7). However, when considering the Hg:Se interaction, the fraction of Hg that remains available in each studied species was estimated to be zero, and all studied species could be consumed without any risk of reaching Hg PTI (Table S7).

4. Discussion

This study provided detailed information on the concentrations of essential, potentially essential and non-essential trace elements in a wide range of tropical small-scale fisheries species from the Seychelles, caught in both nearshore and offshore waters. We highlighted the importance of taxonomy-related physiological processes and trophic ecology (i.e., vertical habitat, diet and trophic position) in explaining interspecific difference in trace element concentrations in fisheries species. We also greatly expanded our understanding of micronutrient supply and contaminant exposure in Seychellois diet, showing that Seychelles fisheries resources bring substantial amounts of Cu, Fe, Se and Zn to human diets with very low health risk associated with to Ag, Cd, Hg and Pb dietary exposure.

4.1. *Trace elements in Seychelles small-scale fisheries compared to literature and reference values*

Trace element profiles in tropical fish from Seychelles waters were dominated by Fe and Zn, followed by As > Se > Cu. Crustaceans and cephalopods exhibited the highest concentrations in As > Zn > Cu (i.e., 15–25, 5–6 and 3–24 fold times higher than in the studied fish, respectively), while their Fe content was two-fold lower than in fish. The patterns observed in this study were very similar to those observed in large pelagic fish (mackerels, tuna and swordfish) from the Western Indian Ocean (Bodin et al., 2017; Chouvelon et al., 2017; Kojadinovic et al., 2007), and in reef-associated demersal and benthic fish (parrotfish, emperors, groupers and snappers) from the tropical ecosystems of South India (Laccadive Sea; Rejomon et al., 2010; Shalini et al., 2021), New Caledonia (Coral Sea; Metian et al., 2013) and Paracel islands (South China Sea; Gu et al., 2015; Li et al., 2020).

Among the 54 studied marine species, Hg exhibited high concentrations (mean values >0.5 $\mu g \cdot g^{-1}$ ww) in swordfish and sharks, and low concentrations (<0.15 $\mu g \cdot g^{-1}$ ww) in benthic species (goatfishes, cephalopods and crustaceans), while all other species had concentrations between 0.10 and 0.35 $\mu g \cdot g^{-1}$ ww. From those values, none of the individuals, all species mixed, exceeded the maximum limit (ML) of 0.5 $\mu g \cdot g^{-1}$ ww defined for fisheries products by international instances, and only 28 swordfish (3 % of the total number of analysed individuals) composing the high range group showed Hg concentrations higher than the value of 1 $\mu g \cdot g^{-1}$ ww set up specifically for predatory fish (Codex Alimentarius Commission, 2011; EC, 2011, 2006). The maximum concentration of 2.3 $\mu g \cdot g^{-1}$ ww was recorded in one swordfish individual while the other individuals exhibited Hg concentrations between 1.0 and 1.6 $\mu g \cdot g^{-1}$ ww.

Pb showed low concentrations in the muscle of Seychelles small-scale fisheries species, the highest being observed in swordfish (mean value of 0.05 $\mu g \cdot g^{-1}$ ww). Considering the MLs defined for fish (0.3 $\mu g \cdot g^{-1}$ ww), crustaceans (excluding head and thorax meat of spiny lobsters; 0.5 $\mu g \cdot g^{-1}$ ww) and cephalopods (1 $\mu g \cdot g^{-1}$ ww) (Codex Alimentarius Commission, 2011; EC, 2011, 2006), only four swordfish over the 1032 analysed individuals (i.e., 0.4 %) exceeded Pb MLs with a maximum concentration of 0.59 $\mu g \cdot g^{-1}$ ww.

Seychelles small-scale fisheries species were characterised by low Cd concentrations (mean values < 0.10 $\mu g \cdot g^{-1}$ ww), with the exception of the pink ear emperor *L. lentjan* and the spanner crab *Ranina ranina* (mean values of 0.16 and 0.44 $\mu g \cdot g^{-1}$ ww, respectively). Five MLs have been defined in the case of Cd: 1 $\mu g \cdot g^{-1}$ ww for cephalopods, 0.5 $\mu g \cdot g^{-1}$

ww crustaceans (excluding head and thorax meat of spiny lobsters), 0.3 $\mu g \cdot g^{-1}$ ww for swordfish, 0.1 $\mu g \cdot g^{-1}$ ww for tuna and mackerel species, and 0.05 $\mu g \cdot g^{-1}$ ww for other fish species (Codex Alimentarius Commission, 2011; EC, 2011, 2006). Considering those limits, only 3 % of the total number of analysed individuals was reported to exceed Cd ML. It included 1 spanner crab, 2 shoemaker spinefoot (*S. sutor*), and 30 dermersal teleost fish (i.e., 3 barracudas, five emperors, 10 trevallies and 12 groupers). The maximum Cd concentration was recorded in the spanner crab (0.70 $\mu g \cdot g^{-1}$ ww), while fish had concentrations comprised between 0.05 and 0.20 $\mu g \cdot g^{-1}$ ww.

Although consensual thresholds are inexistent for essential elements, guidance values in muscle are recommended in some countries, such as 20 $\mu g \cdot g^{-1}$ ww for Cu and 50 $\mu g \cdot g^{-1}$ ww for Zn (Franklin and Jones, 1995). None of the Seychelles small-scale fisheries species reached theses limits.

4.2. Factors influencing trace element availability in small-scale fisheries

Trace element accumulation in Seychelles small-scale fisheries was influenced by the physiology and trophic ecology of the studied species, and by the availability of trace elements in the consumers' environment and/or diet. Here, crustacean species were grouped together in the clustering, being the species with the highest As, Cu and Zn concentrations, and the lowest Fe, Hg and Se concentrations. Decapod crustaceans are known to have high Cu and Zn uptake rates from food due to high physiological needs for these elements: Zn is well-known to be a cofactor in numerous enzymes (Rainbow, 2002), while Cu constitutes an essential compound of hemocyanin, a protein involved in the transport of oxygen in the blood of crustaceans (Taylor and Anstiss, 1999). In addition, decapod crustaceans are known to detoxify trace elements by storing them into trace element-rich granules (Rainbow, 1998) and previous work reported that the most common granules were those containing Cu and Zn (Nassiri et al., 2000). The low concentrations of other trace elements in the muscle of the crustacean species analysed in our study could also be explained by the morphology of these species: as their body is covered by an impermeable cuticle, trace element uptake from water is highly limited for decapod crustaceans (Rainbow, 1998). The trophic pathway would thus be the main pathway for these crustaceans' exposure to trace elements, as shown for cephalopods, sharks and teleost fishes (e.g., Bustamante et al., 1998; Mathews and Fisher, 2009). This suggests that their food items contain low levels of Fe, Hg and Se and/or these elements are poorly assimilated and retained. In the case of Hg, usually known to biomagnify through food webs, this would be consistent with the trophic positions of the crustacean species analysed in this study, which seemed to be lower than all other species (i.e., they had the lowest $\delta^{15}N$ values). Although we could not calculate their absolute trophic levels due to a lack of isotopic baseline in the Seychelles, this was supported by previously estimated trophic positions of these species compared to pelagic and demersal species (Sardenne et al., 2017). In addition, all species analysed here were scavengers and thus fed partially on large pieces of animal tissues (Palomares and Pauly, 2020). While digestive tissues like liver or digestive gland are known to be trace elements-rich, being detoxifying organs, muscle generally has a limited role both in terms of detoxification and storage. For scavenging decapod crustaceans, low trace element intake is thus expected from their food, which would partly explain their low concentrations in some trace elements (Rainbow, 1998).

In crustacean species analysed in this study, As concentrations were also remarkably high compared to sharks and teleost fishes (21 to 36 times higher). Decapod crustaceans, like the spiny lobster and spanner crab, are known to preferentially retain As in the form of arsenobetaine (Khokiattiwong et al., 2009), which could explain high As concentrations in these species. However, concentrations exceeding the maximum values reported in crustaceans (i.e., 95.3 $\mu g \cdot g^{-1}$ ww) suggest a link with the bioavailability of As in their food items. Indeed, the four crustacean species analysed here are known to feed partly on invertebrates like bivalves, while spiny lobsters have been reported to also feed on macroalgae (Sardenne et al., 2021). Although bivalves generally display low As uptake from seawater (Gómez-Batista et al., 2007; Hédouin et al., 2009), As accumulation can be very high when there is a disequilibrium between phosphorous (P) and nitrogen (N). As can replace P in phytoplankton growing in enriched-N waters, leading to As bioaccumulation to high levels as shown in some filter-feeder bivalves from New Caledonia (Hédouin et al., 2009; Metian et al., 2008). Such processes could also occur in waters surrounding the granitic islands of the Mahé Plateau, especially around Mahé Island, where crustaceans were caught. Indeed, due to local rainfall dynamics and to sewage discharge, waters in this area tend to be enriched in N, further destabilising the N:P ratio (Littler et al., 1991). The subsequent enhanced As accumulation in both primary producers and bivalves could thus transfer up the food chain to crustaceans feeding on them, thus enhancing As accumulation in their tissues. This deserves further investigation to determine if As highly accumulates in bivalves from the Seychelles coastal waters and effectively transfers from bivalves to crustaceans, or if dietary As could originate from another prey in decapod crustaceans' diet. Analyses of the physicochemical forms under which As is present in crustacean species' prey (i.e., proportions of arsenobetaine and iAs) are also needed.

Although taxonomy played a significant role in trace element accumulation for crustaceans, there was no clear clustering between shark and teleost fishes. Previous work on trace elements accumulation in these species showed differences in trace elements uptake from seawater, while assimilation efficiency from food was generally similar between sharks and teleosts (Jeffree et al., 2010; Mathews et al., 2008). Our results thus support the hypothesis that the main pathway for trace element uptake in these species is from food and not from the dissolved phase (Mathews and Fisher, 2009).

Habitat and diet types poorly explained trace element patterns in the clustering, but species were mainly grouped according to their vertical habitats (i.e., benthic, demersal and pelagic), suggesting that trace element exposure varies according to the considered marine compartment. This is supported by trace element dynamics in the marine environment, as sediments are known to be reservoir of trace elements (Neff, 2002). Benthic species, feeding on prey living on the seafloor, are thus more exposed to trace element intake through the trophic pathway (Wang, 2002). In addition, by feeding close to the seafloor, demersal species are more prone to feed on benthic feeders and thus are expected to be more exposed to trace element uptake than pelagic species (Rejomon et al., 2010). It is also possible that trophic position played a role in trace element accumulation in each marine compartment. Pelagic species, in group 3, had the highest Hg and Se concentrations among all groups and were among the species with the highest $\delta^{15}N$ values. As Hg is known to biomagnify along food webs and Se co-accumulates with Hg especially in case of high Hg concentrations (Bodin et al., 2017; Lavoie et al., 2013), it was thus expected that pelagic species in this study had the highest Hg and Se concentrations.

4.3. Benefit-risk assessment: Seychelles small-scale fisheries in human diets

Given the importance of seafood in a healthy diet, and especially in SIDS like the Seychelles where tropical small-scale fisheries are key food items in local populations' diets, knowledge on the trace element availability for artisanal fisheries is vital to better understand micronutrient supply and contaminant exposure in human diets.

Among all analysed species, crustaceans (i.e., spiny lobsters and the spanner crab) were particularly good sources of the essential trace elements Cu and Zn, as they brought in average >100 % of daily Cu needs and >56 % of daily Zn needs for children, young adults and adult women. Other species such as the big blue octopus, the bigeye trevally, the bludger, the bigeye snapper, the Indian mackerel, the little tunny, the swordfish and the blacktip shark were still a good source of Zn in adult women diets, bringing at least 10 % of their daily needs. Although the contribution of most of the studied Seychelles small-scale fisheries species to daily Fe needs was relatively low regardless of the population category, it could reach 5–15 % for trevallies, the Indian mackerel and the little tunny, especially for young adults and adult women. This is highly important for pregnant women, as it has been shown that, in combination with deficiency in other elements like Ca, Fe and/or Zn deficiency could increase risk of pre-eclampsia, hypertension or miscarriage during pregnancy (Kim et al., 2012; Shen et al., 2015), and could affect new-born health (Khoushabi et al., 2016). Although some of these teleost fish species were high in Hg content (i.e., number of daily servings before reaching PTI ≤ 1), which is known to have negative effects on foetal development (Mahaffey, 2004), the MHg:MSe ratio for these species was well below 1, suggesting very low risk of Hg poisoning. Thus, these species could be good candidates to help fight Fe and/or Zn deficiency in pregnant women.

All species exhibited levels of As and Se that met the dietary requirements for adult women and for all population categories, respectively, while they were very poor sources of Mn (one portion ≤ 1 % of all categories daily needs). Although no safety limit was found for As, its most toxic forms are known to be the inorganic forms (Sharma and Sohn, 2009), which are in low concentrations in seafood (i.e., 4.4 % in fish and 2.2 % in crustaceans; Uneyama et al., 2007). The estimated iAs content in our study was thus low for all species, with concentrations below or close to 1 $\mu g \cdot g^{-1}$ ww, suggesting low risk of toxicity. With regards to Se, the number of daily servings before reaching PTI was low for two emperors and two hammerhead sharks, and remained low for the emperors even after taking account the Hg:Se interaction. These results would suggest a potential risk of Se excess especially for children, although the intra-species variability of Se concentrations should be further investigated (i.e., only 2 and 3 individuals of the blackeye and pink ear emperors analysed, respectively). Further studies would also be needed to determine the fish consumption habits of Seychellois children in order to refine the age-specific mean weight of a daily portion used in the calculation of PTI, and the risk of Se excess.

For all analysed species, the number of daily servings before reaching Cd PTI was high (mostly $\geq$3 daily servings) for all population categories. However, for the species with the highest Cd concentrations (i.e., spanner crab, *Ranina ranina*) and for the pink ear emperor (*Lethrinus lentjan*), the number of daily servings before reaching PTI was very low for all three categories ($\leq$2 daily servings), suggesting risk of poisoning if eaten in excessive amount. These results should however be taken with caution in view of the low number of individuals analysed for those two species (i.e., $n = 5$ and 3 for *R. ranina* and *L. lentjan*, respectively). Although Hg concentrations were high in some species, the MHg:MSe ratio was $<$1 and the HBVSe was $>$0 in all species. Thus, our results confirmed those of Bodin et al. (2017), Hollanda et al. (2017) and Robinson and Shroff (2020), showing that there is a no risk of Hg poisoning for all categories through Seychelles fisheries products' consumption.

5. Conclusion and recommendations

This study provided essential baseline information on mineral supply and contaminant exposure for a SIDS community, the Seychelles, through the consumption of their main small-scale fisheries species. By identifying intraspecific difference in essential and potentially essential trace element supply and in risk of poisoning for both essential and non-essential trace elements, we highlighted the importance of consuming tropical small-scale fisheries products and diversifying the type of species consumed to meet mineral needs and remain healthy. We also showed the importance of marine species characteristics (i.e., presence/absence of regulation and/or detoxifying mechanisms, vertical habitat, diet and trophic position) in the understanding of such intraspecific difference in mineral supply and contaminant exposure. Further studies would however be needed to strengthen and complete our findings in particular with regards to species for which only few individuals were analysed in this study, and to other exploited species/families (e.g., shellfish) and seafood edible parts (e.g., fish and crustacean eggs) that were not investigated here. Last, efforts should be considered in determining the supply of other micronutrients such as essential fatty acids, amino acids, and vitamins, and exposure to organic contaminants from the tropical small-scale fisheries. Gathering data on the full nutritional profile of the main tropical small-scale fisheries is essential to SIDS as the Seychelles for the development of dietary guidelines and policies for their populations.

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Review & editing: all co-authors.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The dataset analysed in the current study is available from the corresponding author on reasonable request. The R code used to compute the cluster analysis and to represent the dendrogram and associated heatplot is available on Github: https://github.com/sabino/TraceElement_Cluster_Analysis.

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Appendix A. Supplementary data

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