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Elemental composition of small pelagic fishes in three East African lakes: Implications for nutritional security

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ABSTRACT

Micronutrient deficiencies and food insecurity constitute major threats to human health across Africa. With decreasing availability of large-bodied fishes (>20 cm), strategies have developed to target small pelagic fish (SPF) species (<20 cm total length) to improve the food availability; yet little is known regarding their nutritional content. Three species of SPFs - *Engraulicypris bredoi* (muziri), *Brycinus nurse* (ragoogi) and *Rastrineobola argentea* (mukene) - were collected from lakes Albert, Victoria, and Nabugabo in Uganda, East Africa. The content of essential elements (Ca, Fe, K, Mg, Na, P, Se, and Zn) and non-essential, potentially toxic elements (Cd and Pb) were measured and compared in fishes across landing sites within lakes Victoria (*R. argentea*) and Albert (*B. nurse, E. bredoi*) and between lakes (*R. argentea*). *Rastrineobola argentea* was the most nutritious of the fishes examined, although some variation was present in their elemental concentration among landing sites. Overall, all three species contain high levels of essential nutrients and fall within a safe range for non-essential, toxic elements based on current consumption habits. These SPFs can play an important role in addressing nutritional deficiencies in Uganda, and effort should be made to increase the availability, accessibility, and consumption of these under-utilized small fishes.

1. Introduction

Food insecurity and micronutrient deficiencies (also known as “hidden hunger”) pose serious challenges to human health and economic advancement. Globally, it is estimated that two billion people lack key micronutrients, and 155 million children are stunted, with this number increasing in Africa (Hawkes and Fanzo, 2017). Three billion people worldwide are affected by iron deficiency, with the prevalence being highest in South East Asia and Africa (WHO, 2001). Zinc deficiency is also widespread in developing countries, particularly in sub-Saharan Africa and South East Asia, where approximately one third of the populations are affected (Brown et al., 2004). Such micronutrient deficiencies are typically more pronounced among women of reproductive age (15–49 years) and children under 5 years of age in rural and peri-urban communities.

In Uganda, the focus of this study, 29 % of children under the age of 5 are stunted (short for their age), and 11 % are underweight (UBOS & ICF, 2018). The Uganda Demographic and Health Survey (2018) also reported high levels of anaemia in women and children that likely reflects several factors including iron deficiency. Micronutrients are integral to many biological processes and must be present in sufficient amounts to ensure healthy and regular physiological and biochemical functions. In Uganda, women and children living in poor or low-income settings (i.e., Base of the Pyramid, BoP, populations) are particularly impacted by low micronutrient availability in their diet associated with limited access to animal protein and other micronutrient rich food products (Wanyama et al., 2019). Increasing the consumption of calcium, iron, and zinc is of particular interest for human health in the region although the consumption of selenium, magnesium, potassium, sodium, and phosphorus is also relevant from a nutrition perspective.

Abbreviations: SPFs, Small pelagic fish(es); BoP, Base of the Pyramid; BDL, Below detection limit.

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Given the striking statistics on micronutrient deficiencies globally, and specifically in Uganda, there is an accelerating need to develop interventions to improve micronutrient availability and intake.

Fish provide not only an excellent source of protein but are also a rich source of bioavailable omega-3 fatty acids, amino acids, vitamins, and minerals (Tacon and Metian, 2013; Bogard et al., 2015; Kasozi et al., 2018; Hicks et al., 2019). Small pelagic fishes (SPFs) can play a particularly important role in tackling nutritional deficiencies because they are consumed whole and typically have high levels of bioavailable elements (i.e., iron, zinc, calcium; Kawarazuka and Béné, 2011; Thilsted et al., 2016; Byrd et al., 2020). Minerals tend to concentrate in the head, bones, and viscera of the fish, and therefore consuming the whole fish can vastly increase the nutrients obtained compared to the muscle tissue alone, which tends to be more commonly consumed from larger species (Roos et al., 2003, 2007; Thorseng and Gondolf, 2005; Kawarazuka and Béné, 2011). Small pelagic fishes can also be a more financially viable option making them more accessible to low-income households. They are traditionally more affordable than the larger fish species, can be bought in smaller quantities if necessary, and can be stored up to two months without refrigeration (as they are often dried). They can also be easily shared among household members and provide a more equal spread of nutrients per portion compared to larger fish where nutrient content varies between the body parts consumed (Thilsted et al., 1997; Genschick et al., 2018).

A recent analysis of micronutrient concentrations of global fisheries suggest that fish-based food strategies could contribute substantially to global food and nutrition security (Hicks et al., 2019; Golden et al., 2021). However, overfishing of inland waters threatens the biodiversity and ecosystem services that these systems provide (Allan et al., 2005). In Uganda, fish have become less available mainly due to intense fishing and declining catches of large fishes (>20 cm, total length), as well as increased demand for exported fish, in particular, *Lates niloticus* (Nile perch). Although Uganda is above the average per-capita fresh fish consumption of Africa (9.1 kg/person/year in 2009; OECD/FAO, 2013) at 10.73 kg/person/year in 2018 (FAOSTAT, 2021), it is far lower than the WHO recommendation of 25 kg/person/year. This per capita consumption rate is expected to decrease further in coming decades across Africa, due to increase in the size of the human population, income disparity, food prices, and export of fish (OECD/FAO, 2013), creating an even larger disparity in food resources, particularly affecting the BoP communities. In response to the decreasing catch, availability, and accessibility of large-bodied fishes, fisheries in inland waters of East Africa have developed strategies for targeting small-bodied pelagic species (<20 cm total length). In Uganda, these species include *Engraulicypris bredoi* (locally known as muziri), *Brycinus nurse* (locally known as ragoogi), and *Rastrineobola argentea* (locally known as mukene), and constitute > 80 % of fish catches in Lake Albert (*E. bredoi* and *B. nurse*) and 60 % in Lake Victoria (*R. argentea*), respectively (Nakiyende et al., 2013; LVFO, 2016; Mangeni-Sande et al., 2019).

The transition from large-bodied to small-bodied fishes in Uganda reflects a pattern across Africa of increasing use of and dependence on small pelagic fish species. In African lakes and reservoirs, the landings of small-sized fishes including herring (Clupeidae), cyprinids, and characins have steadily increased over the past three decades, and they now comprise nearly 75 % of the total yields for freshwater catches for African lakes (Kolding et al., 2019). These fishes represent an important food resource given their generally high turnover rate, which Kolding and colleagues (2019) estimate to be at least twice the biomass production rate of large-bodied fish stocks, as well as their high protein content and micronutrient concentrations (Kabahenda et al., 2011; Kasozi et al., 2018). Despite the accelerating exploitation of SPFs, national food policies in various African countries still overlook the vital links among production and distribution of small-bodied fish, human health, and food security (Kolding et al., 2019); and many facets of the biology of these small species remain less-well studied than in larger commercial fishes.

In terms of the value of SPFs in tackling micronutrient deficiencies, there are many gaps regarding the understanding of the nutrient composition of these fishes and whether nutrient profiles differ within and among populations (due to geographical location, fishing ground, body size, etc.). The overall goal of this study was to quantify the composition of elements in *R. argentea, B. nurse,* and *E. bredoi* from lakes across Uganda, East Africa to address knowledge gaps. The objectives of the study were to: (1) determine the concentration of essential elements relevant to nutritional security (Ca, Fe, Zn, K, Mg, Na, P, and Se), (2) compare the concentration of elements within and between lakes, and (3) analyze the concentrations of non-essential, potentially toxic elements (Cd and Pb) that are relevant for food safety. Variation was examined across landing sites within lakes Victoria (*R. argentea*) and Albert (*B. nurse, E. bredoi*) and between lakes (*R. argentea*). Gaining a thorough understanding of the nutritional content and safety of SPFs in Uganda can assist in designing strategies that can be incorporated into regional food security plans and help to combat the micronutrient deficiencies among vulnerable BoP communities.

2. Methods

2.1. Study sites & species

Lake Victoria is the largest tropical lake in the world, with its waters shared by Uganda, Kenya, and Tanzania (68,800 km^2, average depth of 40 m and max depth of 80 m; Kendall, 1969; Stager et al., 1996). Over the past century, Lake Victoria experienced dramatic ecological changes associated with intense fishing, eutrophication, and the introduction of non-native fishes in the 1950 s and 60 s including the predatory *L. niloticus* (see reviews by Kaufman, 1992; Balirwa et al., 2003; Chapman et al., 2008). Although populations of many fish species had declined prior to the *L. niloticus* invasion, the increase in the *L. niloticus* population in the 1980's coincided with the further decline or disappearance of around 40 % of the 500 + species of endemic haplochromine cichlids, as well other non-cichlid fish species (Kaufman, 1992; Witte et al., 1992; Balirwa et al., 2003; Chapman et al., 2008). In contrast, *R. argentea* increased dramatically in biomass in the 1980's (Wanink, 1999; Sharpe and Chapman, 2014, 2018), which has been attributed to reduced competition with haplochromine cichlids, among other factors (Goldschmidt et al., 1993; Wanink, 1998; Wanink and Witte, 2000). This alteration in the species composition of the system led to Lake Victoria becoming Africa's largest in-land commercial fishery focusing on two main interests: (1) large-bodied fishes (*L. niloticus* and four tilapiine species; Odongkara et al., 2005; Odongkara et al., 2009), and (2) the small, but abundant, *R. argentea* (Sharpe et al., 2012; Sharpe and Chapman, 2018).

Lake Nabugabo is a satellite lake of Lake Victoria that is comparatively shallower in depth (average depth of 3.1 m, and maximum depth of 8 m) and smaller in area (33 km^2; Stager et al., 2005; Nyboer and Chapman, 2013). The former bay was isolated from Lake Victoria ~5000 years ago (Stager et al., 2005). *Lates niloticus* was introduced into Lake Nabugabo in the 1960's, and its establishment in the system coincided with the decline or disappearance of several fish species (Ogutu-Ohwayo, 1993). These changes led to a switch in the lake's fishery from one focused on a diverse set of native fishes to one currently focused on the three species: *L. niloticus, R. argentea,* and *Oreochromis niloticus* (Ogutu-Ohwayo, 2000; Wandera, 2000, 2005; Groves et al., 2022). Data on changes in the abundance of *R. argentea* following the upsurge of *L. niloticus* are not available, but *R. argentea* has clearly persisted with *L. niloticus*, and an artisanal fishery for *R. argentea* has developed over the past decade (Groves et al., 2022).

Lake Albert is a large lake (~5600 km^2, average depth of 25 m, max depth of 60 m) lying within the Albertine Rift with its waters shared by Uganda and the Democratic Republic of the Congo (DRC; Lake Albert, 2013). The lake is a major source of fisheries production for both Uganda and DRC (Nakiyende et al., 2013). Although Lake Albert contains fewer endemic species than other African Great Lakes, it is home to 55 fish species and accounts for upwards of 30 % of Uganda's fish production (Wandera and Balirwa, 2010). Similar to Lake Victoria, dramatic changes to the Lake Albert fishery over the past four decades has led to a reduction of larger species and the development of a fishery focused on two smaller species: *E. bredoi* and *B. nurse* (Mbabazi et al., 2012; Taabu-Munyaho et al., 2012; Nakiyende et al., 2013).

Rastrineobola argentea (Pellegrin, 1904), locally known as mukene in Uganda, is a small (<7 cm) pelagic cyprinid, endemic to the Lake Victoria Basin (Wandera, 2000, 2005; Sharpe et al., 2012). With the upsurge in the population of *R. argentea* in the 1980's and development of the commercial fishery, *R. argentea* has become the most important fishery by mass in Lake Victoria (Sharpe et al., 2012; Njiru et al., 2014; LVFO, 2016).

Brycinus nurse, a small characid fish (<15 cm) known locally as ragoogi, and *Engraulicypris bredoi*, a small cyprinid fish (<5 cm) known locally as muziri in Uganda (Poll, 1945), are pelagic species endemic to Lake Albert. *Engraulicypris bredoi* is now the most dominant fishery by mass in Lake Albert with an estimated annual catch of 78,000 tonnes in 2012 accounting for roughly 51 % of the catch (Taabu-Munyaho et al., 2012). *Brycinus nurse* is the second most important commercial species harvested at 51,000 tonnes and approximately 34 % of total catch (Taabu-Munyaho et al., 2012).

All three of these small fishes are typically harvested at night (although *B. nurse* can be harvested during the day) using floating oil lamps and are captured using lampara nets (small seines, usually 5 mm mesh size; Sharpe et al., 2012; Taabu-Munyaho et al., 2012). Fish are typically dried whole and consumed locally or shipped regionally throughout East Africa. These small species of fish have become an extremely important source of food and an economically valuable resource for Uganda in recent decades.

2.2. Sample collection

A random bulk primary sample of *Rastrineobola argentea* was collected from three landing sites (Kikondo, Kiyindi, and Lambu) on Lake Victoria and one landing site on Lake Nabugabo (Luwafu) in November of 2019 (Fig. 1). Fish were collected from multiple sites within Lake Victoria and from Lake Nabugabo to detect variation within and between lakes in elemental concentrations. After dark, local fishers were met by boat at each landing site where a cup (>100 individuals) of live *R. argentea* was collected from the haul of one fisherman and euthanized immediately in a mixture of clove oil and ethanol. Fish were then gently rinsed in water to remove as much of the clove oil mixture as possible before being placed in a plastic bag on ice. Likewise, a random bulk sample of *Brycinus nurse* and *E. bredoi* samples were also collected from two landing sites (Kaiso and Dei) on Lake Albert in February of 2020 (Fig. 1) and similarly processed. Research protocols were reviewed and approved by McGill University's Animal Care Committee.

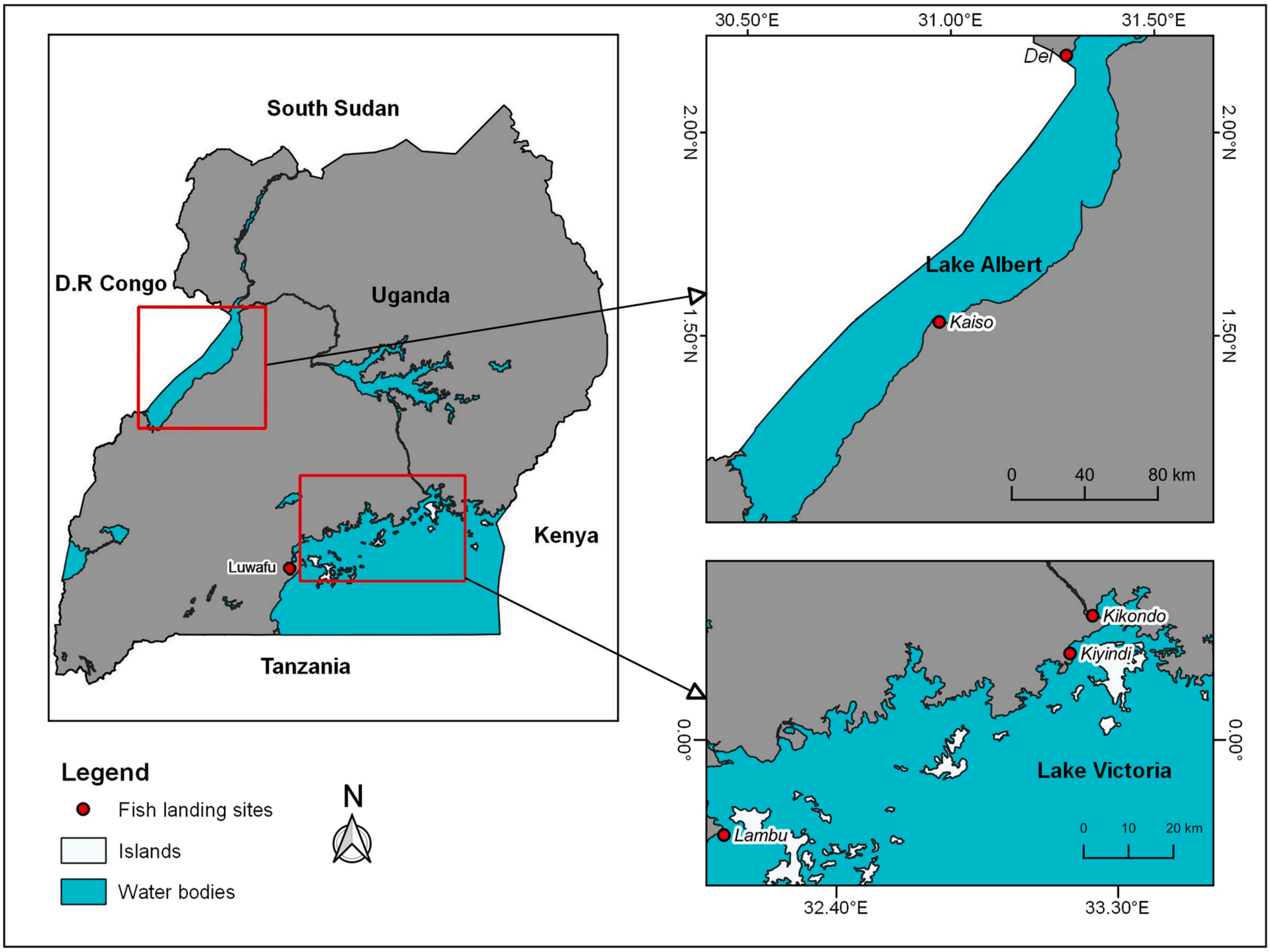

Fig. 1. Map of the landing sites on lakes Victoria, Nabugabo, and Albert. Landing sites on Lake Victoria (Kikondo, Kiyindi, and Lambu) and Lake Nabugabo (Luwafu) were sampled in November 2019. Landing sites on Lake Albert (Kaiso, Dei) were sampled in February 2020.

2.3. Sample preservation and laboratory analysis

A cup of fish was retrieved from the catch of a local fisher as a random primary sample. From the cup of fish collected, 20 individual fish from each primary sample (i.e., each species at each site) were selected ad litem, and total length (measured from the anterior of the jaw to the posterior of the compressed caudal fin, cm), standard length (measured from the anterior of the jaw to the posterior of the caudal peduncle, cm), and wet mass (g) were recorded (Table 1). Upon recording biometric information for each individual, the samples were preserved by placing them in labeled, plastic weigh boats and putting them into a food dehydrator, where they were dried at 60 °C until a constant mass was achieved (± 0.01 g), which occurred within 24 h of drying. Once dried, specimens were reweighed so moisture content could be calculated. Fish were then tagged and placed into individually marked polyethylene vials, which were sealed with parafilm for transport to the laboratory at McGill University in Montreal, Canada.

Once in the lab, fish samples were prepared for element analyses using a combined dry-ashing and acid digestion method (see Nesbitt et al., 2022 for details). In brief, upon homogenization of samples (analytical sample), a 0.015 g portion of homogenate (analytical portion) was transferred into heat resistant vials and placed in a muffle furnace at 500 °C for 24 h. Following dry-ashing, samples were digested in optima grade hydrogen peroxide (H_2O_2), trace metal grade nitric acid (HNO_3), and trace metal grade hydrochloric acid (HCl). Following digestion, the sample matrix was diluted with Type 1 (Ultrapure) water to a total volume of ~15 mL.

Ionic concentrations of a suite of elements (Ca, Cd, Fe, K, Mg, Na, P, Pb, Se, and Zn) were determined on the digested, homogenized, whole fish samples by optical emission spectrometry (ICP-OES). Calibration curves for each element were constructed using a commercial, aqueous 1000 mg/L certified standard solutions. Detection limits for each element were, in mg/L (ppm), as follows: Ca (0.845), Cd (0.001), Fe (0.019), K (0.261), Mg (0.280), Na (0.277), P (0.278), Pb (0.006), Se (0.010), and Zn (0.010). Each individual fish sample was measured five times to produce a mean individual value and reproducibility of this analysis was better than 3.0 % Relative Standard Deviation (RSD). Data from the ICP-OES are reported in mg/L of solution, so measurements had to be converted into mg/g of sample using the following equation:

$$\mathit{Element}\left(\frac{\mathrm{mg}}{\mathrm{g}}\right)=\frac{\mathit{Element}\left(\frac{\mathrm{mg}}{\mathrm{L}}\right)*\text{Diluted sample }\mathit{volume}\ (\mathrm{L})}{\text{Mass of digested sample (g)}}$$

It should be noted that possible contamination of samples from the solvents used for euthanasia was explored in a comparison between samples in this study and samples purchased from local fisherman that were already dead and therefore not immersed in clove oil. From a consumption perspective, differences between treatment groups, although statistically significant, are small. This comparison can be seen in detail in Table S1 in the supplementary material.

2.4. Statistical analysis

2.4.1. Differences in essential elements among species

To compare differences in essential elements (Ca, Fe, K, Mg, Na, P, Se, and Zn) among fish species, samples were combined across landing sites for each species (*R. argentea:* n = 80*, B. nurse*: n = 40, *E. bredoi:* n = 40). This was necessary as the experimental design was not fully crossed (i.e., fish were not all sampled from the same lakes and sites due to inherent differences in the species distributions). Averages were calculated for all elements using values above detection limit with the exception of selenium. Selenium was calculated by assuming that samples that were below detection limit (BDL) were at the detection limit. This was necessary for selenium, as only ~25 % of samples were detectable (41/160). Calculating averages in this way will provide conservative estimates where values could be slightly overestimated, but it helps to avoid skewing means as would occur if only values above BDL are used. No statistical analysis was run on Se, but means are reported (see Section 2.4.3 for more detail). Body size effects were not tested for when comparing the three species, as there were very few size effects detected within species (see below), and *B. nurse* was much larger than the other two species, so there was no overlap in size between *B. nurse* and either *E. bredoi* or *R. argentea.* ANOVA or Welch's ANOVA was used to detect differences among species as indicated above. The Games-Howell post-hoc analysis was performed on Welch's ANOVA, while a Tukey SD post-hoc test was used to identify significant differences of ANOVA/ANCOVA models.

2.4.2. Differences in essential elements among sites

Variation in essential elements (Ca, Fe, K, Mg, Na, P, Se, and Zn) among landing sites was analyzed for each species separately. Samples of individual *Rastrineobola argentea* were compared among four landing sites (Kikondo, Kiyindi, Lambu, Luwafu, n = 20 per site) on lakes

Table 1
Biometric information on the three small species of fish collected from each landing site on Lake Victoria (*R. argentea*), Lake Nabugabo (*R. argentea)* and Lake Albert (*B. nurse* and *E. bredoi*) in November 2019 and February 2020. Mean values are given with a standard error (SE) and the range (in brackets).

Site	Species	n	Total Length (cm) Mean ± SE (Range)	Standard Length (cm) Mean ± SE (Range)	Mass (g) Mean ± SE (Range)
Lake Victoria	***Rastrineobola argentea***				
	Kikondo	20	4.0 ± 0.1 (3.3–5.0)	3.4 ± 0.1 (2.8–4.3)	0.5 ± 0.0 (0.2–0.9)
	Kiyindi	20	4.7 ± 0.1 (4.4–5.2)	4.0 ± 0.1 (3.6–4.4)	0.8 ± 0.0 (0.6–1.1)
	Lambu	20	4.2 ± 0.1 (3.5–5.1)	3.5 ± 0.1 (2.9–4.2)	0.6 ± 0.0 (0.3–1.1)
Lake Nabugabo	***Rastrineobola argentea***				
	Luwafu	20	4.7 ± 0.1 (4.4–5.1)	3.9 ± 0.1 (3.6–4.3)	0.7 ± 0.0 (0.5–0.8)
Lake Albert	***Brycinus nurse***				
	Dei	20	9.0 ± 0.3 (7.4–12.2)	7.2 ± 0.2 (5.9–9.6)	9.2 ± 1.0 (4.4–24.4)
	Kaiso	20	7.2 ± 0.2 (5.9–8.6)	5.6 ± 0.1 (4.6–6.7)	4.3 ± 0.3 (2.3–6.9)
Lake Albert	***Engraulicypris bredoi***				
	Dei	20	4.1 ± 0.1 (2.5–4.7)	3.4 ± 0.1 (2.1–4.0)	0.5 ± 0.0 (0.1–0.9)
	Kaiso	20	3.6 ± 0.1 (3.2–4.1)	3.0 ± 0.1 (2.6–3.6)	0.3 ± 0.0 (0.2–0.5)

* Total length was measured from the most anterior part of the jaw to the posterior of the compressed caudal fin, while standard length was measured from the most anterior part of the jaw to the posterior of the caudal peduncle.

Victoria (three sites) and Nabugabo (one site); *E. bredoi* and *B. nurse* were compared between Kaiso and Dei landing sites on Lake Albert (n = 20 per species per site). As was done with the species differences, all elements were calculated with values above detection limit except for selenium, where samples below detection were assumed to be at the detection limit. To explore effects of body size on elements, linear regressions were run with element concentration (dependent variable) and standard length of specimens for each species and site. When significant effects were detected, ANCOVA was used to test for site differences in element concentration with site as the fixed factor and standard length as the covariate. If there was no significant interaction between standard length and site, the term was removed from the model. In general, body size effects on element concentration were small, and only observed for a few nutrients, so remaining site comparisons were tested using an ANOVA. Welch's ANOVA was used when variance was unequal among groups. The Games-Howell post-hoc analysis was performed on Welch's ANOVA, while a Tukey SD post-hoc test was performed for ANOVA/ANCOVA models. All statistical analyses were conducted in R v 4.0.4 (R Core Team, 2019).

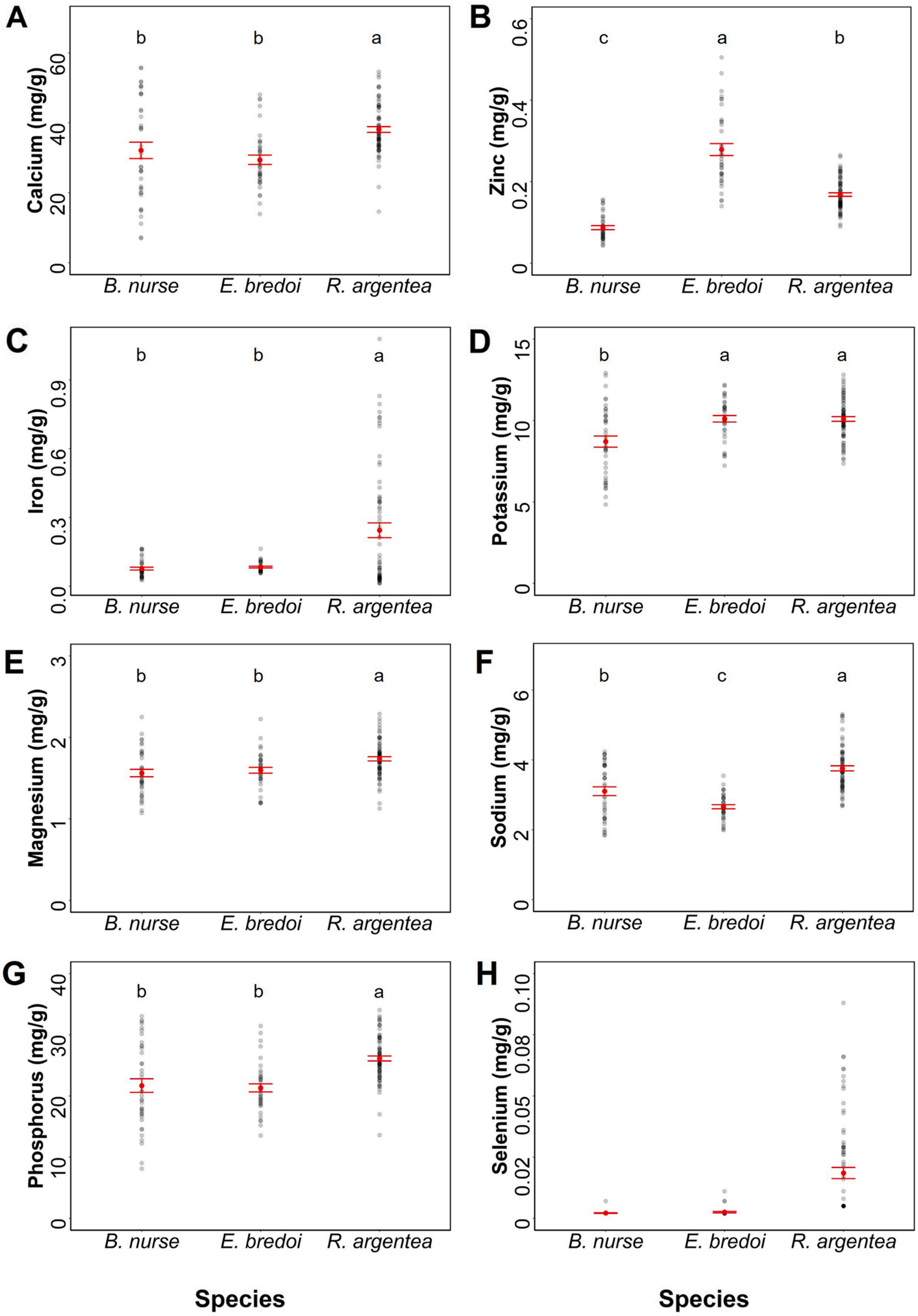

Fig. 2. Essential element concentrations in three species of small fishes. Concentrations of A) calcium, B) iron, C) zinc, D) potassium, E) magnesium, F) sodium, G) phosphorus, and H) selenium in mg/g in dried *R. argentea, B. nurse*, and *E. bredoi* collected from lakes Victoria, Nabugabo, and Albert in November 2019 and February 2020. Mean values are represented by a red dot with standard error bars. Superscript letters that differ represent significant differences based on post-hoc analyses at $p < 0.05$.

2.4.3. *Concentrations of non-essential, toxic elements for food safety*

Most samples analyzed for cadmium and lead had concentrations below detection limits, therefore samples were combined across landing sites for each species. Estimated values of Pb and Cd were calculated using the same method as selenium where samples below detection were assumed to be at the detection limit. Statistical analyses were not run on these elements, however, mean values are reported along with the percentage of samples BDL.

3. Results

3.1. *Differences in essential elements among species*

Among the three SPFs, *R. argentea* had the highest concentrations of calcium (Welch's ANOVA: F = 16.268, df = 2, $p < 0.001$), iron (Welch's ANOVA: F = 12.909, df = 2, $p < 0.001$), magnesium (ANOVA: F = 8.424, df = 2, $p < 0.001$), sodium (Welch's ANOVA: F = 68.27, df = 2, $p < 0.001$), and phosphorus (Welch's ANOVA: F = 22.612, df = 2, $p < 0.001$), while *E. bredoi* had the highest concentration of zinc (Welch's ANOVA: F = 122.97, df = 2, $p < 0.001$; Fig. 2). Calcium, iron, magnesium, and phosphorus did not differ between *E. bredoi* and *B. nurse*. Zinc differed among all species with the highest values present in *E. bredoi*, followed by *R. argentea*, and the lowest in *B. nurse*. Potassium was lower in *B. nurse* than in the two smaller species. Sodium was highest in *R. argentea*, followed by *B. nurse*, and then *E. bredoi* (Fig. 2). Selenium values were higher in *R. argentea* (56.25 % of values below a detection limit of 0.005) than in *B. nurse* (97.5 % of values below a detection limit of 0.002) or *E. bredoi* (92.1 % of values below a detection limit of 0.002) (Fig. 2). The average moisture content was 76.5 % for *R. argentea*, 72.9 % for *B. nurse*, and 78.2 % for *E. bredoi*.

3.2. *Differences in essential elements among sites*

For *R. argentea,* all elements except potassium (and excluding Se) showed significant differences among the four landing sites (Table 2). Calcium was the only element to exhibit a size effect with larger fish characterized by a higher calcium concentration (ANCOVA: F = 5.654, df = 3, p = 0.02). In general, elemental concentrations tended to be higher at Kiyindi and Lambu in Lake Victoria than at Kikondo (Lake Victoria) and Luwafu (Lake Nabugabo; Table 2). Differences in selenium concentrations in the fish at landing sites could not be analyzed for any of the species due to a low percentage of values above detection limit.

The elemental composition of *B. nurse* did not differ between landing sites with respect to mean concentrations of calcium, zinc, iron, potassium, sodium, or phosphorus (Table 3). Magnesium, however, was found to be higher at Kaiso compared to Dei (Table 3). Potassium was the only element that displayed a significant size effect with larger fish exhibiting a lower concentration (ANCOVA: F = 11.468, df = 1, p = 0.002).

For *E. bredoi*, mean concentrations of calcium, zinc, sodium, and phosphorus did not differ between the two landing sites on Lake Albert (Kaiso and Dei). The average concentration of potassium and magnesium was higher in *E. bredoi* collected from Kaiso, while the average iron concentration was higher in fish from Dei (Table 4). Zinc was the only element to exhibit a size effect across sites with higher concentrations in larger fish (ANCOVA: F = 12.791, df = 1, p = 0.001).

3.3. *Concentrations of non-essential, toxic elements for food safety*

For cadmium, the average concentration reported for *R. argentea* was 0.001 ± 0.0001 (86.25 % of values below a detection limit of 0.0009), while that of *B. nurse* was found to be 0.0006 (97.5 % below a detection limit of 0.0005), and *E. bredoi* was 0.0006 ± 0.000058 (84.2 % below a detection limit of 0.0005). *Rastrineobola argentea* was the only species to produce detectable lead concentrations (0.0044 ± 0.0005, 90 % below a detection limit of 0.003), while 100 % of *B. nurse* and *E. bredoi* samples were below a detection limit of 0.0018.

4. Discussion

Rastrineobola argentea, Engraulicypris bredoi, and *Brycinus nurse* are small species that have come to dominate the Ugandan fishery by mass in lakes Victoria (*R. argentea*) and Albert (*B. nurse, E. bredoi*) in recent years, and have quickly become an important source of food and revenue for Ugandans. Given the importance of these SPFs to nutritional and financial security, it is crucial to gain a better understanding of their nutrient composition. *Rastrineobola argentea* was found to have the highest nutritional value overall, although elements did show a significant amount of variation among sites. Non-essential, toxic elements (Cd and Pb) were also identified to be within a healthy range for consumption for all three species, as all values were within WHO guidelines. These three SPFs are also reported to be high in protein and fat (IOC, 2012). If harvested sustainably and preserved properly, these species can contribute to tackling nutritional deficiencies in the region.

Table 2

Concentrations of elements in *R. argentea* from the Lake Victoria Basin. Species averages are provided along with averages for each of the four sites they were collected from. Three sites were on Lake Victoria (Kikondo, Kiyindi, and Lambu) and one site was on Lake Nabugabo (Luwafu). Fish were collected in November 2019. Statistical analyses were run on site differences and are represented with superscript letters. Those that differ represent significant differences based on post-hoc analyses at $p < 0.05$. Mean values for dried fish are given in mg/g with a standard error (SE) and the range (in brackets).

	R. argentea (mg/g) Mean ± SE (Range)	Kikondo (mg/g) Mean ± SE (Range)	n	Kiyindi (mg/g) Mean ± SE (Range)	n	Lambu (mg/g) Mean ± SE (Range)	n	Luwafu (mg/g) Mean ± SE (Range)	n	Test	F	df	p
Calcium	38.08 ± 1.12 (14.58–54.62)	36.20 ± 1.78^{b} (14.58–54.62)	19	39.10 ± 1.65^{a} (32.35–50.42)	20	41.80 ± 1.52^{a} (31.85–53.70)	19	35.01 ± 1.61^{b} (32.17–41.18)	18	ANCOVA	4.426	3	0.007
Zinc	0.17 ± 0.01 (0.09–0.27)	$0.16 \pm 0.01^{b,c}$ (0.09–0.27)	20	0.19 ± 0.01^{a} (0.15–0.23)	19	$0.18 \pm 0.01^{a,b}$ (0.12–0.26)	20	0.15 ± 0.01^{c} (0.12–0.19)	20	Welch's ANOVA	14.206	3	<0.001
Iron	0.24 ± 0.02 (0.01–1.08)	0.05 ± 0.04^{b} (0.01–0.11)	16	0.04 ± 0.04^{b} (0.01–0.08)	18	0.36 ± 0.04^{a} (0.04–0.80)	18	0.50 ± 0.04^{a} (0.05–1.08)	18	Welch's ANOVA	27.671	3	<0.001
Potassium	10.09 ± 0.18 (7.36–12.81)	9.89 ± 0.29^{a} (7.59–12.03)	18	10.56 ± 0.27^{a} (7.36–12.81)	20	10.19 ± 0.29^{a} (8.05–12.23)	18	9.69 ± 0.28^{a} (8.15–11.39)	19	ANOVA	1.858	3	0.145
Magnesium	1.74 ± 0.03 (1.13–2.29)	1.59 ± 0.05^{c} (1.13–2.12)	18	1.87 ± 0.04^{a} (1.55–2.23)	20	$1.81 \pm 0.05^{a,b}$ (1.34–2.29)	18	$1.67 \pm 0.04^{b,c}$ (1.48–1.89)	20	ANOVA	7.585	3	<0.001
Sodium	3.76 ± 0.07 (2.69–5.31)	3.41 ± 0.12^{b} (2.69–4.59)	18	4.37 ± 0.11^{a} (3.23–5.31)	20	3.48 ± 0.12^{b} (2.69–4.17)	17	3.68 ± 0.12^{b} (2.95–4.24)	18	ANOVA	15.048	3	<0.001
Phosphorous	26.12 ± 0.54 (13.59–34.02)	23.46 ± 0.78^{b} (13.59–31.56)	18	27.58 ± 0.74^{a} (22.48–32.75)	20	27.54 ± 0.74^{a} (21.49–34.02)	20	$25.63 \pm 0.74^{a,b}$ (22.43–29.50)	20	ANOVA	6.559	3	<0.001

Table 3

Concentrations of elements in *B. nurse*. Species averages are provided along with averages for each of the sites they were collected from on Lake Albert – Kaiso and Dei. Fish were collected in February 2020. Mean values for dried fish are given in mg/g with a standard error (SE) and the range (in brackets).

	B. nurse (mg/g) Mean ± SE (Range)	Kaiso (mg/g) Mean ± SE (Range)	n	Dei (mg/g) Mean ± SE (Range)	n	Test	F	df	p
Calcium	32.14 ± 1.57^{b} (7.00–55.75)	32.04 ± 3.40 (13.18–55.71)	19	32.24 ± 3.32 (7.00–55.75)	20	ANOVA	0.002	1	0.967
Zinc	0.09 ± 0.01^{c} (0.04–0.16)	0.09 ± 0.01 (0.06–0.15)	20	0.08 ± 0.01 (0.04–0.16)	20	ANOVA	0.687	1	0.413
Iron	0.08 ± 0.03^{b} (0.03–0.16)	0.07 ± 0.01 (0.03–0.16)	20	0.08 ± 0.01 (0.03–0.16)	20	ANOVA	1.399	1	0.244
Potassium	8.70 ± 0.24^{b} (4.84–12.91)	9.02 ± 0.52 (5.81–12.91)	20	8.37 ± 0.52 (4.84–12.76)	20	ANCOVA	0.564	1	0.457
Magnesium	1.56 ± 0.04^{b} (1.07–2.25)	1.66 ± 0.06 (1.19–2.25)	20	1.45 ± 0.05 (1.07–1.83)	18	ANOVA	6.361	1	0.016
Sodium	3.10 ± 0.10^{b} (1.84–4.23)	3.29 ± 0.17 (2.01–4.16)	20	2.91 ± 0.17 (1.84–4.23)	20	ANOVA	2.331	1	0.135
Phosphorous	21.68 ± 0.76^{b} (8.10–33.02)	21.95 ± 1.60 (12.74–33.02)	19	21.43 ± 1.56 (8.10–31.83)	20	ANOVA	0.055	1	0.816

Table 4

Concentrations of elements in *E. bredoi*. Species averages are provided along with averages for each of the sites they were collected from on Lake Albert – Kaiso and Dei. Fish were collected in February 2020. Mean values for dried fish are given in mg/g with a standard error (SE) and the range (in brackets).

	E. bredoi (mg/g) Mean ± SE (Range)	Kaiso (mg/g) Mean ± SE (Range)	n	Dei (mg/g) Mean ± SE (Range)	n	Test	F	df	p
Calcium	29.43 ± 1.59^{b} (13.92–48.07)	30.60 ± 1.85 (21.55–48.07)	20	28.12 ± 1.95 (13.92–46.66)	18	ANOVA	0.856	1	0.361
Zinc	0.28 ± 0.01^{a} (0.14–0.51)	0.29 ± 0.02 (0.14–0.42)	20	0.26 ± 0.02 (0.20–0.51)	18	ANCOVA	0.798	1	0.378
Iron	0.08 ± 0.03^{b} (0.06–0.16)	0.08 ± 0.004 (0.06–0.11)	20	0.09 ± 0.01 (0.07–0.16)	18	Welch's ANOVA	4.779	1	0.037
Potassium	10.10 ± 0.25^{a} (7.2–12.17)	10.65 ± 0.25 (7.79–12.17)	20	9.48 ± 0.26 (7.22–12.13)	18	ANOVA	10.801	1	0.002
Magnesium	1.60 ± 0.04^{b} (1.19–2.22)	1.67 ± 0.05 (1.19–2.22)	20	1.52 ± 0.05 (1.20–1.87)	18	ANOVA	4.998	1	0.032
Sodium	2.66 ± 0.10^{c} (1.99–3.55)	2.72 ± 0.08 (2.01–3.55)	20	2.59 ± 0.09 (1.99–3.29)	18	ANOVA	1.251	1	0.271
Phosphorous	21.30 ± 0.77^{b} (13.53–31.44)	21.98 ± 0.90 (15.98–31.44)	20	20.55 ± 0.95 (13.53–29.00)	18	ANOVA	1.204	1	0.280

4.1. Elemental concentrations

4.1.1. Difference among species

Among the three SPFs, *R. argentea* was found to be the richest in calcium, iron, magnesium, sodium, and phosphorus, whereas *E. bredoi* had the highest levels of zinc (Fig. 2). In general, all three species exhibited high concentrations of elements, although levels of *E. bredoi* and *B. nurse* typically fell slightly below that of *R. argentea*. Variation among the species may reflect differences in food preference/availability, individual species uptake mechanisms, and/or the aqueous concentration of elements in their environment.

Increasing the availability, accessibility, and consumption of SPFs in Uganda could greatly contribute to nutritional security, especially that of vulnerable populations. Although all eight elements examined in this study (Ca, Zn, Fe, Se, K, Mg, Na, P) are involved in important physiological processes and their intake is recommended to meet nutritional requirements, increasing the dietary intake particularly of iron, zinc, and calcium is an important goal when addressing micronutrient deficiencies (i.e., “hidden hunger”). These elements can be more difficult to acquire from plant-based food sources (Gibson et al., 1998, 2010) and with the low intake of animal products especially in women and children throughout Uganda (FANTA-2, 2010; Kyamuhangire et al., 2013; Wanyama et al., 2019), identifying food sources rich in these elements can improve nutrient intake. A study by Kyamuhangire et al. (2013) analysed the daily micronutrient intake and inadequacies of children ranging from 2 to 5 years of age and women of reproductive age in three regions across Uganda (Kampala, northern rural regions, and western rural regions). Results of the study indicated that 55–75 % of children and 65–89 % of women had an inadequate intake of iron, while 74–82 % of children and 18–36 % of women had inadequate intake of zinc, and 98–100 % of children and 84–99 % of women had inadequate intake of calcium. These results corroborate with findings of various Ugandan national policy documents. For example, the Uganda Demographic and Health Survey reported that 53 % of children under 5 years of age and 32 % of women between 15 and 49 are anaemic (UBOS and ICF, 2018), while the Food and Nutritional Technical Assistance report estimated that 20–69 % of children and 21–29 % of adults are deficient in zinc (FANTA-2, 2010). The results presented here demonstrate that all three species of SPFs examined contain high levels of iron (0.08–0.24 mg/g), zinc (0.09–0.28 mg/g), and calcium (29.43–38.08 mg/g, Table 5), and therefore could be very important in reducing nutritional deficiencies prevalent across Uganda. These findings are supported by a comprehensive nutrient gap assessment study that was conducted by White and colleagues (2021) for East and Southern Africa (including Uganda), which revealed that small, dried fishes were the best source for six key micronutrients (zinc, iron, vitamin A, vitamin B12, folate, and calcium). A serving of 100 g of dried SPFs was reported to achieve an average of 88% of requirements across these six micronutrients for children aged 6–23 months, making them an excellent option to incorporate into regional food security plans (White et al., 2021).

When the three species analysed in this study are compared to larger fish often consumed within the region, such as the popular *L. niloticus*, it is apparent that they can provide superior nutritional content per serving in terms of some important elements. For example, a study by

Kabahenda et al. (2011) found that a 100 g serving of *L. niloticus* filet contained 1.06 mg of iron, 0.72 mg of zinc, and 134.24 mg of calcium, while the same sized serving of sun-dried *R. argentea* contained 10 times the iron content (10.68 mg), 14 times the zinc content (10.25 mg), and 11 times the calcium content (1556.39 mg). In the current study, similar or higher levels of calcium (2942–3808 mg), iron (7.6–26.3 mg), and zinc (13.6–27.9 mg) were detected for 100 g of dried *R. argentea*, *B. nurse*, and *E. bredoi*. Such differences in the nutritional content of small vs. large fishes are likely to reflect, at least in part, the fact that small fishes are eaten whole; while larger fish are typically fileted, and only the muscle tissue is consumed. By eating the fish whole, body parts that are high in nutrients (i.e., head, bones, viscera, scales, eyes etc.) are eaten, improving the nutrients received by the consumer.

4.1.2. *Difference among sites*

Fish primarily ingest minerals either directly from the water they inhabit or from dietary sources, and thus their environment can affect their elemental composition. For *R. argentea,* concentrations of elements were often lower in specimens collected from Luwafu and Kikondo than in conspecifics from Kiyindi and Lambu. Elements such as calcium, potassium, and sodium are absorbed directly from the water, although uptake can also be supplemented by dietary sources if aqueous concentrations are low. Comparatively, phosphorus is primarily absorbed through diet, while iron, magnesium, and zinc are taken up from both the water and food (Terech-Majewska et al., 2016). Water chemistry has been shown to play a vital role in fishes' ability to sequester nutrients, and environments with low aqueous concentrations may therefore be reflected by lower internal concentrations in inhabiting fishes. A recent study demonstrated that both aqueous calcium concentration and scalar calcium concentration of *R. argentea* were lower in Lake Nabugabo than in fish from Lake Victoria (Nesbitt et al., 2022). In general, Lake Nabugabo is known to be an ion poor water body due to the regional bedrock composition and filtration of inflows by the surrounding swamp (Beadle, 1974; Standley et al., 2012*)*. Comparatively, Kikondo lies within the Napoleon Gulf of Lake Victoria where water flows into the Nile River potentially creating a unique aqueous environment compared to the rest of the lake. Ionic values reported by Hecky and Bugenyi (1992) for the Napoleon Gulf (7.82 mg/g for Na, 3.52 mg/g for K, 2.19 mg/g for Mg, and 4.81 mg/g for Ca) were lower than data reported by Standley et al. (2012) for the Ugandan waters of Lake Victoria (10.40 mg/g for Na, 11.47 for K, 2.82 mg/g for Mg, and 7.05 mg/g for Ca). Such differences in ionic concentrations could potentially contribute to lower internal element concentrations of *R. argentea* from this site. In comparison to Luwafu and Kikondo, Lambu and Kiyindi are sites that are highly impacted by human activities and lie within sheltered bays. These sites may have higher ion concentrations, which could be reflected in the element concentration of *R. argentea*.

For *E. bredoi* and *B. nurse* sampled from two locations on Lake Albert (Kaiso and Dei), element concentrations were similar between the landing sites, with exception of magnesium in *B. nurse* and magnesium, potassium, and iron in *E. bredoi*. Where significant, differences in mean concentrations were relatively small. The difference between the two sites could potentially be due to differences in aqueous concentrations and/or food sources available; however, additional studies would be required to address this. Although some statistical differences were found for each of the species at different landing sites, it should be noted that these differences are relatively small and will likely not have a large impact on the average daily nutrient intake of consumers.

4.2. *Fish consumption*

4.2.1. *Safe consumption limits of non-essential, toxic elements*

According to the most recent report by World Health Organization (WHO, 1996) on non-essential, toxic elements, a person can safely consume 0.001 mg of cadmium and 0.0036 mg of lead per kg of body weight per day without experiencing toxic effects from these elements. Based on these levels, the amount of *R. argentea, B. nurse,* and *E. bredoi* (in grams of dry fish) that is safe to consume per day can be estimated. Even though samples listed as BDL could be far below the detection limit, it was assumed that they were at detection limit, making the consumption recommendations presented here conservative as they are likely overestimating the concentration of non-essential, toxic elements in the fish. However, this provides a baseline estimate that could be refined with future analyses run at a finer resolution with a lower detection limit (i.e., ICP-AES).

Safe consumption limits were estimated for children by using a mass of 20 kg, and for adults using a mass of 60 kg. Cadmium has the lowest daily intake limit, and therefore, is the element constraining how many fish can be safely eaten per day. Combining this information, children can safely intake 4.75 g of *R. argentea*, 9.75 g of *B. nurse,* and 8.75 g of *E. bredoi* in dry weight per day while remaining within safe consumption limits. However, adults can safely consume 14.25 g of *R. argentea*, 29.25 g of *B. nurse,* and 26 g of *E. bredoi* per day (dried fish). FAOSTAT (2021) states that on average Ugandan adults consume 10.73 kg of fresh fish a year. Since SPFs are typically consumed dried, the average moisture content of collected samples (~75 %) was used to calculate how much dry fish would equate to the estimated consumptions of fresh fish, giving an average consumption of 2.68 kg of dried fish per year with ~7.5 g/day for adults and ~3.75 g/day for children (assuming children consume half that of adults). Based on these estimates of per capita fish consumption data adults and children would be well within a safe range as it is unlikely that one individual would consume this number of fish per day.

4.2.2. *Daily nutrient targets*

Using the nutritional content of *R. argentea, E. bredoi* and *B. nurse,* in conjunction with the FAO/WHO daily recommended nutrient intake, the proportion of elements taken in per day from one serving of fish can be assessed. Values provided by the joint FAO/WHO report (2002) give recommended nutrient intakes in mg/day for people to meet crucial levels necessary for human health, growth, and development. As above, if one assumes an estimated average consumption of 2.68 kg of dried fish per year (~7.5 g/day for adults and ~3.75 g/day for children in Uganda), the mean essential element concentrations (mg/g) can be multiplied by the consumption estimates (g/day) to provide intake of each element acquired if only that fish species was consumed in the estimated amount per day. This can then be compared to the WHO recommended nutrient intake of each essential element to show how consuming each of these species can help contribute to meeting these goals as presented in Fig. 3.

The FAO/WHO report recommends that people consume between 500 and 800 mg of calcium per day depending on their life stage (i.e., children vs adult's vs pregnant/lactating women etc.; FAO/WHO, 2002). These targets are partially fulfilled (approximately one quarter to a third) with a 7.5 g daily portion (dry weight) of any of the three species in this study (Fig. 3A). Comparatively, guidelines for iron consumption assume 10 % bioavailability from food and account for growth needs, basal losses, and menstrual losses in females. Daily recommended iron intakes are between 5.8 and 38.6 mg/day (FAO/WHO, 2002). *Rastrineobola argentea* provides approximately one tenth of the recommended daily intake, while *E. bredoi* and *B. nurse* fulfil approximately one twentieth of daily values (Fig. 3B). Finally, the FAO/WHO (2002) recommends people consume 4.1–10 mg per day of zinc depending on their life stage. *Rastrineobola argentea* can fulfill 15–25 % of daily requirements, while *E. bredoi* can meet 20–40 % of requirements and *B. nurse* provides approximately 10 % of daily intake (Fig. 3C). Although all elements investigated in this study are important for human health, Ca, Fe, and Zn are particularly relevant elements for nutritional deficiencies and hidden hunger throughout Uganda, therefore their results were emphasized here. From the data presented, it is evident that all three species can contribute to daily nutritional recommendations and should be promoted as part of a healthy diet.

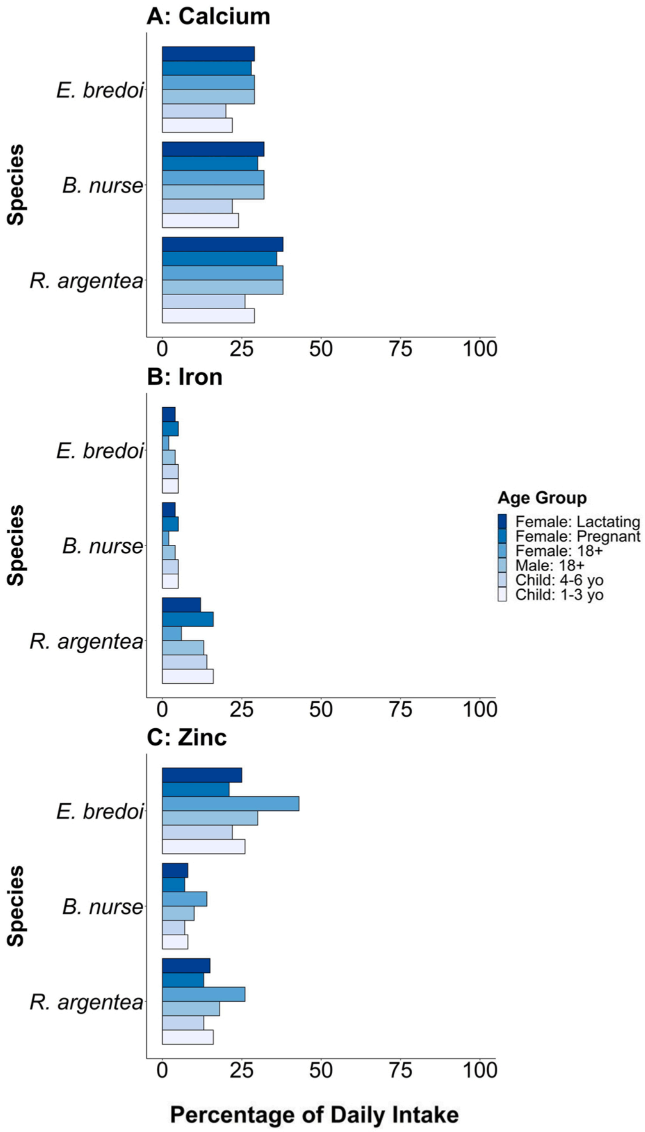

Fig. 3. Daily nutritional value of three species of small fishes. The percentage of daily nutritional intake of A) calcium, B) iron, and C) zinc in dried *R. argentea, B. nurse*, and *E. bredoi* that are met by consuming one portion of dried fish (~7.5 g/day of for adults and ~3.75 g/day for children). Values are based off FAO/WHO guidelines for recommended daily consumption levels (FAO/WHO, 2002). Values for pregnant females represent necessary nutritional intakes during the third trimester.

4.3. *Implications for food and nutritional security*

Although the fisheries on lakes Albert, Victoria, and Nabugabo heavily target small fishes for local consumption, post harvest losses of these species are greatly lowering the amount of end-product available. Physical loss has been found to be highest during the harvest and ferrying process (spillage) and during the drying process (predation by birds and animals). Once harvested, spoilage then often occurs due to poor handling and preservation methods, and this type of loss is typically higher in small fishes than larger fishes due to their increased surface area to volume ratio. Given the high nutritional values of these fish, and the opportunity they provide to meet the dietary requirements of BoP communities in Uganda, strategic interventions along the value chain could greatly increase their availability, accessibility, and ultimately, consumption.

One primary strategy to combat these issues has been to improve the traditional open-air sun drying method typically used to preserve the fishes. Solar tent dryers are currently being developed as a method to protect the product from contaminants such as dust, insect remains, and animal droppings. Other preservation methods such as salting, deep frying, fermentation, or milling into flour to be used as an additive for enriching plant-based carbohydrates could also reduce the amount of product lost to spoilage and improve the diversity of fish-enriched products in local diets. It is likely that different preservation methods would affect the nutrient composition of the fish products, and thus detailed research should be conducted to determine what could create the most nutritious food source. It is acknowledged that the nutrient content of *R. argentea, E. bredoi,* and *B. nurse* found here would likely vary with alternative drying methods, but the results presented in this study demonstrate the high nutritional content of these three species and can be used as a reference to compare additional methods to. We also note that the method used to process fish, which included euthanization by emersion in clove oil, may have affected elemental concentrations, though fish were rinsed in water before drying. All fish were processed similarly to ensure robust comparisons among sites and among species.

With improved quality of SPF products, it is likely that lucrative markets would offer higher economic returns for value chain actors, therefore helping to improve livelihoods for fishers while also providing a superior food source. Although the preservation approaches mentioned above are more expensive than the traditional open-air sun-drying method, access to lucrative markets could offset the investment costs. Developing affordable preservation methods such as those mentioned above will be a more effective way to increase the amount of fish accessible to humans, as opposed to increasing the harvest rates, which will only place further pressure on the fish populations. Improved handling and processing practices along the value chain of SPFs would ensure continued availability of the fishes, while also considering the sustainability of the fishery.

The value of the SPFs for food security in the region and the increased harvesting levels for the three species in this study highlight the importance of creating management strategies that ensure sustainability of the SPF fisheries. Mangeni-Sande et al. (2019) reported a 27 % decrease in the size at maturity of *R. argentea* in Lake Victoria between the 1970 s and 2015, with immature fish largely harvested from inshore and mid-island waters. In Lake Nabugabo, Groves et al. (2022) found no difference in the size at maturity of *R. argentea* between 2008/9 and 2016/17; however, the abundance of *R. argentea* (fishery independent data) decreased dramatically over the same time period. Such changes are consistent with harvest-induced change, though other factors (e.g., predation, water quality) may also have played a role (Mangeni-Sande et al., 2019). All three SPFs (*R. argentea, B. nurse, and E. bredoi*) have become the target of increasing fishing pressure to the point where they are now the most important fish species (by biomass) in lakes Albert and Victoria. Changes observed in the size and abundance of in *R. argentea* in lakes Victoria and Nabugabo point to the importance of monitoring and management of these fisheries.

4.4. *Conclusions*

Overall, the three species (*R. argentea, B. nurse,* and *E. bredoi*) as whole, dried fish provide high levels of essential elements required in the human diet, and this study highlights their importance in offsetting nutritional deficiencies among vulnerable groups in Uganda. All three species were found to be safe for consumption as they contain low levels of non-essential, toxic elements (lead or cadmium), but detection limits need to be considered in light of how much fish can be safely included in the diet per kg of body mass of consumers. Although some variation was present in the composition of elements in the fishes with geographical location and size, all species caught at any of the sites will provide high nutritional value to the consumer and will be helpful in creating fish-enriched products to support health management strategies. Mindful interventions should be implemented in the fisheries to improve accessibility and availability of *R. argentea*, *E. bredoi*, and *B. nurse* to consumers, in particular, women and children under 5 years of age and in the rural and peri-urban communities who are at high risk for experiencing nutritional deficiencies.

CRediT authorship contribution statement

Shelby Clarke: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **William Nesbitt:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Jackson Efitre:** Writing – review & editing, Project administration, Funding acquisition. **Margaret Masette:** Writing – review & editing. **Lauren J. Chapman:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106479.

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