

TRACE ELEMENT CONCENTRATION IN MUSCLE AND LIVER OF FOUR SCIAENID FISHES IN SABINE LAKE (TEXAS/LOUISIANA)

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Abstract.—Sabine Lake is a shallow, estuarine water body situated between Texas and Louisiana with outflow to the Gulf of Mexico. The Louisiana side of the lake is a protected natural area while the Texas side has several commercial industries that likely contribute to trace element contamination. This study determined the concentrations of 15 trace elements in four recreationally and ecologically important sciaenid fishes from Sabine Lake: Atlantic croaker (*Micropogonias undulatus*), red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), and spotted seatrout (*Cynoscion nebulosus*). Axial muscle and liver tissues were tested using inductively coupled plasma mass spectrometry (ICPMS). Liver tissue had greater concentrations of trace elements compared to muscle tissue within each species. There were significant differences in liver tissue among the four species for As, Cd, Co, Cr, Cu, Fe, Pb, Se, V, and Zn. Significant difference in only Hg concentration was exhibited in muscle tissue among the fish species. Fish caught on the Texas side of the lake were also found to have significantly higher concentrations of Cu than on the Louisiana side. Fish belonging to the benthic foraging guild had significantly higher concentrations in the liver for the majority of metals compared to pelagic and generalist foragers. Due to the economically important recreational fishery in Sabine Lake, these data establish important baselines for future contaminant and trophic studies.

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Keywords: Sciaenidae, Se:Hg molar ratios, trace elements, muscle, liver

Coastal marine fishes often utilize estuarine habitats for ontogenetic development and may also reside there throughout their life. Sabine Lake is an estuarine lake straddling the border of Texas and Louisiana that drains into the Gulf of Mexico and is economically important due

to its recreational fisheries (Charles 2005). The lake provides an important habitat for many aquatic species, especially fishes, as it offers both protection and abundant food sources throughout many life stages (Llanos et al. 1998; Dauvin 2008). The lake is uniquely situated in that the Louisiana shore is an undeveloped, protected tract within the Sabine National Wildlife Refuge while the Texas shore is industrially developed, including chemical plants and oil refineries (Figure 1). The 181 km² lake maintains a mean low water depth of 3 m, though the ship channels to Port Arthur, Texas, have been dredged to a depth of more than 12 m (Texas Department of Water Resources 1981). The lake receives drainage from the Neches River which carries runoff from agricultural and chemistry industries throughout the watershed. A commercial port and associated ship traffic are located on the Texas shore of the lake, which is subjected to periodic maintenance sediment dredging (Ravichandran et al. 1995; Harrel & Smith 2002).

Trace elements (TE) naturally enter the ecosystem through the Earth's crust at low concentrations (Singh et al. 2011). Domestic and industrial waste waters, sewage, fossil fuels, agricultural runoff, combustion of municipal waste, vessel maintenance and operations, and port dredging all can contribute to elevated trace element contamination (Degtiareva & Elektorowicz 2001; Wuana & Okieimen 2011; Tchounwou et al. 2012; Ali & Khan 2019; Richir et al. 2021; Lim et al. 2022). Organisms can bioaccumulate contaminants through water, the atmosphere, or food consumption that can cause drastic trophic level effects at high levels (Ali & Khan 2019; Sonone et al. 2020; Saidon et al. 2024). Contaminants include any high-density metal or metalloid element (As and Se) that can be toxic at low concentrations (Nagajyoti et al. 2010; Zeitoun & Mehana 2014). Essential TEs are needed in small quantities for the proper growth, development, and vital metabolic activities of organisms. The essential element Se has a strong binding affinity to Hg preventing its absorption and potential detrimental effects within the body (Soto-Jiménez 2011). Fish can accumulate these elements from the water through their gills as well as through ingestion of prey items (Zeitoun & Mehana 2014; Ali & Khan 2019).

The family Sciaenidae, commonly called drums, contains important fishes to both recreational and commercial coastal fisheries. Due to their economic value, it is important to understand the different environmental impacts facing sciaenids to ensure a sustainable multi-species fishery. As readily available estuarine fishes in Sabine Lake, sciaenids are easily accessible to recreational fishers while being surrounded by potential anthropogenic contaminant sources.

This study examines four sciaenid species: Atlantic croaker (*Micropogonias undulatus*), red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), and spotted seatrout (*Cynoscion nebulosus*). Spotted seatrout is within a pelagic foraging guild since its diet consists mostly of shrimp and other teleosts (McMichael & Peters 1989; Hall-Scharf et al. 2016). Atlantic croaker and red drum are both in the generalist foraging guild as their prey consists of mixed benthic invertebrates and teleosts (Overstreet & Heard 1978a; 1978b; Facendola & Scharf 2012). The diet of black drum primarily consists of a variety of benthic invertebrates so it is part of the benthic foraging guild (Deary et al. 2017; Rubio et al. 2018).

As a site of important recreational fisheries, TE concentrations in Sabine Lake fishes can provide insight into the contaminants' present potential sources, and pathway to human diet. Fish muscle is readily consumed by humans and can store pollutants, but the lipid-rich liver more readily stores and detoxifies them (Ardeshir et al. 2017; Zhang et al. 2017). Muscle and liver tissues of these four sciaenid species were analyzed for 15 TEs: aluminum (Al), arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), vanadium (V), and zinc (Zn). Due to dietary preferences, concentrations can vary among foraging guilds in fishes. Focusing on one family of fishes, the objectives of this study were to (1) determine the concentrations of TEs in the fish muscle and liver tissue among the species, (2) compare TE concentrations among the foraging guilds, (3) correlate TE concentrations with fish length, and (4) assess concentrations in fish tissues between Texas and Louisiana.

MATERIALS & METHODS

Collection and processing.—Twenty-eight fish were collected throughout the Sabine Lake system (including adjacent saltmarshes and rivers) (Figure 1) from April through October 2018 using gillnets, bag seines, and bay trawl gears as a joint project between Florida International University and Sam Houston State University. Specimens were collected under IACUC protocol 16-02-18-1003-3-01 issued to P. Matich, Sam Houston State University at the time of study.

Muscle and liver samples were collected from each fish, frozen, and shipped to Nova Southeastern University (NSU) where they were kept in a standard -10°C freezer until sample processing. The tissue samples were dried at 60°C for a minimum of 72 h. Dried samples were ground and homogenized manually by mortar and pestle then stored in labeled glass vials at room temperature until digestion.

Size groupings were used rather than age-classes because of the short time period of the sampling season and rapid growth at early ontogenetic stages. Fish size-class designations were based on prior studies (Overstreet & Heard 1978b; Blasina et al. 2010; Akin & Winemiller 2015) and broadly represent functional feeding groups. Atlantic croaker and spotted seatrout had one size class (197–233 mm standard length (SL) (n=5), above the size at maturity per Diamond et al. (1999) and (294–350 mm SL (n=5), above the size at maturity per Nieland et al. (2002)). Red and black drum each had two size classes (red drum: 283–294 mm SL (n=5) and 409–492 mm SL (n=5), below the size of maturity per Wilson & Nieland (1994)) and (black drum: 184–193 mm SL (n=3) and 233–289 mm SL (n=5), below the size at maturity per Fitzhugh et al. (1993), respectively).

Trace element analysis.—Dried and ground tissue samples were weighed to 0.1 ± 0.01 g into a 100 mL Telfon PTFE tube. The digestion protocol is a modification of U.S. Environmental Protection Agency (EPA) Method 200.8, Rev. 5.4 (EPA 1994), with sample preparation by SW-846 Method 3050B (EPA 1996). Muscle samples were digested overnight with 5 mL of nitric acid (HNO₃) and 1 mL of hydrogen peroxide (H₂O₂) at room temperature. An additional 1 mL of H₂O₂ was added to the samples that were not fully digested and the tubes were

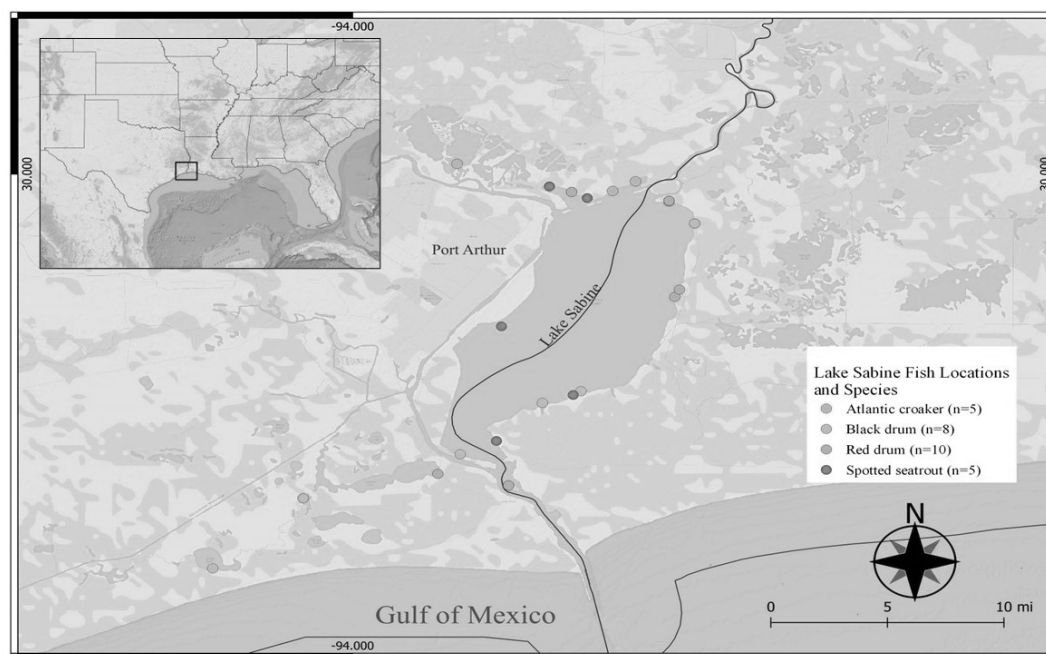


Figure 1. Map of Sabine Lake at the border of Texas and Louisiana near the Gulf of Mexico. State border is indicated by the line bisecting the lake. Sampling locations are indicated by black diamonds. Waters adjacent to the Sabine National Wildlife Refuge along the Louisiana side of Sabine Lake are protected coastal marshes, contrasted with the industrialized shoreline of Port Arthur and Port Neches on the Texas side.

placed on a ModBlock™ digester block (CPI International, Santa Rosa, CA) at 60° C for one hour. Liver samples were digested with 4 mL of HNO₃ and 1 mL of H₂O₂ and heated at 60° C on a digester block for one hour. Samples that were not fully digested received an additional 1 mL of HNO₃ and 1 mL of H₂O₂ and heated at 60° C for an additional hour. The digested samples were reduced in volume to approximately 2.5 mL and diluted to 25 mL using ultrapure deionized water (18.2 MΩ; Barnstead water purification system, Thermo Fisher Scientific, Waltham, MA). Samples were shipped to the Center for Trace Analysis at the University of Southern Mississippi and analyzed using an Element XR™ sector-field inductively coupled plasma mass spectrometer (ICPMS; Thermo Fisher Scientific) with a Peltier-cooler spray chamber (PC-3; Elemental Scientific, Inc., Omaha, NE). Prior to analysis, digested samples were diluted 5-fold in 0.64 M ultrapure nitric acid (Seastar Baseline, Sidney, British Columbia, Canada) containing

2 ppb indium as an internal standard. Diluted samples were held in acid-washed Teflon autosampler vials. Mass spectrometer scans were performed in low (Cd-111, Hg-199, 200, 201, 202, Pb-208), medium (Al-27, V-51, Cr-52, Mn-55, Fe-56, Co-59, Ni-60, Cu-63, Zn-66), and high (As-75, Se-77,82) resolution, depending on the isotope. Mo-98 was monitored to correct for MoO^+ interference on Cd. Standardization was achieved through external standards, with a high standard and a blank re-run every eight samples. For the elements Hg and Se where multiple isotopes were determined, no significant analytical differences were noted between the isotopes. Two USGS reference water concentrations were also assessed as part of each analytical run to verify the standardization. In several cases, sample calibration was also verified by standard additions. Blanks of ultrapure deionized water and trace metal basis nitric acid (3%, 4%, 5%) were used for quality control. No spiked or duplicate samples were used. The ICPMS detection limits of each element are provided in Supplemental Table 1, https://doi.org/10.32011/txjsci_77_1_Article3.S01. Certified reference materials of dogfish liver (DOLT-5) and fish protein (DORM-4) were purchased from the National Research Council, Canada, NRC, Division of Chemistry to validate our analytical method. DORM-4 had percent recoveries of 70.1-107% while DOLT-5 ranged from 60.4-147% for all metals except Hg, which had higher recoveries than expected.

Se:Hg.—The molar ratio of Se to Hg was calculated for the muscle and liver tissues of each individual in the study using the equation:

$$\frac{Se}{Hg} = \left(\frac{\frac{Se}{78.96}}{\frac{Hg}{200.59}} \right)$$

Molar ratios more accurately represent the proportions of Se and Hg by accounting for their molar mass. Molar ratios of each sample exceeding 1 indicate that Se may have a protective effect against Hg toxicity (Berry & Ralston 2008). Alternatively, a molar ratio ≤ 1 is indicative of most Se being bound to Hg, potentially resulting in oxidative stress risk if any additional unbound Hg exists (Cáceres-Saez et al. 2013).

Statistical analysis.—Arithmetic and geometric means were calculated for the 15 metals/metalloids; geometric means were used for statistical analyses. TE concentrations that were below detection limits were assigned a value of one-half of the detection limit for statistical analysis (Supplemental Table 1, https://doi.org/10.32011/txjsci_77_1_Article3.S01). Data were not normally distributed so a log scale transformation was performed and a non-parametric post-hoc test applied. Muscle and liver concentrations were compared using the Mann-Whitney Wilcoxon one-tailed test. TE concentrations were compared among species and foraging guilds using the Kruskal-Wallis test. Differences in concentrations between size classes for black drum and red drum muscle and liver tissue were compared using the Mann-Whitney Wilcoxon two-tailed test. Correlation between TE concentrations and species size class were evaluated using the Spearman rank correlation test. TE concentrations between Texas and Louisiana fish were compared using the Mann-Whitney Wilcoxon two-tailed test. Spearman rank correlation determined the strength of the relationship between Se and Hg concentrations for each sample. All statistical calculations were performed using R software for Mac version 4.0.5 (R Core Team 2021) and significance was $p \leq 0.05$.

RESULTS

Interspecies variation in trace element concentrations.—Black drum liver tissue had significantly greater concentrations of As, Cd, Fe, and V ($P=0.002$, $P=0.009$, $P=0.006$, and $P<0.001$, respectively) compared to Atlantic croaker, significantly greater concentrations in Cd, Co, Pb, Se, V, and Zn ($P=0.009$, $P=0.02$, $P<0.001$, $P=0.008$, $P<0.001$, and $P=0.02$, respectively) than spotted seatrout, and significantly greater concentrations of Cu and Pb ($P=0.01$ and $P<0.001$, respectively) than red drum. Red drum had significantly greater As concentrations in liver tissues than Atlantic croaker ($P=0.002$) and greater Cr concentrations in liver tissue than black drum ($P=0.01$). Conversely, spotted seatrout had significantly greater Hg concentrations in muscle tissue than black drum ($P=0.020$). All other interspecific differences for TE concentrations in muscle tissue were insignificant (Figures 2 & 3). Data

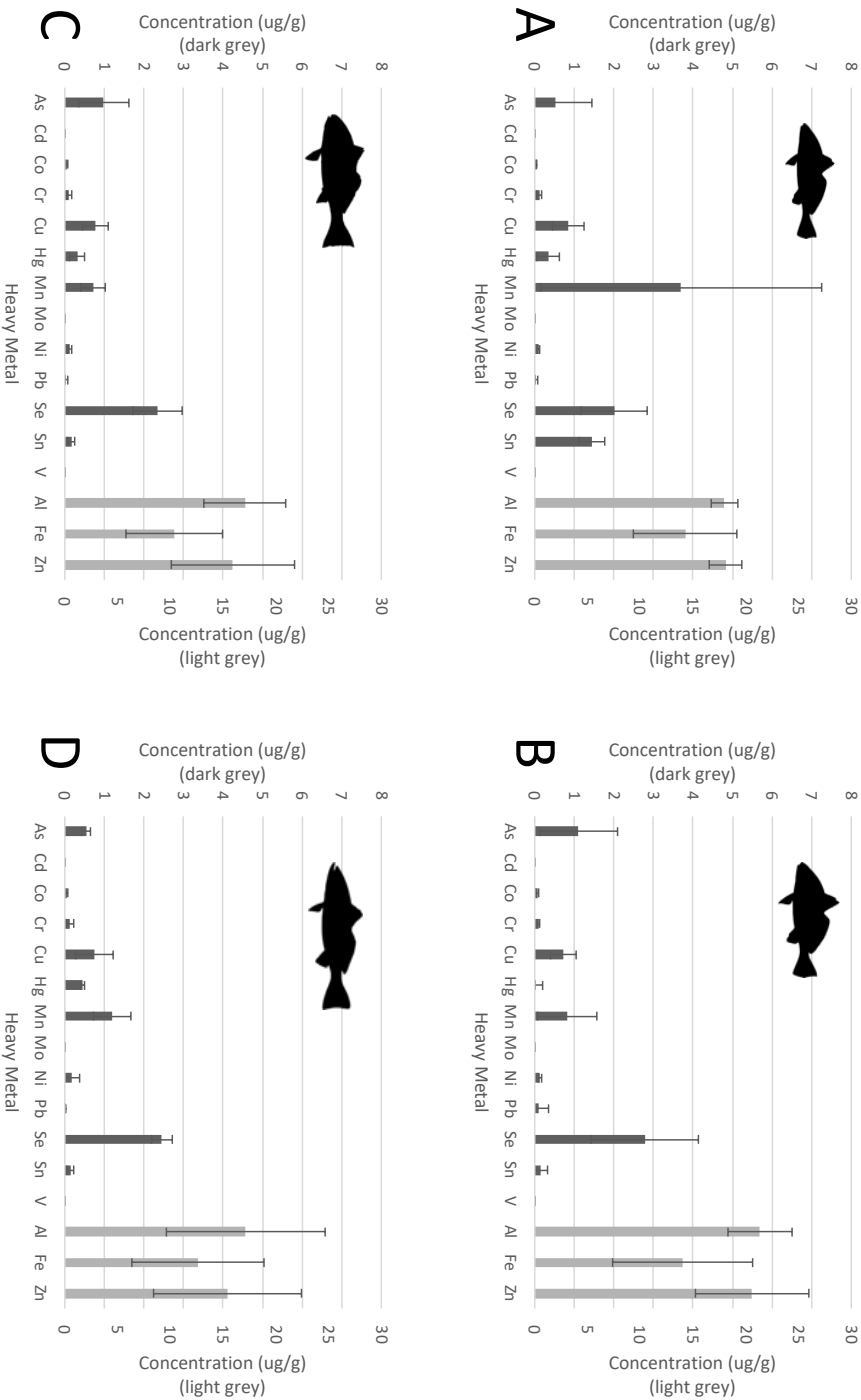


Figure 2. Trace element concentration in muscle tissue of Atlantic croaker (A), black drum (B), red drum (C), and spotted seatrout (D). Error bars represent standard deviation. Note the two concentration axes reflecting the magnitude of difference between trace elements. Values represent individuals by species combined across sampling locations in both states.

concentrations in muscle tissue were insignificant (Figures 2 & 3). Data are provided in Supplemental Table 2, https://doi.org/10.32011-txjsci_77_1_Article3.S02.

Tissue comparisons.—All 15 TEs were detected in both muscle and liver of all species other than Mo which was not detected in any of the muscle tissue samples. Across all species Al, Fe, and Zn exhibited the greatest concentrations in both muscle and liver tissues; Cu had the greatest concentrations in liver tissues across all fish species. Liver concentrations were significantly greater than in muscle for all metal/metalloids except Hg (Tables 1 & 2).

Foraging guild comparisons.—Significant differences in liver concentrations among the three foraging guilds existed for nine TEs: Cd (Kruskal-Wallis, $df=2$, $\chi^2=8.4373$, $P=0.015$), Co (Kruskal-Wallis, $df=2$, $\chi^2=9.3398$, $P=0.009$), Cr (Kruskal-Wallis, $df=2$, $\chi^2=10.712$, $P=0.005$), Cu (Kruskal-Wallis, $df=2$, $\chi^2=10.878$, $P=0.004$), Fe (Kruskal-Wallis, $df=2$, $\chi^2=9.377$, $P=0.009$), Pb (Kruskal-Wallis, $df=2$, $\chi^2=15.292$, $P<0.001$), Se (Kruskal-Wallis, $df=2$, $\chi^2=8.270$, $P=0.016$), V (Kruskal-Wallis, $df=2$, $\chi^2=15.242$, $P<0.001$), Zn (Kruskal-Wallis, $df=2$, $\chi^2=9.359$, $P=0.009$).

The benthic (two size-classes of black drum) and pelagic (spotted seatrout) foraging guilds' liver concentrations differed significantly for all of these nine TEs except Cr: Cd (Dunn, $Z=2.713$, $P=0.02$), Co (Dunn, $Z=3.001$, $P=0.008$), Cu (Dunn, $Z=2.751$, $P=0.012$), Fe (Dunn, $Z=2.617$, $P=0.018$), Pb (Dunn, $Z=3.385$, $P=0.001$), Se (Dunn, $Z=2.873$, $P=0.012$), V (Dunn, $Z=3.545$, $P=0.001$), and Zn (Dunn, $Z=2.985$, $P=0.009$). The benthic and generalist (Atlantic croaker and two size-classes of red drum) foraging guilds' liver concentrations differed significantly for six of the nine TEs: Cd (Dunn, $Z=2.256$, $P=0.048$), Cr (Dunn, $Z=-3.212$, $P=0.001$), Cu (Dunn, $Z=2.953$, $P=0.009$), Fe (Dunn, $Z=2.687$, $P=0.022$), Pb (Dunn, $Z=3.390$, $P=0.002$), and V (Dunn, $Z=3.191$, $P=0.003$). When significantly different, TE concentrations in liver of benthic guild specimens were higher than both pelagic and generalist guild specimens.

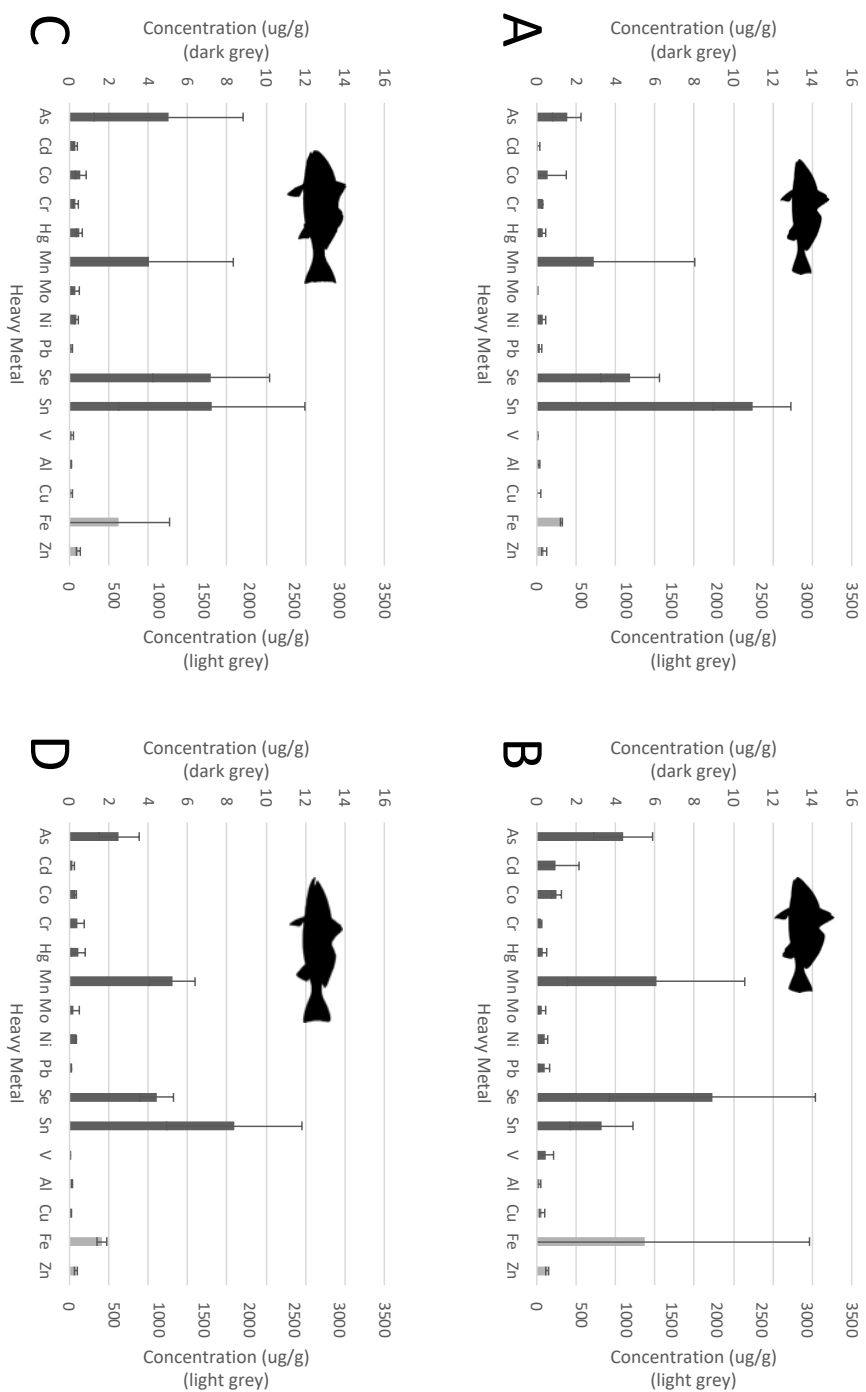


Figure 3. Trace element concentration in liver tissue of Atlantic croaker (A), black drum (B), red drum (C), and spotted seatrout (D). Error bars represent standard deviation. Note the two concentration axes reflecting the magnitude of difference between trace elements. Values represent individuals by species combined across sampling locations in both states.

Table 1. Trace element concentration in Atlantic croaker and black drum given in ug/g. Each value was reported as an arithmetic mean (upper, regular font) and geometric mean (lower, italicized font) of samples in the species/size class $\pm$ standard deviation. Aluminum (Al), iron (Fe), and zinc (Zn) had the highest concentrations for muscle tissues across all species. Aluminum (Al), copper (Cu), iron (Fe), and zinc (Zn) had the highest concentrations in liver tissues across all species. Liver tissues had higher trace element concentrations than muscle tissues.

	Atlantic Croaker		Black Drum			
	197-233 mm SL (n=5)		184-193 mm SL (n=3)		23-289 mm SL (n=5)	
	Muscle	Liver	Muscle	Liver	Muscle	Liver
Al	18.0 $\pm$ 0.0323 <i>18.0$\pm$1.25</i>	26.3 $\pm$ 0.137 <i>25.3$\pm$9.60</i>	18.6 $\pm$ 0.0477 <i>18.6$\pm$2.04</i>	29.5 $\pm$ 0.143 <i>28.4$\pm$9.09</i>	27.3 $\pm$ 0.252 <i>23.2$\pm$2.69</i>	38.5 $\pm$ 0.276 <i>32.1$\pm$15.3</i>
As*	0.748 $\pm$ 0.454 <i>0.516$\pm$0.935</i>	1.65 $\pm$ 0.181 <i>1.54$\pm$0.718</i>	1.45 $\pm$ 0.166 <i>1.38$\pm$0.526</i>	5.36 $\pm$ 0.167 <i>5.09$\pm$2.03</i>	1.18 $\pm$ 0.296 <i>0.974$\pm$1.03</i>	4.40 $\pm$ 0.204 <i>4.03$\pm$0.464</i>
Cd	0.00239 $\pm$ 0.298 <i>0.00196$\pm$0.0017</i>	0.141 $\pm$ 0.996 <i>0.0601$\pm$0.0798</i>	0.00326 $\pm$ 0.0971 <i>0.00320$\pm$0.0007</i>	0.795 $\pm$ 0.640 <i>0.486$\pm$0.624</i>	0.00199 $\pm$ 1.52 <i>0.000217$\pm$0.00345</i>	2.19 $\pm$ 0.500 <i>1.38$\pm$2.77</i>
Co*	0.0465 $\pm$ 0.109 <i>0.0453$\pm$0.0148</i>	0.907 $\pm$ 0.646 <i>0.543$\pm$0.968</i>	0.0687 $\pm$ 0.129 <i>0.0668$\pm$0.0186</i>	0.858 $\pm$ 0.0219 <i>0.857$\pm$0.0383</i>	0.0783 $\pm$ 0.145 <i>0.0751$\pm$0.0293</i>	1.52 $\pm$ 0.383 <i>1.12$\pm$0.921</i>
Cr*	0.130 $\pm$ 0.203 <i>0.118$\pm$0.0617</i>	0.292 $\pm$ 0.0492 <i>0.291$\pm$0.0389</i>	0.0906 $\pm$ 0.0901 <i>0.0893$\pm$0.0176</i>	0.226 $\pm$ 0.0579 <i>0.224$\pm$0.0286</i>	0.192 $\pm$ 0.419 <i>0.117$\pm$0.0151</i>	0.227 $\pm$ 0.0605 <i>0.225$\pm$0.0525</i>
Cu*	1.01 $\pm$ 0.857 <i>0.857$\pm$0.401</i>	70.0 $\pm$ 0.990 <i>14.9$\pm$32.8</i>	0.875 $\pm$ 0.805 <i>0.805$\pm$0.425</i>	46.4 $\pm$ 0.208 <i>42.9$\pm$22.0</i>	0.717 $\pm$ 0.138 <i>0.687$\pm$0.219</i>	80.6 $\pm$ 0.147 <i>76.8$\pm$9.03</i>
Fe*	14.9 $\pm$ 0.153 <i>14.3$\pm$4.87</i>	359 $\pm$ 0.369 <i>273$\pm$9.18</i>	15.7 $\pm$ 0.198 <i>14.7$\pm$6.75</i>	782 $\pm$ 0.0569 <i>777$\pm$102</i>	14.7 $\pm$ 0.173 <i>13.7$\pm$3.44</i>	1980 $\pm$ 0.357 <i>1570$\pm$1850</i>
Hg	0.396 $\pm$ 0.282 <i>0.342$\pm$0.293</i>	0.364 $\pm$ 0.222 <i>0.329$\pm$0.150</i>	0.0816 $\pm$ 2.52 <i>0.00396$\pm$0.0865</i>	0.234 $\pm$ 0.470 <i>0.172$\pm$0.175</i>	0.213 $\pm$ 0.597 <i>0.139$\pm$0.109</i>	0.654 $\pm$ 0.389 <i>0.454$\pm$0.239</i>
Mn*	5.19 $\pm$ 0.495 <i>3.70$\pm$3.55</i>	4.12 $\pm$ 0.469 <i>2.88$\pm$5.17</i>	1.05 $\pm$ 0.234 <i>0.968$\pm$0.454</i>	8.98 $\pm$ 0.335 <i>7.26$\pm$6.67</i>	0.929 $\pm$ 0.297 <i>0.746$\pm$0.293</i>	6.29 $\pm$ 0.256 <i>5.46$\pm$3.55</i>
Mo*	BDL <i>BDL</i>	0.0859 $\pm$ 1.59 <i>0.0202$\pm$0.0567</i>	BDL <i>BDL</i>	0.216 $\pm$ 0.121 <i>0.211$\pm$0.0596</i>	BDL <i>BDL</i>	0.367 $\pm$ 0.344 <i>0.296$\pm$0.245</i>
Ni*	0.108 $\pm$ 0.175 <i>0.101$\pm$0.0228</i>	0.338 $\pm$ 0.148 <i>0.324$\pm$0.125</i>	0.0811 $\pm$ 0.173 <i>0.0767$\pm$0.0303</i>	0.356 $\pm$ 0.0212 <i>0.355$\pm$0.0154</i>	2.31 $\pm$ 0.977 <i>0.204$\pm$0.0369</i>	0.473 $\pm$ 0.146 <i>0.453$\pm$0.163</i>
Pb	0.0624 $\pm$ 0.426 <i>0.0394$\pm$0.0290</i>	0.161 $\pm$ 0.199 <i>0.148$\pm$0.110</i>	0.304 $\pm$ 0.737 <i>0.127$\pm$0.382</i>	0.304 $\pm$ 0.0785 <i>0.301$\pm$0.0508</i>	0.211 $\pm$ 0.578 <i>0.0908$\pm$0.0678</i>	0.595 $\pm$ 0.331 <i>0.477$\pm$0.462</i>
Se*	2.09 $\pm$ 0.133 <i>2.01$\pm$0.833</i>	4.97 $\pm$ 0.158 <i>4.74$\pm$1.49</i>	2.86 $\pm$ 0.188 <i>2.69$\pm$1.19</i>	7.76 $\pm$ 0.169 <i>7.37$\pm$3.01</i>	3.00 $\pm$ 0.164 <i>2.84$\pm$1.01</i>	10.9 $\pm$ 0.210 <i>10.0$\pm$4.02</i>
Sn	2.66 $\pm$ 0.478 <i>1.46$\pm$0.320</i>	11.4 $\pm$ 0.155 <i>10.9$\pm$1.97</i>	0.203 $\pm$ 0.359 <i>0.168$\pm$0.121</i>	3.28 $\pm$ 0.432 <i>2.43$\pm$2.75</i>	0.227 $\pm$ 0.448 <i>0.153$\pm$0.110</i>	4.01 $\pm$ 0.0783 <i>3.96$\pm$0.885</i>
V	0.00893 $\pm$ 0.259 <i>0.00798$\pm$0.0029</i>	0.0566 $\pm$ 0.617 <i>0.0363$\pm$0.0373</i>	0.00821 $\pm$ 0.225 <i>0.00747$\pm$0.0041</i>	0.345 $\pm$ 0.100 <i>0.339$\pm$0.0791</i>	0.0103 $\pm$ 0.464 <i>0.00615$\pm$0.00391</i>	0.671 $\pm$ 0.369 <i>0.525$\pm$0.624</i>
Zn*	18.9 $\pm$ 0.135 <i>18.1$\pm$1.54</i>	91.5 $\pm$ 0.224 <i>82.6$\pm$26.9</i>	20.79 $\pm$ 0.137 <i>20.1$\pm$6.23</i>	120 $\pm$ 0.0564 <i>119$\pm$14.8</i>	24.3 $\pm$ 0.244 <i>20.9$\pm$3.61</i>	120 $\pm$ 0.0849 <i>118$\pm$13.4</i>

* = essential element

BDL = below detection limit

Table 2. Trace element concentration in red drum and spotted seatrout given in ug/g. Each value was reported as an arithmetic mean (upper, regular font) and geometric mean (lower, italicized font) of samples in the species/size class $\pm$ standard deviation. Aluminum (Al), iron (Fe), and zinc (Zn) had the highest concentrations for muscle tissues across all species. Aluminum (Al), copper (Cu), iron (Fe), and zinc (Zn) had the highest concentrations in liver tissues across all species. Liver tissues had higher trace element concentrations than muscle tissues.

	Red Drum		409-492 mm SL (n=5)		Spotted Seatrout	
	283-294 mm SL (n=5)				294-350 mm SL (n=5)	
	Muscle	Liver	Muscle	Liver	Muscle	Liver
Al	15.5 $\pm$ 0.0839 <i>15.3$\pm$1.74</i>	24.9 $\pm$ 0.117 <i>24.1$\pm$3.66</i>	21.1 $\pm$ 0.206 <i>19.1$\pm$5.41</i>	22.9 $\pm$ 0.0804 <i>22.5$\pm$0.755</i>	17.8 $\pm$ 0.134 <i>17.1$\pm$7.54</i>	48.2 $\pm$ 0.357 <i>33.8$\pm$2.11</i>
As*	1.02 $\pm$ 0.168 <i>0.956$\pm$0.343</i>	5.10 $\pm$ 0.187 <i>4.73$\pm$2.59</i>	1.13 $\pm$ 0.223 <i>1.02$\pm$0.740</i>	5.76 $\pm$ 0.192 <i>5.36$\pm$3.88</i>	0.554 $\pm$ 0.0930 <i>0.545$\pm$0.108</i>	2.65 $\pm$ 0.151 <i>2.52$\pm$1.04</i>
Cd	0.000599 $\pm$ 0.400 <i>0.000453$\pm$0.00058</i>	0.293 $\pm$ 0.147 <i>0.280$\pm$0.0835</i>	0.00229 $\pm$ 1.54 <i>0.000232$\pm$0.00262</i>	0.594 $\pm$ 0.431 <i>0.354$\pm$0.0480</i>	0.00163 $\pm$ 0.415 <i>0.00119$\pm$0.00108</i>	0.280 $\pm$ 0.474 <i>0.159$\pm$0.0795</i>
Co*	0.0455 $\pm$ 0.185 <i>0.0424$\pm$0.0146</i>	0.786 $\pm$ 0.227 <i>0.699$\pm$0.200</i>	0.0742 $\pm$ 0.297 <i>0.0600$\pm$0.0359</i>	0.487 $\pm$ 0.200 <i>0.450$\pm$0.320</i>	0.0614 $\pm$ 0.211 <i>0.0559$\pm$0.0236</i>	0.334 $\pm$ 0.200 <i>0.304$\pm$0.0317</i>
Cr*	0.0874 $\pm$ 0.052 <i>0.0869$\pm$0.0105</i>	0.295 $\pm$ 0.092 <i>0.290$\pm$0.0381</i>	0.177 $\pm$ 0.306 <i>0.144$\pm$0.0850</i>	0.370 $\pm$ 0.112 <i>0.360$\pm$0.150</i>	0.158 $\pm$ 0.267 <i>0.136$\pm$0.102</i>	0.476 $\pm$ 0.289 <i>0.395$\pm$0.375</i>
Cu*	0.889 $\pm$ 0.108 <i>0.869$\pm$0.212</i>	28.2 $\pm$ 0.286 <i>23.5$\pm$11.7</i>	0.728 $\pm$ 0.135 <i>0.701$\pm$0.372</i>	23.9 $\pm$ 0.305 <i>19.5$\pm$18.2</i>	0.795 $\pm$ 0.154 <i>0.755$\pm$0.474</i>	18.3 $\pm$ 0.156 <i>17.4$\pm$6.34</i>
Fe*	9.30 $\pm$ 0.124 <i>9.00$\pm$4.13</i>	488 $\pm$ 0.250 <i>421$\pm$198</i>	12.6 $\pm$ 0.159 <i>11.9$\pm$6.50</i>	762 $\pm$ 0.165 <i>720$\pm$412</i>	15.5 $\pm$ 0.296 <i>12.6$\pm$6.27</i>	360 $\pm$ 0.0584 <i>358$\pm$55.1</i>
Hg	0.312 $\pm$ 0.241 <i>0.281$\pm$0.184</i>	0.422 $\pm$ 0.162 <i>0.402$\pm$0.112</i>	0.414 $\pm$ 0.199 <i>0.380$\pm$0.183</i>	0.688 $\pm$ 0.248 <i>0.595$\pm$0.298</i>	0.507 $\pm$ 0.229 <i>0.452$\pm$0.0409</i>	1.67 $\pm$ 0.701 <i>0.468$\pm$0.354</i>
Mn	1.04 $\pm$ 0.264 <i>0.896$\pm$0.324</i>	6.21 $\pm$ 0.154 <i>5.95$\pm$0.471</i>	0.595 $\pm$ 0.0688 <i>0.589$\pm$0.0929</i>	3.14 $\pm$ 0.240 <i>2.74$\pm$0.888</i>	1.45 $\pm$ 0.340 <i>1.20$\pm$0.466</i>	6.85 $\pm$ 0.323 <i>5.22$\pm$1.19</i>
Mo	BDL <i>* BDL</i>	0.408 $\pm$ 0.352 <i>0.331$\pm$0.170</i>	BDL <i>BDL</i>	0.301 $\pm$ 0.351 <i>0.244$\pm$0.243</i>	BDL <i>BDL</i>	0.800 $\pm$ 0.807 <i>0.198$\pm$0.328</i>
Ni*	0.0914 $\pm$ 0.190 <i>0.0842$\pm$0.0451</i>	0.316 $\pm$ 0.0733 <i>0.313$\pm$0.0416</i>	1.47 $\pm$ 0.905 <i>0.185$\pm$0.0653</i>	0.663 $\pm$ 0.373 <i>0.457$\pm$0.147</i>	0.289 $\pm$ 0.441 <i>0.190$\pm$0.177</i>	0.394 $\pm$ 0.246 <i>0.336$\pm$0.0240</i>
Pb	0.0311 $\pm$ 0.228 <i>0.0274$\pm$0.0131</i>	0.101 $\pm$ 0.0810 <i>0.0998$\pm$0.0138</i>	0.0709 $\pm$ 0.552 <i>0.0383$\pm$0.0473</i>	0.114 $\pm$ 0.378 <i>0.0848$\pm$0.102</i>	0.0361 $\pm$ 0.241 <i>0.0322$\pm$0.00459</i>	0.0889 $\pm$ 0.152 <i>0.0847$\pm$0.0470</i>
Se*	2.55 $\pm$ 0.0693 <i>2.52$\pm$0.527</i>	8.09 $\pm$ 0.104 <i>7.93$\pm$0.512</i>	2.21 $\pm$ 0.0868 <i>2.17$\pm$0.367</i>	6.66 $\pm$ 0.0913 <i>6.53$\pm$0.947</i>	2.46 $\pm$ 0.0312 <i>2.46$\pm$0.266</i>	4.57 $\pm$ 0.116 <i>4.44$\pm$0.853</i>
Sn	0.435 $\pm$ 0.550 <i>0.188$\pm$0.0668</i>	6.83 $\pm$ 0.182 <i>6.36$\pm$2.27</i>	0.362 $\pm$ 0.534 <i>0.168$\pm$0.0973</i>	8.65 $\pm$ 0.158 <i>8.22$\pm$4.02</i>	0.178 $\pm$ 0.310 <i>0.143$\pm$0.0891</i>	8.69 $\pm$ 0.131 <i>8.38$\pm$3.42</i>
V	0.00274 $\pm$ 0.275 <i>0.00235$\pm$0.002</i>	0.114 $\pm$ 0.158 <i>0.109$\pm$0.0517</i>	0.00634 $\pm$ 0.574 <i>0.00315$\pm$0.004</i>	0.196 $\pm$ 0.420 <i>0.130$\pm$0.128</i>	0.00675 $\pm$ 1.18 <i>0.00210$\pm$0.0078</i>	0.0744 $\pm$ 0.502 <i>0.0392$\pm$0.0318</i>
Zn*	15.2 $\pm$ 0.097 <i>14.9$\pm$3.21</i>	124 $\pm$ 0.165 <i>116$\pm$14.0</i>	18.3 $\pm$ 0.181 <i>17.0$\pm$5.15</i>	86.3 $\pm$ 0.122 <i>83.6$\pm$24.8</i>	15.8 $\pm$ 0.111 <i>15.4$\pm$7.01</i>	74.6 $\pm$ 0.088 <i>73.4$\pm$14.4</i>

* = essential element

BDL = below detection limit

No significant differences were detected in muscle tissue concentrations among foraging guilds except for Hg (Kruskal-Wallis, $df=2$, $\chi^2=9.472$, $P=0.009$). Mercury concentrations differed significantly in muscle tissue between the benthic and generalist guild (Dunn, $Z=-2.559$, $P=0.0210$) and the benthic and pelagic foraging guilds (Dunn, $Z=-2.761$, $P=0.0173$).

Size class comparisons.—Atlantic croaker had a strong negative correlation between Cu concentration and standard length for muscle tissue ($P<0.001$). Spotted seatrout had a strong negative correlation between As ($P=0.04$), Hg ($P<0.001$), and Se ($P<0.001$) concentrations and standard length for liver tissue. Spotted seatrout had a strong positive correlation between V concentration and standard length for muscle tissue ($P=0.04$). Red drum had a strong negative correlation between Mn and standard length for both muscle and liver tissue ($P=0.03$ and $P=0.01$, respectively). All other standard length and TE concentration correlations were not significant. Red and black drum size classes displayed no significant differences for any of the elements in both muscle and liver tissue except Mn in red drum muscle ($P=0.03$).

No significant differences between Texas and Louisiana fishes were detected for any TEs except Cu ($P=0.046$). Copper was significantly higher for both muscle and liver tissues from Texas sampling locations ($P=0.046$) (Figure 4).

Se:Hg molar ratios.—All individuals and tissues had a molar ratio of Se:Hg greater than one, indicative of Se binding with much of the THg and neutralizing potential toxic effects.

DISCUSSION

Trace elements within Sabine Lake.—The unique location of Sabine Lake as an estuarine body with both freshwater drainage into the lake and outflow into the Gulf of Mexico presents the opportunity to indirectly determine how TE contaminants through industrialization (Texas side) can ecologically impact protected areas (Louisiana side).

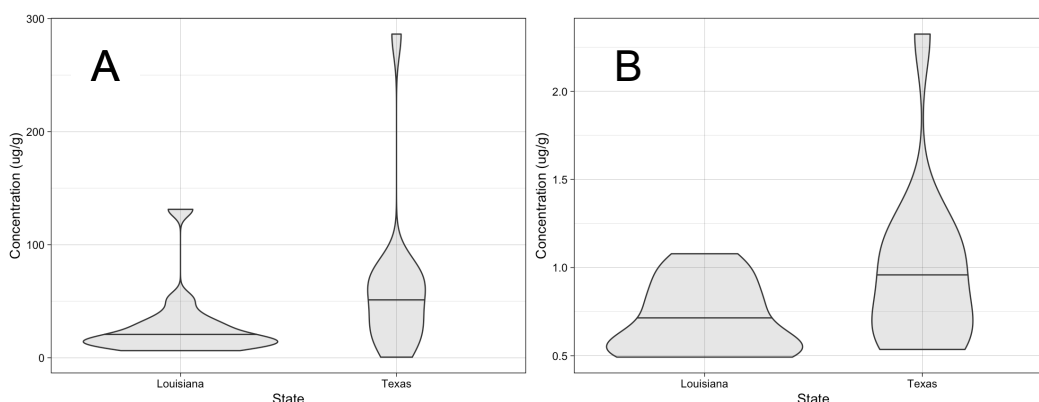


Figure 4. Copper (Cu) concentrations (ug/g) are shown for liver (A) and muscle (B) for all sciaenid fish species combined from the Texas or Louisiana side of the lake. Horizontal line in the violin plot represents the respective mean value.

Ravichandran et al. (1995) investigated TE contaminants in Sabine-Neches estuary sediments and found Pb and Zn to be enriched. However, the present study is the first conducted on any of the organisms in the estuary.

Overall, there is broad TE contamination of the sciaenids in Lake Sabine with no discernable pattern, likely indicating a well-mixed estuary due to tidal mixing and individual fish movement, despite the protected habitat on the Louisiana side. Anthropogenic sources of Cu, the one metal with differences between the sides of the lake, include anti-fouling paints for vessels, mining, industry, and agriculture (Comber et al. 2022). Sampling did not occur in either the Port Arthur or Sabine-Neches Canals, which carry most of the large ship traffic, so we could not evaluate fully the effects on contamination severity with proximity to the port. However, many of these anthropogenic Cu sources are found along the lower stretches of the Neches River from Beaumont to Port Arthur, Texas. While sampling the canals for fishes may be logistically challenging or difficult due to nautical security, these sites likely have organisms with higher concentrations of TEs than the main part of the lake.

Tissue comparisons.—The overall greater concentrations of TEs in liver versus muscle tissue likely result from the different physiological function of each organ. The liver acts as a detoxifying

organ and it would accumulate high levels of contaminants like potentially toxic elements (Zhao et al. 2012). Fishes also tend to accumulate these heavier elements in fatty tissue, and liver is a fatty organ while muscle is relatively low in fat for these species (Authman et al. 2015). Several prior trace element studies of sciaenid fishes have found similar results with liver tissue having higher concentrations than muscle tissue (Zhao et al. 2012; El-Moselhy et al. 2014; Méndez-Rodríguez et al. 2021).

Trace element concerns.—TEs can cause physical deformities, negatively affecting metabolic processes, delay in development, and stunting growth when embryonic or larval fish are exposed (Zeitoun & Mehana 2014; Sfakianakis et al. 2015). Physical deformities developed from larval exposure to TEs can affect swimming and foraging abilities into adulthood. Adult exposure can negatively affect reproduction and disrupt the endocrine system (Zeitoun & Mehana 2014; Sfakianakis et al. 2015). The thresholds for TE contaminants to cause adverse effects in many fishes remains unknown (Sfakianakis et al. 2015), and the exact effects of TE contamination depend on water chemistry, metal/metalloid/nonmetal interactions with each other, the concentration of the metal/metalloids, as well as life stage and fish species (Sfakianakis et al. 2015). None of the fish from these sampling efforts were visibly deformed externally, but future studies may wish to examine earlier life stages of these sciaenids for TE contaminant effects.

Se:Hg molar ratio.—All individuals had a molar ratio of Se:Hg greater than one, indicating selenium may offer protection from mercury toxicity. Selenium is toxic in excess quantities, although the molar ratio seen in this study does not indicate whether selenium is at high enough concentration to cause lethal or sublethal effects (Gochfield & Burger 2021). This work also simply considered total mercury (THg). Future work should also categorize the mercury species as inorganic and organic forms of the element can affect organisms differently.

Conclusions.—Sciaenid fishes support a recreational fishery throughout Sabine Lake, and the present study provides baseline data

for 15 TEs in these four fishes at early life stages. Differences in concentrations between the species' liver and muscle, but not among species themselves, suggest tissue composition (lipid concentration differences) and the detoxifying function of the liver likely play a role in the bound elements. Differences between liver and muscle metal concentrations were also noted among the three foraging guilds, with higher concentrations seen in the benthic guild than in the pelagic or generalist guilds. Prey differences may be responsible for the significance in specific TEs expressed by the liver. Other than Atlantic croaker, with no minimum size, none of the individuals in this study were of retainable sizes (Texas Parks & Wildlife Department 2024), nor are fish livers usually eaten by anglers. Further investigation using a larger specimen size range (including legally retainable sizes) and prey items will help better assess TE bioaccumulation and biomagnification within the food web and over ontogenetic development, as foraging guilds within small size classes are not necessarily the same at larger, adult sizes. Rapid ontogenetic development, particularly in the smaller size classes, may explain the lack of bioaccumulation differences but only further study will be able to attest to this assumption. Future investigation is needed to determine if the levels of TE contamination within the fish of Sabine Lake are lethal or cause sublethal effects as well as further assessment of potential differences between the east and west sides.

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