ASSESSMENT OF MERCURY IN SELECTED GAME FISH FOOD WEBS IN THE TEXAS COASTAL ZONE: FINAL REPORT

by

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EXECUTIVE SUMMARY

Mercury, in the form of methylmercury, is the only metal that bioaccumulates through all trophic levels in aquatic food chains. This results in the toxicant mainly residing in the muscle tissue of fish, a highly nutritious food, and an important protein source for many people and communities. Elevated MeHg also impacts the health of fish and other wildlife including both lethal and sublethal effects. Mercury is a potent neurotoxin, and may also have cardiovascular, reproductive, and immune system effects. The environmental and health effects of mercury are due to the conversion of Hg(II), which does not bioaccumulate to any great degree, to MeHg, a process that readily occurs in areas where sediments are saturated and hypoxic, such as wetlands, as well as the upper, photic areas of the open. MeHg is synthesized from Hg(II) mostly by methylating microbes, which include many species of anaerobic and aerobic free-living bacteria and fungi.

In the Gulf of Mexico, the highest concentrations of total Hg in sediments, as well as MeHg in oyster tissue are found in Lavaca Bay, Texas, and Tampa Bay and Florida Bay in Florida. Lavaca Bay has been the epicenter for mercury contamination and studies of heavy metals on the Texas Gulf of Mexico coast. The Alcoa/Lavaca Bay Superfund Site (designated in March 1994) consists of the Point Comfort Operations Plant, Dredge Island and portions of Lavaca Bay, Cox, Bay, Cox Creek, Cox Cove, Cox Lake, and western Matagorda Bay. Analysis of 2006/2007 "Mussel Watch" data on mercury in oyster tissues and sediments indicated that while there were detectable concentrations of total mercury in virtually all Texas bay sediments, concentrations were below 0.051 ppm (51 ppb), the maximum "background" concentration set by NOAA (2008) except for 2 sites in Galveston Bay (Galveston Bay ship channel, Offatts Bayou), the East Matagorda Bay site, and 2 sites in Lavaca Bay (Gallnipper Point, Lavaca River mouth). Currently fish consumption advisories for blackfin tuna (*Thunnus atlanticus*), blue marlin (*Makaira nigricans*), little tunny (*Euthynnus alletteratus*), crevalle jack (*Caranx hippos*), king mackerel (*Scomberomorus cavalla*), shark (any), swordfish (*Xiphias gladius*), and wahoo (*Acanthocybium solandri*) due to mercury concentrations that exceed health guidelines established by Texas Department of State Health Services (0.7 mg/kg [700 ng/g dw; 700 ppb]) exist for all waters off the Texas Coast.

Goals and Objectives

In this study, we expand knowledge of movement of methylmercury through aquatic food webs in Lavaca Bay, San Antonio Bay, and Nueces Bay to improve management of this pollutant in the Texas coastal zone. Our objectives were: 1) to analyze tissues and major food organisms of three Texas coastal game fishes (red drum [*Sciaenops ocellatus*]; black drum [*Pogonias cromis*]; spotted seatrout [*Cynoscion nebulosus*]) to assess concentrations of mercury in the Lavaca Bay, Nueces Bay, and San Antonio Bay food webs; 2) to conduct stomach content analysis on the selected games fishes to determine and/or confirm their food choices; 3) to conduct stable isotope analysis on selected predator and prey organisms to determine and/or confirm their food web linkages; and, 4) to construct a model of likely pathways of mercury bioaccumulation in food webs of the bays.

Methods

Red drum, black drum, and spotted seatrout for this study were captured in gillnets by Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Division during their semi-annual resource monitoring sampling between April 2013 and November 2013; we made collections during both spring/summer and fall/winter sampling. Prey species and sediment samples were collected twice in each bay: once during spring/summer and once during fall/winter. Phytoplankton and zooplankton were sampled twice in each bay during spring/summer when organisms were abundant enough that amounts sufficient for analysis could be collected. All mercury (inorganic, methylmercury) analyses were conducted at the National High Magnetic Field Laboratory and Department of Earth, Ocean and Atmospheric Sciences at Florida State University during July 2013 using a Tekran®2700 Mercury Analysis System. All stable isotope analyses were conducted by the Texas A&M University Corpus Christi Isotope Core Laboratory. Carbon elemental and isotopic compositions were determined using a Costech ECS4010 elemental analyzer (EA) connected to a continuous flow Thermo Delta V Plus isotope ratio mass spectrometer (IRMS) via a Thermo Conflo IV interface.

Results

Inorganic mercury was the most abundant chemical species of mercury in all three bays although very little of either inorganic or methylmercury was present in sediments in San Antonio Bay. Proportionally, methylmercury represented 1% or less of total mercury in sediments. Methylmercury represented less than 0.5% of total mercury in phytoplankton in all three bays. In zooplankton, neither inorganic nor methylmercury were concentrated compared to either the environment or to the phytoplankton; concentrations of both chemical species were less than those measured in both sediments and phytoplankton in all three bays. Inorganic mercury was the majority of mercury detected in polychaetes.

The concentration of methylmercury in mollusk tissues varied greatly within the group with the lowest concentrations measured in eastern oysters (*Crassostrea virginica*) in any bay and the highest concentrations in squid (Order Teuthida) in Lavaca Bay. The differences in concentrations reflect accumulation due to the diets of the organisms, particularly the scraping foraging behavior of the gastropods and their focus on epiphytes and/or epibenthic algae, and predation by squid. Mean tissue concentrations of methylmercury were similar across crustacean groups, although blue crab concentrations were higher than other crustaceans in Lavaca Bay

Methylmercury concentrations in Atlantic croaker (*Micropogonias undulatus*), spot (*Leistomus xanthurus*), and pinfish (*Lagodon rhomboides*) collected from Lavaca Bay are 2 to 10 times greater than concentrations in the same fish species collected from the other bays. Mercury tissue concentrations in gamefish were greatest in Lavaca Bay and least in San Antonio Bay. Methylmercury was the predominant form of mercury regardless of species or size class.

Based on $\delta^{15}N$ values, food chains in Lavaca and Nueces bays appear to be short with most higher organisms feeding at a similar trophic level. In contrast, the food web structure in San Antonio Bay is characterized by distinct positions for each of species or species category, and much clearer distinctions between the carbon sources used by each. Benthic diatoms ($\delta^{15}N$ ~18-

20‰) appear to be the most likely source of carbon for most organisms; very few consumers appeared to depend solely on carbon derived from phytoplankton. In this study, values for the lowest consumer levels were just above the estimated phytoplankton baseline (10‰) in both Lavaca and Nueces bays whereas there is a clear increase in trophic level in San Antonio Bay between the estimated phytoplankton baseline and the lowest consumer levels (~13–14‰). The differences between the highest and lowest mean $\delta^{15}N$ is 7‰ in Lavaca Bay and 6.2‰ in Nueces Bay or a maximum of 2 trophic levels. On the other hand, in San Antonio Bay, the difference between the highest and lowest mean $\delta^{15}N$ is 12.3‰, or nearly 4 trophic levels.

Omnivory appears to be the feeding mode for most organisms in Lavaca and Nueces bays whereas food resources appear to be more distinct and species- or species category-specific in San Antonio Bay. The small number of trophic levels in Lavaca and Nueces bays results in very steep increases from low to high and very high concentrations in some organisms. In San Antonio Bay, MeHg concentrations also increase with trophic level, but the rate of increase is less rapid, largely due to the overall lower concentrations of mercury in organisms, but also because the food chain is longer.

Conclusions

- Mercury was present in organisms in all three bays; methylmercury was generally the predominant species except in phytoplankton, zooplankton, and polychaetes in which inorganic mercury predominated.
- Mercury concentrations in organisms were lower in San Antonio than in either Lavaca or Nueces bays; mercury concentrations in the largest black drum (*Pogonias cromis*, >399 mm), and in both size classes of red drum (*Sciaenops ocellatus*), and spotted seatrout (*Cynoscion nebulosus*) in both Lavaca and Nueces bays exceeded TDSHS "action levels."
- Mercury concentrations generally increased with the size of the organism.
- Food webs in Lavaca and Nueces bays are shorter than in San Antonio Bay due to the destabilizing effects of omnivory which prevents many higher organisms from reaching their maximum trophic level
- Because food webs are short in Lavaca and Nueces bays, methylmercury is accumulates in the highest trophic levels more rapidly than in San Antonio Bay where there are more trophic levels and more normal food web relationships (i.e., more organisms are reaching their maximum trophic level.
- Estuarine food webs in the Texas coastal zone are complex, but it is clear that bioaccumulation and biomagnification of mercury increases as the trophic level and size of organisms increases.
- The differences among and between the three bays in this study are due to the relative importance of omnivory in the food chains that make up the food web which reflects the disturbance within the bay system. This disturbance may be due to contaminants, such as mercury, or to natural factors, such as fluctuating salinities.

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INTRODUCTION

Mercury, in the form of methylmercury (CH_3Hg^+, MeHg hereafter), is the only metal that bioaccumulates through all trophic levels in aquatic food chains (Lawson and Mason 1998). This results in the toxicant mainly residing in the muscle tissue of fish, a highly nutritious food, and an important protein source for many people and communities (Mergler et al. 2007). Mercury is a potent neurotoxin, and may also have cardiovascular, reproductive, and immune system effects. Human health effects from mercury include nervous system deterioration, impairment of hearing, speech, vision, mobility, and chewing and swallowing, involuntary muscle movements, and corrosion of skin and mucous membranes (USGS 1995). Worldwide, populations that live near oceans, rivers and lakes, or hydroelectric dams and for whom fish is a dietary mainstay, such as in the Amazon River Basin, or on the Faroes or Seychelles islands, are the most likely to be affected (Mergler et al. 2007). However, members of more affluent societies who can afford to buy and consume large quantities of marine fish are also affected. In 2010-2011 the US Environmental Protection Agency (USEPA) issued fish consumption advisories in at least one waterbody in 28 states due to fish tissue mercury concentrations that exceeded levels that were safe for human consumption (http://fishadvisoryonline.epa.gov/Advisories.aspx).

Mobilization of mercury into ecosystems occurs through mining, its use as a catalyst (chlor-alkali plants) or amalgam (gold recovery, dental fillings), its presence as a trace contaminant in coal and other metal ores, and it use in products like paints and electronic devices (Driscoll et al. 2013). Table 1 shows the primary sources of anthropogenic mercury emissions. Mercury entry into aquatic ecosystems occurs primarily through atmospheric mobilization and deposition especially associated with coal-fired powerplants (Fry and Chumchal 2012; Driscoll et al. 2013) although both natural mercury emissions and re-emitted mercury also play a role (USEPA 1997, Driscoll et al. 2013). It is important to understand the difference between primary and secondary (re-emission) sources of mercury (Driscoll et al. 2013). Primary sources transfer mercury (elemental or Hg[0]) stored in the lithosphere to the atmosphere with a residence time of several months to a year, which means it can be transported for great distances. Mercury that is bound to particulates (inorganic [Hg^{2+}] or Hg[II]) and transferred to the atmosphere has a much shorter residence time (hours to days), is deposited locally or regionally, and is the primary source of inputs into ecosystems. Secondary sources transfer mercury (Hg[0] or Hg[II]) among surface reservoirs via the atmosphere. Thus, mobilization of mercury from the lithosphere represents "new" mercury and increases the global pool in surface reservoirs whereas secondary sources redistribute "old" mercury within and among ecosystems. Worldwide, east Asia accounts for about 40% of primary anthropogenic emissions. Emissions have remained relatively stable since 1995 because emissions have declined in the developed world, offsetting increases in the developing world (Figure 1).

The environmental and health effects of mercury are due to the conversion of Hg(II), which does not bioaccumulate to any great degree, to MeHg, a process that readily occurs in areas where sediments are saturated and hypoxic, such as wetlands, as well as the upper, photic areas of the open ocean (Driscoll et al. 2013). MeHg is synthesized from Hg(II) mostly by methylating microbes, which include many species of anaerobic and aerobic free-living bacteria and fungi, (Jackson 1998). In estuaries, as well as other aquatic ecosystems, SO_4^{2-} reducing bacteria are the dominant methylating organisms under anoxic conditions, and when sulfates are limiting. These

Table 1. Sources of anthropogenic mercury emissions. From USEPA 1997.

Area (non-point) Sources	Point Sources		
	Combustion	Manufacturing	Miscellaneous
Electric (usually fluorescent) lamp breakage	Utility boilers	Chlor-alkali production	Oil shale retorting
Paints	Commercial/industrial boilers	Lime manufacturing	Mercury catalysts
Laboratory uses	Residential boilers	Primary mercury production	Pigment production
Dental preparations	Municipal waste combustors	Mercury compounds production	Explosives manufacturing
Mobile sources (cars, etc.)	Medical waste incineration	Battery production	Geothermal power plants
Agricultural burning	Sewage sludge incinerators	Electrical apparatus manufacturing	Turf products
Landfills	Hazardous waste combustion	Carbon black production	
Sludge application	Wood-fired boilers	Byproduct coke production	
	Residential wood stoves	Primary copper smelting	
	Crematories	Cement manufacturing	
		Primary lead smelting	
		Petroleum refining	
		Instrument manufacturing	
		Secondary mercury production	
		Zinc mining	
		Fluorescent lamp recycling	
		Pulp and paper mills	

bacteria may be most important in the methylation process and subsequent contamination of shallow-water food webs when they are found at the redox interface (Fry and Chumchal 2012). The aquatic mercury cycle is shown in Figure 2.

Elevated MeHg also impacts the health of fish and other wildlife including both lethal and sublethal effects (Driscoll et al. 2013). Similarly to humans, other vertebrate organisms such as fish, and piscivorous and insectivorous birds and mammals in aquatic habitats and adjacent

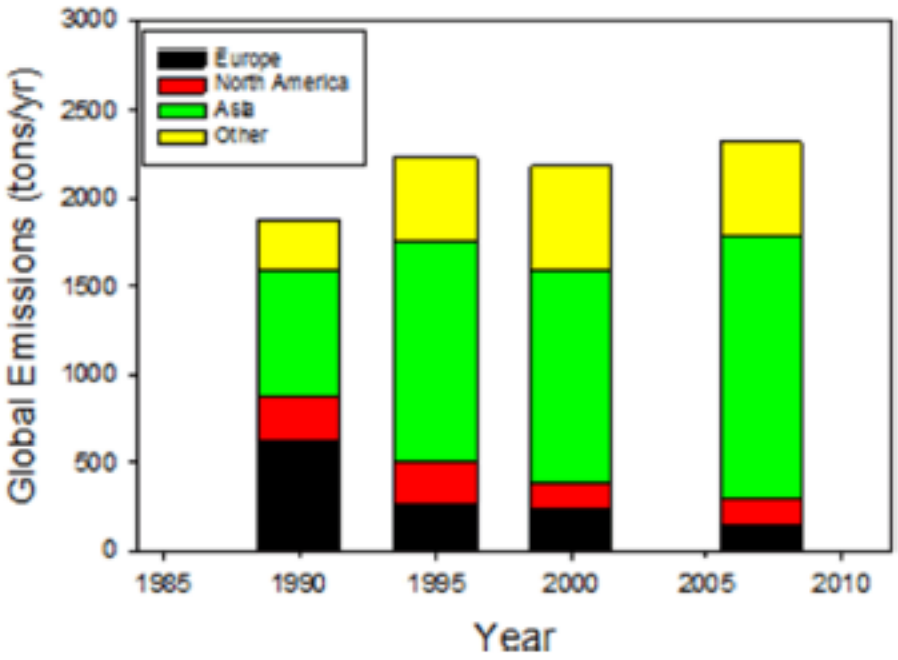

Figure 1. Global emissions of mercury. From Driscoll et al. (2013).

ecosystems exhibit reproductive effects, such as changes in embryonic development and reduced reproductive output, hormonal changes and physiologic changes, and motor impairment and other neurological changes. While the effects on organisms at the top of the food web are relatively well known, virtually nothing is known about either direct or indirect effects of MeHg on organisms at the base of the food web (Fleeger et al. 2003).

Mercury in Food Webs

Unless otherwise noted, this section was synthesized and summarized from a very thorough review of bioaccumulation and biomagnification of mercury in food webs by Kidd et al. (2012).

Organisms at the base of aquatic food chains (i.e., phytoplankton, epiphytes, zooplankton) generally bioconcentrate Hg (i.e., concentrations in organisms exceed those in the environment) via passive diffusion of mercury across membranes. At higher trophic levels, Hg exposure can occur through both passive diffusion and active uptake via Na^{+} and Ca^{2+} channels (for example, through gills) from the water, but more importantly, through diet (i.e., bioaccumulation), with the importance of diet increasing as trophic level increases. Biomagnification of Hg in food webs occurs when concentrations of mercury in predators exceed that of their prey. Biomagnification of mercury has been clearly demonstrated in freshwater and marine/estuarine systems. When sensitive species are impaired by lethal or sublethal effects, the resulting ecological effects can result in trophic cascades, competitive release, or other alterations of ecological function (Fleeger et al. 2003).

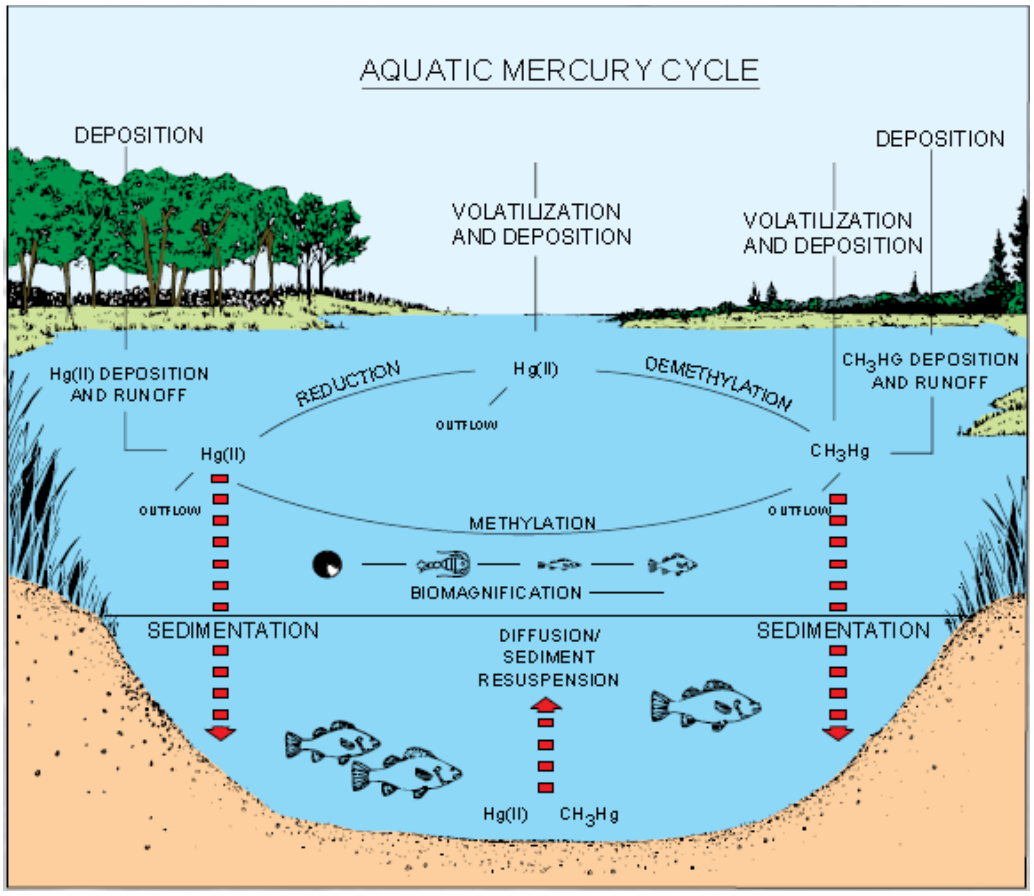

Figure 2. Mercury cycling in aquatic environments showing the conversion of Hg species to MeHg, the most toxic form that bioaccumulates and causes human health effects. From USGS 1995.

The amount of mercury that can be directly taken up by organisms is determined by the bioavailability of Hg(II) and MeHg in the environment, which in turn depends on the presence of complexing ions such as dissolved organic carbon (DOC), sulfides, Cl^- and OH^- that affect the absorbability of Hg. Since MeHg is the most toxic and the most readily accumulated, inhibition or facilitation of microbial methylation due to the presence (or absence) of various chemical components in water/sediments determines bioavailability of mercury to bioconcentrating organisms. In estuarine and marine systems, salinity, oxygen, and sulfate vs sulfide are the main factors that affect how much Hg(II) will become methylated (Kongchum et al. 2006, Fry and Chumchal 2012). Generally, in habitats with relatively low salinities, significant sulfate reduction, and low to moderate accumulation of sulfides rates of methylation are higher than in habitats with higher salinities, greater concentrations of sulfides, and reduced (hypoxic to anoxic) conditions. In the Louisiana coastal zone, Hg concentrations in fish tissue were about 2X greater in oligohaline and freshwater areas than in more saline areas (Fry and Chumchal 2012). Similarly, freshwater marsh sediments contained more total mercury and methylated mercury than saltmarsh sediments (Kongchum et al. 2006). Thus, the bioavailability of methylated mercury will generally decrease with increasing salinity and sulfides. Penetration of sunlight, DOC, and thiols and other sulfur-containing compounds may also affect the relative availability

of Hg(II) for methylation or direct uptake, but the interactions are complex and conflicting relationships among the various chemical species have been reported.

Primary productivity enters aquatic food webs either directly via grazing on phytoplankton, epiphytes, or submerged or emergent aquatic vegetation, or indirectly via the detrital food web which relies on secondary producers (usually invertebrates) to convert detrital material to usable animal biomass that can be transferred to higher trophic levels. The inherent difficulties of separating algae, bacteria, and detritus means that the bioconcentration of Hg in the primary producers is not well known; however, concentrations of seston can be up to 10^6 higher than the surrounding water. MeHg is bioconcentrated by algae more than Hg(II) and smaller algal species contain higher concentrations of MeHg than larger species.

Invertebrate consumers near the base of the food web are exposed to both MeHg and Hg(II) in water and sediments although diet is generally considered the more important pathway of exposure. MeHg is more efficiently retained than Hg(II) because it is stored in the cytoplasm of cells. Mercury concentrations in the tissues of these organisms varies greatly within species and between species depending on their feeding ecology, concentrations/bioavailabilities of the various mercury chemical species in the environment, assimilation efficiencies, excretion rates, lifestage, and the size and productivity of the water body. For example, with regard to feeding ecology, MeHg concentrations in invertebrate predators or collectors can be 2-6 times greater than concentrations in invertebrates classified as grazers or shredders.

Although the skin and gills of fish are avenues for accumulation of mercury directly from the water, like the invertebrates, diet is the more important pathway accounting for ~90% of Hg accumulation. Long-lived fish at the top of the food chain have the highest concentrations of total Hg and most or all is MeHg. There is increasing evidence that these concentrations are resulting in toxic effects to the fish themselves in addition to the toxic effects to humans and piscivorous birds (e.g., pelicans, loons) and mammals (e.g., marine mammals, bears, minks). Figure 3 shows the increases of total mercury in muscle tissues with trophic level in several aquatic habitats.

Stable isotope analyses have advanced the understanding of the biomagnification of contaminants in food webs, in part because they have allowed trophic relationships to be more specifically defined. Nitrogen isotopes are particularly popular for looking at Hg biomagnification because the ratio of ^{15}N to ^{14}N (expressed as $\delta^{15}N$) increases predictably with increasing trophic level and can be used to compare Hg biomagnification across systems. One approach is to regress log Hg vs trophic level (calculated from $\delta^{15}N$) which describes the average increase in Hg per trophic level (Figure 4). Concentrations at the highest trophic levels vary among sites due to differing bioavailabilities in the environment, differing bioaccumulation rates of organisms despite similar trophic position, as a result of differing growth rates or feeding efficiencies (which may relate to system productivity or stressors), and/or longer food chains. Stable isotope studies of marine food webs have shown similar of patterns biomagnification to food webs in freshwater system and that the same factors affect the ultimate concentrations of Hg at the highest trophic levels. Studies using $\delta^{15}N$ have shown that transfer varies across marine systems, but is similar in range to freshwater systems; trophic transfer and retention of MeHg is somewhat more efficient in marine systems. Stable isotopes of carbon (δC^{13}) are not used to

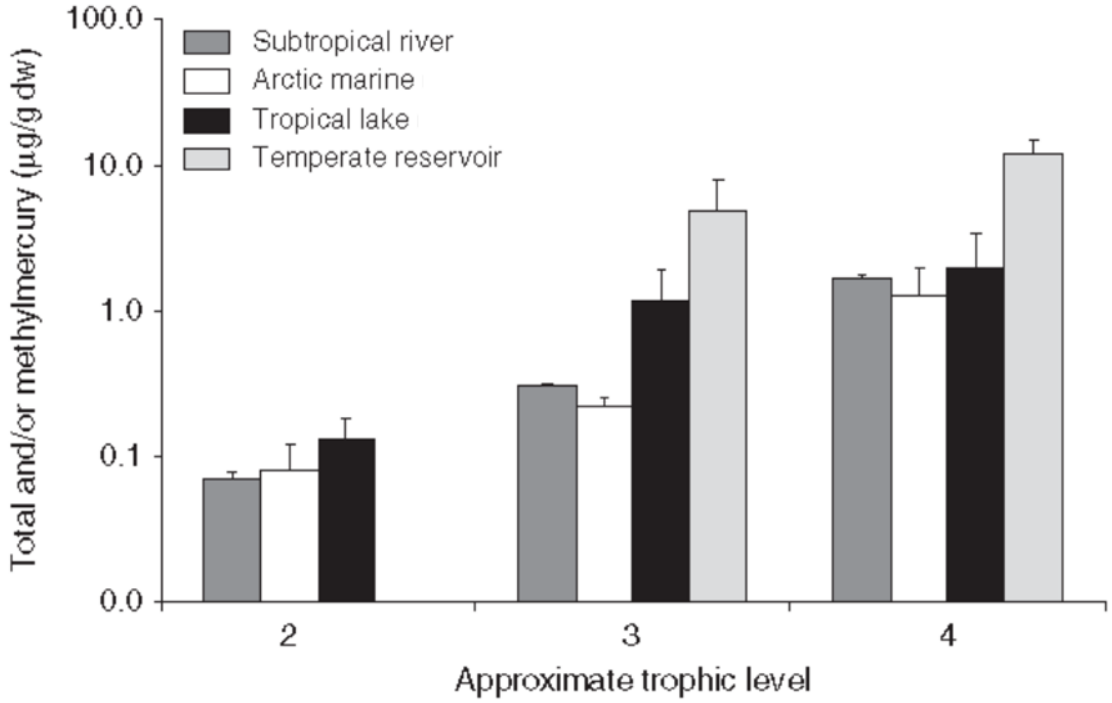

Figure 3. Biomagnification of total mercury by trophic level (coarsely assigned using stable nitrogen isotopes) in various aquatic ecosystems. Example taxa for each level include benthic organisms or planktivorous fish (TL2), forage or omnivorous fish (TL3), and piscivorous fish, birds or mammals (TL4). From Kidd et al. (2012).

explore Hg biomagnification as frequently as $\delta^{15}N$ because the differences in the inputs at the base of the food web means that the added information does not always result in increased explanatory power to models of Hg accumulation in food chains.

Historical Perspective of Mercury Contamination in Texas Bays

In the Gulf of Mexico, the highest concentrations of total Hg in sediments, as well as MeHg in oyster tissue are found in Lavaca Bay, Texas, and Tampa Bay and Florida Bay in Florida (Apeti et al. 2012). Lavaca Bay has been the epicenter for mercury contamination and studies of heavy metals on the Texas Gulf of Mexico coast. The Alcoa/Lavaca Bay Superfund Site (designated in March 1994) consists of the Point Comfort Operations Plant, Dredge Island and portions of Lavaca Bay, Cox, Bay, Cox Creek, Cox Cove, Cox Lake, and western Matagorda Bay (USEPA 2014; Figure 5). Mercury contamination exists throughout the site in the surface soils, shallow groundwater, air, bay sediments, fish, and crabs (ATSDR 2009). The plant was first established as an aluminum smelter in 1948 (shut down in 1980) and has been refining bauxite to produce alumina since 1958 (EPA 2014). The primary source of mercury contamination was the wastewater from the chlor-alkali plant where mercury cathodes were used to produce sodium hydroxide for bauxite refining. From 1965–1970, wastewater containing mercury was transported to Dredge Island which contained an 91 acre lagoon, where it was allowed to settle,

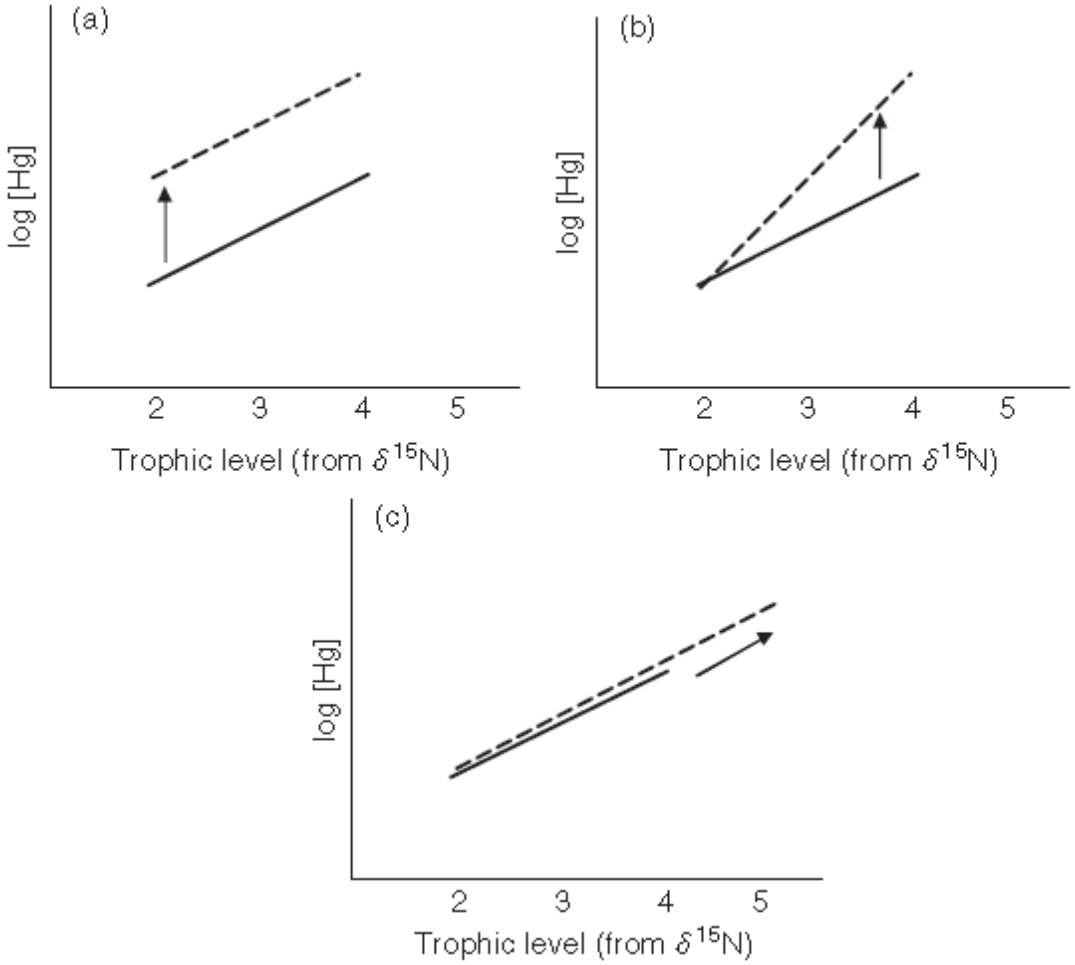

Figure 4. Mercury biomagnification varies in top predators (trophic levels 4 and 5) due to (a) differing bioavailabilities or baseline concentrations; (b) differences in Hg accumulation rates; or (c) longer food chains. From Kidd et al. (2012).

then the overflow was discharged into Lavaca Bay. Prior to 1970 at least 67 pounds of mercury per day were discharged into the bay (ASTDR 2009). After 1970, wastewater was discharged to onshore collection sites or reused in plant operations which reduced the amount of mercury discharged into the bay to about 13 pounds per day. The chlor-alkali plant was removed in 1986.

In 1970 the Texas Department of Health (TDH, now Texas Department of State Health Services [TDSHS]) closed parts of Lavaca Bay to oystering after finding significantly elevated mercury concentrations in oysters and crabs; at that time TDH did have the authority to prohibit fishing or crabbing (ASTDR 2009). The oyster closure was lifted in 1971 after mercury concentrations fell below 0.5 ppm. In 1988, TDH established a 1 mile^2 area of Lavaca Bay around Dredge Island and including a portion of Cox Bay where the taking of finfish and crabs was prohibited (USEPA 2014). The concentration of mercury in these organisms was great enough that their consumption could result in human health impacts (ASTDR 2009). The portion of Cox Bay that had been

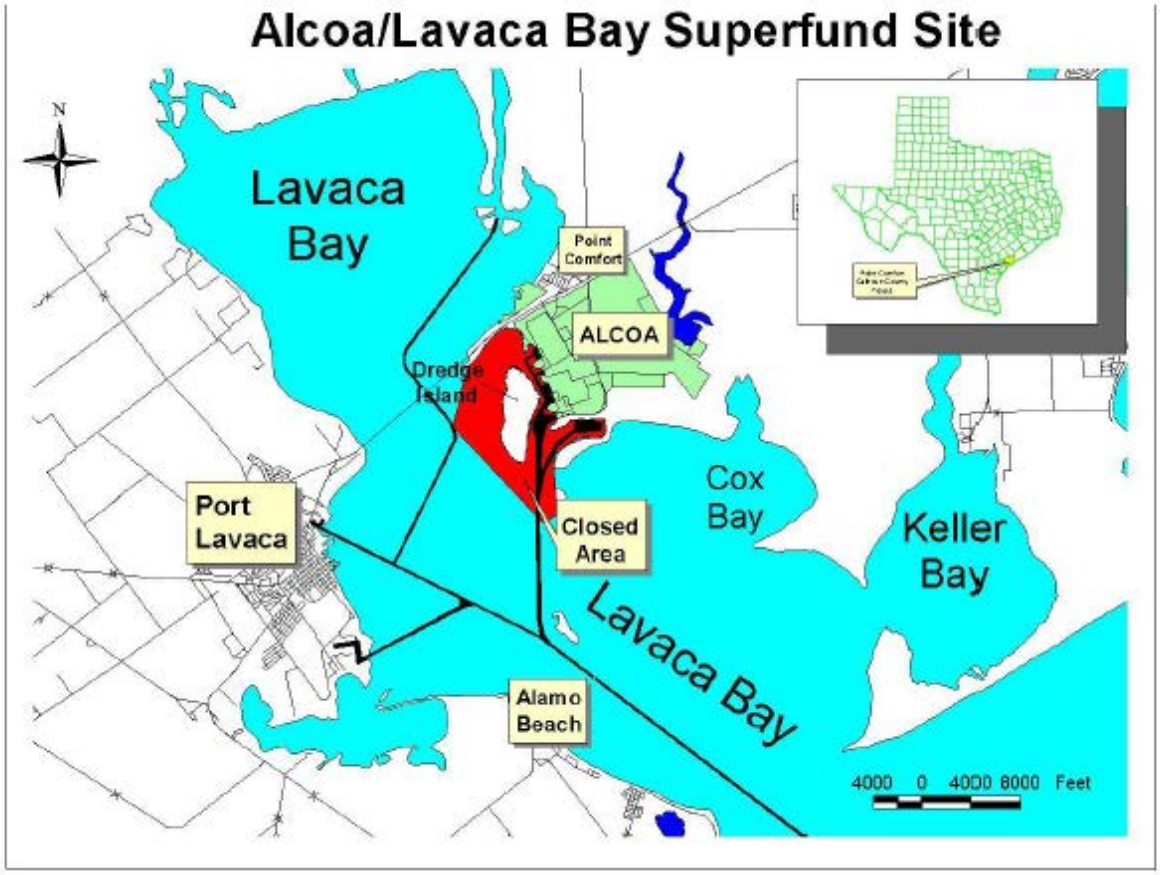

Figure 5. Alcoa/Lavaca Bay Superfund Site showing Dredge Island and the area that is closed to fishing and crabbing (from EPA 2014).

closed was reopened by TDH in 2000 because mercury contamination of finfish and crabs had decreased to concentrations that were acceptable for human consumption (USEPA 2014).

Most of the other bays on the Texas coast exhibit relatively little mercury contamination in water or sediment. While the majority of filter-passing mercury in water coming into Galveston Bay came from the San Jacinto or Trinity rivers, Corpus Christi Bay and Sabine Lake had significant sources of filter-passing mercury within the estuary (Stordal et al. 1996). Morse et al. (1993) noted that Galveston Bay water column and oysters exhibited little evidence of anthropogenic inputs of Hg but when normalized to grain size and reactive-Fe, Hg concentrations in the sediment were 1.5 times higher than sediments in Baffin Bay (reference site), suggesting that historically elevated water column concentrations were likely. Mercury contamination of sediments extends out of Lavaca Bay and into upper Matagorda Bay (Brown et al. 1998). Sediments in San Antonio Bay did not seem to represent a reservoir of metals; Hg in mollusk and crustacean tissues was very low and dredging and resuspension of sediment was not related to metal concentrations in tissues (Sims and Presley 1976). Analysis of 2006/2007 “Mussel Watch” data on mercury in oyster tissues and sediments indicated that while there were detectable concentrations of total mercury in virtually all Texas bay sediments, concentrations

were below 0.051 ppm (51 ppb), the maximum "background" concentration set by NOAA (2008) except for 2 sites in Galveston Bay (Galveston Bay ship channel, Offatts Bayou), the East Matagorda Bay site, and 2 sites in Lavaca Bay (Gallnipper Point, Lavaca River mouth) (Apeti et al. 2012).

Currently fish consumption advisories for blackfin tuna (*Thunnus atlanticus*), blue marlin (*Makaira nigricans*), little tunny (*Euthynnus alletteratus*), crevalle jack (*Caranx hippos*), king mackerel (*Scomberomorus cavalla*), shark (any), swordfish (*Xiphias gladius*), and wahoo (*Acanthocybium solandri*) due to mercury concentrations that exceed health guidelines established by TDSHS (0.7 mg/kg [700 ng/g dw; 700 ppb]) exist for all waters off the Texas Coast (TDSHS 2013). In addition, mean total mercury concentrations in the tissues of oversize red drum (*Sciaenops ocellatus*) collected from the surf zone on the central coast exceeded TDSHS health guidelines (Stunz and Robillard 2011). However, mercury concentrations in species that are targeted in the recreational fishery (i.e., red drum, spotted seatrout [*Cynoscion nebulosus*], southern flounder [*Paralichthys lethostigma*]) were low in minimally impacted coastal areas: Keith Lake (Sabine Estuary), Christmas Bay (Galveston Estuary), Espiritu Santo Bay (Matagorda Estuary), Redfish Bay (Nueces/Aransas estuaries), and South Bay (lower Laguna Madre) (Sager 2004). Stunz and Robillard (2011) present additional mercury tissue concentrations for red drum and spotted seatrout, as well as black drum (*Pogonias cromis*) from Aransas Bay, Nueces Bay, Corpus Christi Bay, and upper and lower Laguna Madre which also show minimal mercury contamination of fish residing within the estuaries. In oyster tissue, the FDA limit for mercury is 1 ppm and oysters collected from bays along the Texas coast in during sampling for NOAA's "Mussel Watch" program in 2006/2007 were all below this threshold (Apeti et al. 2012). In Lavaca Bay near the Dredge Island, mussel watch data shows a steady decrease in mercury concentrations in oyster tissue since 2000 (Figure 6).

Rationale, Goals, and Objectives

The Gulf of Mexico Alliance (GOMA) Water Quality Priority Issue Team's Mercury Workgroup is addressing the issue of mercury in water, sediment, and fish tissues of the Gulf of Mexico. In this study, we expand knowledge of movement of MeHg through aquatic food webs in Lavaca Bay, San Antonio Bay, and Nueces Bay to improve management of this pollutant in the Texas coastal zone. Lavaca Bay (LB), San Antonio Bay (SAB) and Nueces Bay (NB) have extensive oyster reef habitats and are popular areas for fishing and crabbing. These bays serve as nursery areas for shrimps, crabs, and juvenile fishes, and many birds use these areas for feeding. It is important that we assess and supplement the limited data available on mercury concentrations in sediments and tissues of organisms in these ecosystems to determine pathways of mercury movement in the food webs.

Our objectives were: 1) to analyze tissues and major food organisms of three Texas coastal game fishes (red drum [*Sciaenops ocellatus*]; black drum [*Pogonias cromis*]; spotted seatrout [*Cynoscion nebulosus*]) to assess concentrations of mercury in the LB, SAB and NB food webs; 2) to conduct stomach content analysis on the selected games fishes to determine and/or confirm their food choices; 3) to conduct stable isotope analysis on selected predator and prey organisms to determine and/or confirm their food web linkages; and, 4) to construct a model of likely pathways of mercury bioaccumulation in food webs of the bays.

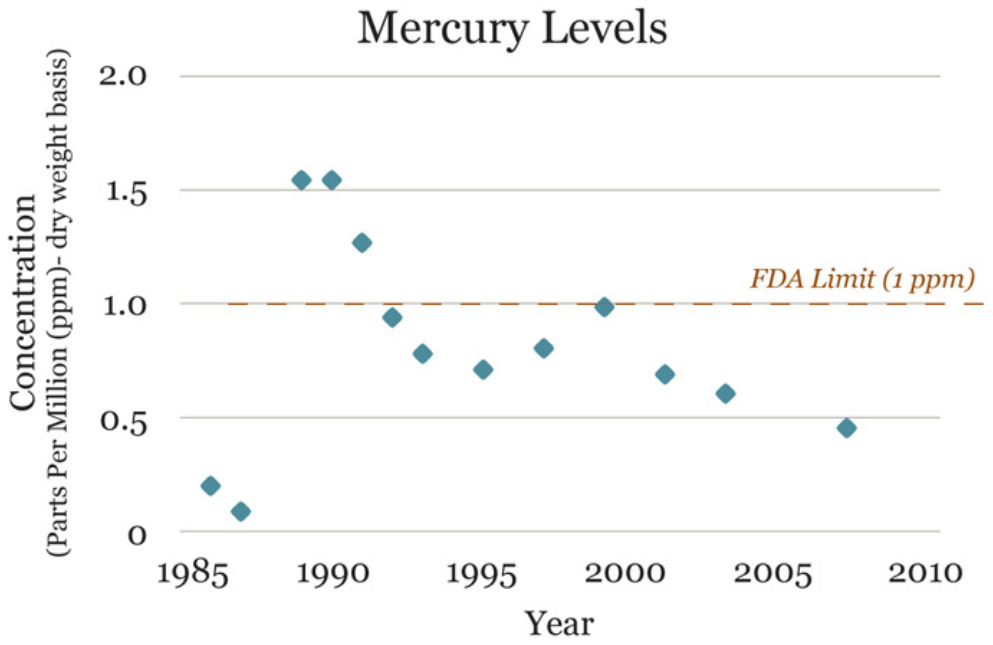

Figure 6. Mercury in oysters at Dredge Island near the Lavaca Bay Superfund site, 1985-2009. From http://stateofthecoast.noaa.gov/musselwatch/musselwatch.html

Study Area

We collected organisms for analysis from three estuarine systems on the central Texas Gulf of Mexico coastline (Figure 7): Lavaca Bay, in the Lavaca-Colorado Estuary (Figure 8); San Antonio Bay, in the Guadalupe Estuary (Figure 9), and Nueces Bay, in the Nueces Estuary (Figure 10). Our expectation was that these bays should represent a gradient of mercury contamination. Each bay was divided into approximately eight sampling regions, with two of these regions occurring in the deeper, open bay area, and the remaining six occurring in the shallow, nearshore area. Each sampling region was intended to encompass a more or less homogeneous sediment and faunal regime. Dates and coordinates of locations for each sampling event are in Appendix 1.

The Lavaca-Colorado Estuary (Figure 8) encompasses ~1450 km^2 including 348 km^2 of marshes/wetlands, 28 km^2 of submerged aquatic vegetation (SAV), primarily in Matagorda Bay (Hicks 2010) and ~11.5 km^2 of oyster reefs in Lavaca Bay (Dellapenna and Simons 2003). Average depth of the estuary is ~2m with maximum depth of 4.3 m in Matagorda Bay (Hicks 2010). Salinity in the estuary averages 23 psu and is lowest in Lavaca, Carancahua, and Tres Palacios bays. The Alcoa/Lavaca Bay Superfund Site is located in Point Comfort and the surrounding area. The population of Port Lavaca and Port Comfort combined is ~13,000. Mercury contamination is expected to be greatest in this bay system.

The Guadalupe Estuary (Figure 9) encompasses about 800 km^2 including ~270 km^2 of marshes/wetlands and 65 km^2 of SAV (Hicks 2010). Average depth in the estuary is 2 m and average salinity is 11 psu, ranging from 0 to 24 in San Antonio Bay due to freshwater inflow

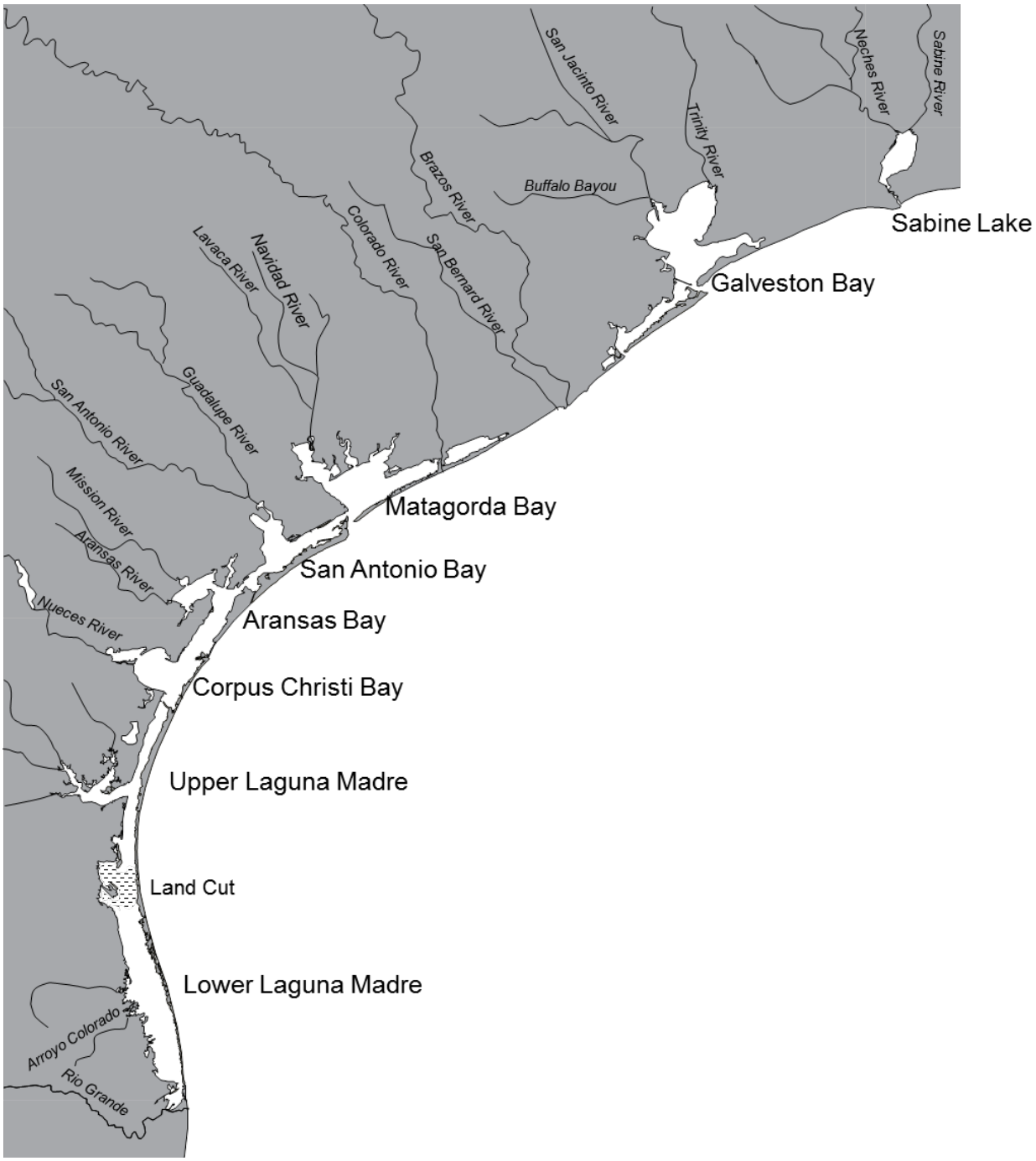

Figure 7. Map of the Texas Gulf of Mexico coast showing the bay systems and associated rivers. From Hicks (2010).

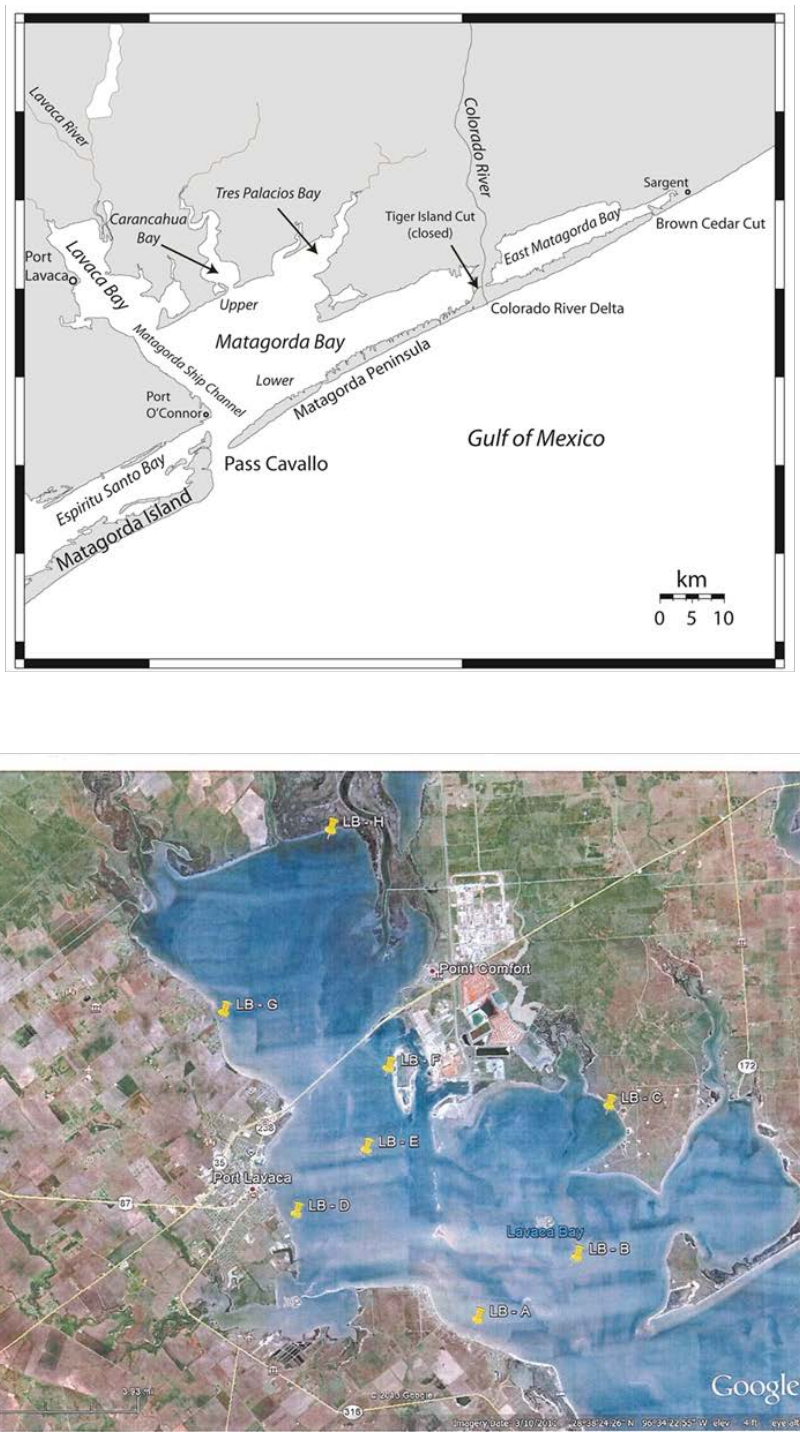

Figure 8. Map of the Lavaca-Colorado Estuary showing the location of Lavaca Bay (top; Hicks 2010) and an aerial view (bottom) of Lavaca Bay showing the locations of sites where various sample types were collected during the study. See Appendix 1 for GPS coordinates of sites and details of which sites were the sources of the various biological materials collected for the study.

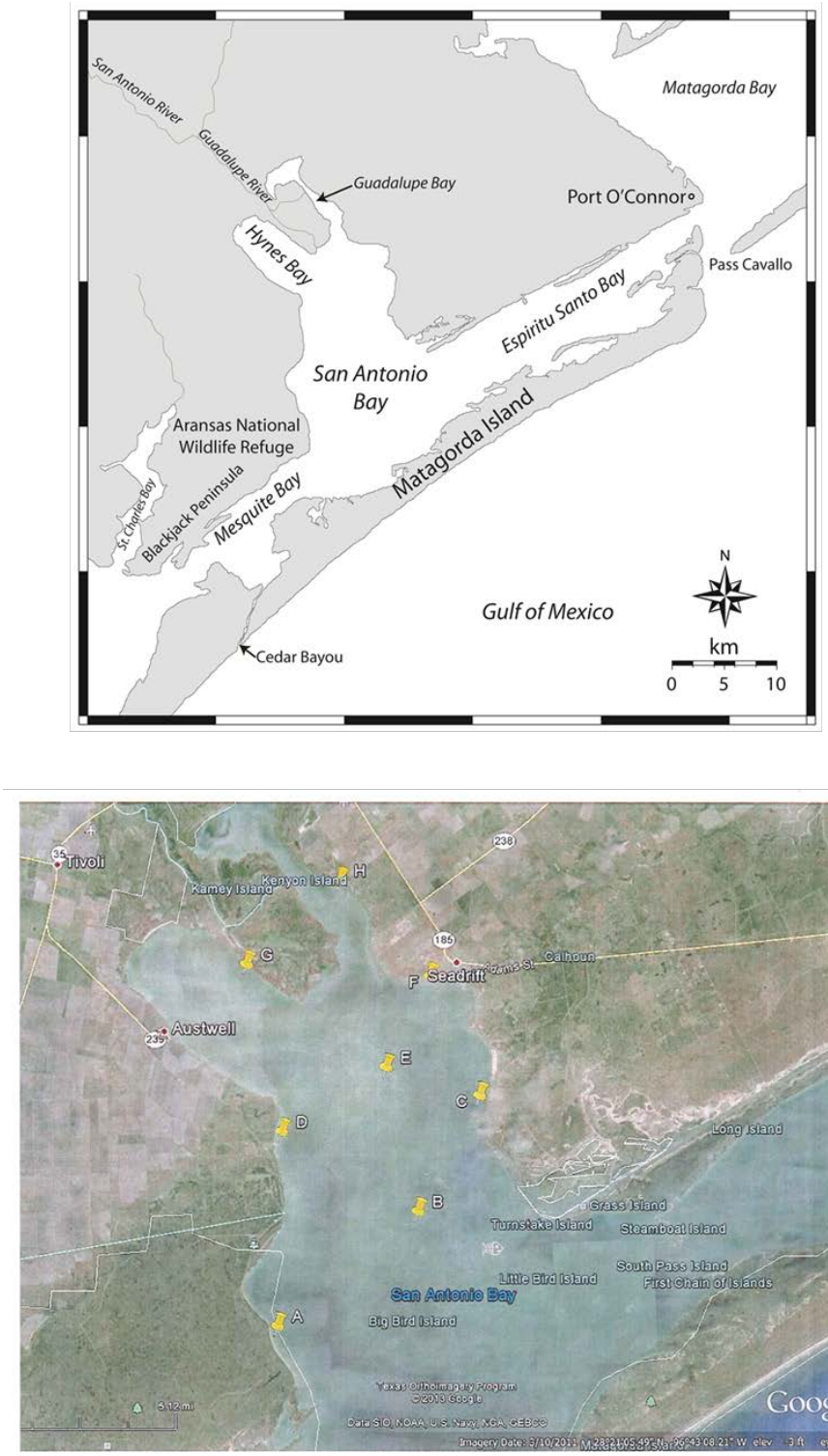

Figure 9. Map of the Guadalupe Estuary showing the location of San Antonio Bay (top; Hicks 2010) and an aerial view (bottom) of San Antonio Bay showing the locations of sites where various sample types were collected during the study. See Appendix 1 for GPS coordinates of sites and details of which sites were the sources of the various biological materials collected for the study.

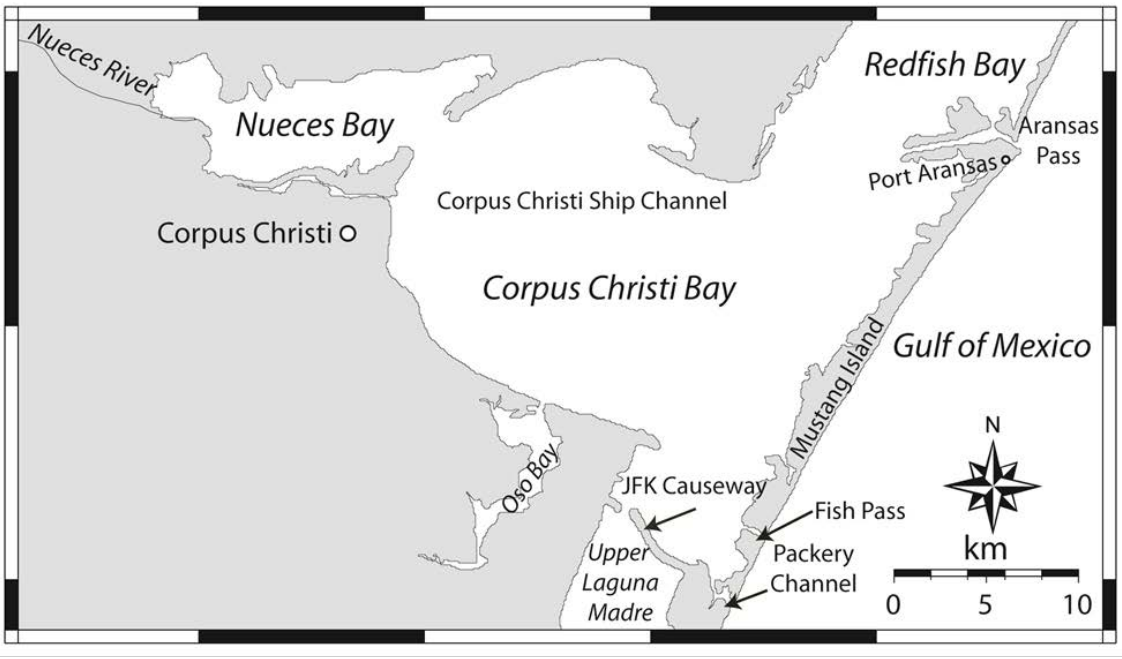

Figure 10. Map of the Nueces Estuary showing the location of Nueces Bay (top; Hicks 2010) and an aerial view (bottom) of Nueces Bay showing the locations of sites where various sample types were collected during the study. See Appendix 1 for GPS coordinates of sites and details of which sites were the sources of the various biological materials collected for the study.

from the Guadalupe River. The low average salinity has allowed formation of numerous oyster reefs which cover an estimated at 6.25 km^2 in San Antonio Bay (Finkbeiner et al. 2009). San Antonio Bay has been heavily impacted by shell dredging, but there is no urban or industrial development in the area and mercury contamination is expected to be low.

The Nueces Estuary (Fig. 10) encompasses about 620 km^2 including ~120 km^2 of marshlands and 53 km^2 of SAV (Hicks 2010). Average depth in the system is 3 m, although average depth in Corpus Christi Bay (4-5 m) is much deeper than the average depth in Nueces Bay (~2 m). Salinity in Nueces Bay is generally near 20 psu, but can range from 0 to 40 psu. Approximately 3.8 km^2 of oyster reef is found in Nueces Bay (Finkbeiner et al. 2009). There is both industrial and urban development surrounding Nueces Bay, particularly on the south shoreline where there is a busy port and ship channel, refineries and other facilities, as well as the city of Corpus Christi with a population of over 316,000. Some mercury contamination is expected but concentrations are not expected to be as high as in Lavaca Bay.

METHODS

Field Sampling

Regardless of the kinds of samples being collected, the longitude and latitude of the site was determined using GPS and physicochemical data (water temperature [°C]; salinity [psu]; and dissolved oxygen [mg/l]) were collected using a YSI 650 multi-parameter display system. Water depth was measured during prey collections using a stadia rod. There were days when one or both instruments malfunctioned, so data were not always collected.

Red drum, black drum, and spotted seatrout for this study were captured in gillnets by Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Division during their semi-annual resource monitoring sampling between April 2013 and November 2013; we made collections during both spring/summer and fall/winter sampling (Appendix 1.1). Time permitting, fishes were measured and weighed in the field by project staff who accompanied TPWD staff when gillnets were picked up and fish were processed. Only fish that were unable to be returned to the wild were kept for this study. All fish retained for this study were bagged and put on ice for transport back to the lab.

Prey species and sediment samples were collected twice in each bay: once during spring/summer and once during fall/winter (Appendix 1.2). At each sampling site, prey items (fishes, crustaceans, and most mollusks) were collected using a 6 m shrimp trawl and/or a 3 m beach seine. Benthic organisms (polychaetes, gastropods, bivalves) and sediments were sampled with PVC core sampler (10 cm diameter) at shallow stations along the shoreline. A Van Veen grab was used to collect sediment samples in deeper depths at the open bay locations. All samples were placed into labeled plastic bags and put on ice for transport back to the lab.

Phytoplankton and zooplankton were sampled twice in each bay during spring/summer when organisms were abundant enough that amounts sufficient for analysis could be collected (Appendix 1.3). Plankton were sampled by pumping water from ~50 cm below the surface of the water for 30–40 minutes. Water passed first through a zooplankton net (~400 µm) then through

the phytoplankton net (20 µm). All samples were placed into appropriately sized Nalgene containers and were transported back to the lab on ice.

Laboratory Methods

Initial Sample Processing

Game fish, prey organisms, sediment samples, and plankton samples were kept on ice or refrigerated and initial processing was completed within 48 hours after which samples were frozen for subsequent processing and/or analyses. Game fishes were weighed and measured (total lenth [TL]; mm) prior to dissection. Lateral muscle tissue was removed from the right and left sides of each fish for mercury and stable isotope analysis; digestive tracts were removed for gut content analysis. All crustaceans, prey/forage fishes, and most mollusks were identified to lowest possible taxon then weighed, measured, and sorted into size class categories prior to freezing: 0-50 mm, 51-100 mm, 101-150 mm, and 151-200 mm. Polychaetes, gastropods and smaller bivalves were removed from benthic core samples and placed into glass vials. Phytoplankton and zooplankton samples were centrifuged to concentrate the sample.

Sample Processing for Mercury and Stable Isotope Analyses

Samples of game fish tissue, prey/forage fish tissue, invertebrate (crustaceans, mollusks, polychaetes) tissue, phytoplankton, zooplankton, and sediment were further processed to prepare them for mercury (inorganic, MeHg) and stable isotope analyses. Processing was similar for both analyses. Samples of muscle, other tissue, or sediment were thawed and bones, skin, scales, and shells were removed as needed. All samples were freeze-dried, ground to a powder and homogenized using a mortar and pestle, then placed in clean, labelled glass vials (1 for mercury analyses, 1 for stable isotope analyses) and stored in a desiccator prior to analysis. Numbers and size classes of organisms prepared for mercury and stable isotope analyses are found in Appendices 2 and 3.

Gut Content Analysis

To attempt to confirm the food choices of the game fishes in this stomach, stomach and intestine content analyses were conducted. Guts were thawed, opened, and assigned a fullness index that ranges from 0 (empty) to 6 (completely full). Gut contents were removed from stomachs, identified (when possible) to the lowest possible taxon then preserved in 70% ethanol for storage.

Mercury Analysis

All mercury analyses were conducted at the National High Magnetic Field Laboratory and Department of Earth, Ocean and Atmospheric Sciences at Florida State University during July 2013. Prior to shipping, a 0.25 g of the powdered, homogenized tissue sample was placed into pre-cleaned, acid washed (2% nitric acid) borosilicate vials. Upon receipt at the lab in Florida, a smaller subsample of the tissue (0.1–0.2 g) was placed in a 20 ml acid-washed glass vial and 5 ml of ultra-pure 6M HNO_3 was added. Vials were sealed and put in an oven at 70 °C for 6 hours

to extract MeHg and inorganic Hg. Samples were then centrifuged and the supernatant was recovered. Inorganic and methylmercury concentrations were measured using Tekran®2700 Mercury Analysis System. Briefly, the extract was diluted 3 times with ultrapure deionized water and a volume of 0.010–0.100 ml of this solution was derivatized in a 30 ml aqueous solution at pH 4.5 after adding 0.030 ml of 1% tetraethylborate as a derivatizating agent and subsequent hand shaking. Depending on the sample, from 0.5 to 30 ng/L of MeHg and inorganic Hg was derivatized for measurements. Then the solution was purged into the Tekran®2700 system, where the ethylated inorganic Hg and MeHg were trapped on a Tenax trap then desorbed and flushed to a gas chromatography oven in a capillary column where they were separated, and finally pyrolyzed and detected via atomic fluorescence spectrometry.

Calibration curves were made with MeHg and inorganic Hg standard solutions of 10 and 500 ng/l, following the same protocol as samples. Certified reference materials for MeHg and total Hg (Tuna muscle ERM-CE 464 and Dogfish liver NRCC DOLT-4) were measured periodically between samples to ensure the accuracy of the analyses. Duplicates of extractions, duplicates of derivatization, as well as samples spiked with MeHg and inorganic Hg standards were also analyzed periodically to ensure the robustness of the method. The precision of the method, as residual standard deviation, was typically lower than 5%. Limit of quantification was typically lower than 0.05 ng/l and lower than 0.2 ng/l for MeHg and inorganic Hg, respectively. Mercury concentrations were reported as ng Hg/g sample on a dry weight basis.

Stable Isotope Analysis

All stable isotope analyses were conducted by the Texas A&M University Corpus Christi Isotope Core Laboratory. Samples (1 mg) of the freeze-dried biological material was weighed on a micro-analytical balance and then placed into three 5 mm × 5mm tin capsules for total carbon and nitrogen analysis. Samples (20 mg) of freeze-dried sediment were placed into 5 mm × 9 mm silver capsules, acid digested with 10% HCl then placed into a dryer for 48 hours prior to analysis.

Carbon elemental and isotopic compositions were determined using a Costech ECS4010 elemental analyzer (EA) connected to a continuous flow Thermo Delta V Plus isotope ratio mass spectrometer (IRMS) via a Thermo Conflo IV interface. Solid samples were loaded into a Costech Zero Blank Autosampler and introduced to the EA where they were combusted in an oxidation furnace set at 1000 °C using dynamic flash combustion in helium carrier gas and excess oxygen gas. The gaseous products were carried to a reduction furnace set at 650 °C. N_2 and CO_2 gas were separated in a 3 m GC column (45 °C) and introduced to the IRMS via the Conflo IV. A multi-point calibration (Costech acetanilide standard: C = 71.09%) was used to determine carbon content. Preliminary isotopic values were measured relative to reference gases analyzed with each sample. Replicate analyses of isotopic standard reference materials USGS 40 (δ13C = -26.39 ‰ VPDB) and USGS 41(δ13C = 37.63 ‰ VPDB) were used to normalize preliminary isotopic values to the AIR and VPDB scales (Paul et al., 2007).

RESULTS & DISCUSSION

Environmental conditions varied little among the bays when collections were made except that salinities in Nueces Bay were typically higher and were sometimes hypersaline (Appendix 1). A total of 303 game fish were collected from the three bays (Table 2). Black drum (*Pogonias cromis*) was the most the most numerous species collected in both Lavaca and San Antonio bays whereas spotted seatrout (*Cynoscion nebulosus*) was the most numerous in Nueces Bay. The average size of all three species of game fish was smallest in San Antonio Bay. The total numbers of nektonic/epibenthic prey were greatest in Lavaca Bay, as was taxon richness (Table 3). Eleven taxa were common to all three bays: eastern oyster (*Crassostrea virginica*); bay squid (*Lolliguncula* sp.); blue crab (*Callinectes sapidus*); brown shrimp (*Farfantepenaeus aztecus*); white shrimp (*Litopenaeus setiferus*); grass shrimp (*Palaemonetes* spp.); bay anchovy (*Anchoa mitchilli*); pinfish (*Lagodon rhomboides*); spot croaker (*Leistomus xanthurus*); and, Atlantic croaker (*Micropogonias undulatus*). These organisms, along with benthic and epibenthic invertebrates such as polychaetes and phytoplankton and zooplankton were the focus of mercury and stable isotope analysis (Appendices 2 and 3).

Gut Contents

Gut contents of game fish were examined to confirm dietary choices. A total of 90 spotted seatrout were examined of which 49 (54%) contained identifiable food items. The most frequently occurring food items were unidentified fish (20%) and penaeid shrimp (8%). Of the 69 red drum examined, 46 (67%) contained items that could be identified. The most commonly occurring food items were brachyuran crabs and crab parts (6.5%), grass shrimp (*Palaemonetes* spp.); 4%), and penaeid shrimp (4%). More than half (55%) of the 93 black drum stomachs examined contained material, but there was nothing that could be definitively identified and all contents were classified as unidentifiable organic matter.

Discussion

The gut contents described here generally conform to the known food habits of red drum and spotted seatrout (Patillo et al. 1997). Red drum are carnivorous throughout their life, with food items ranging from copepods to fish depending on the size of the fish, the size of the prey, and the availability of the various prey. In this study, the smallest red drum were larger than 200 mm TL and groups of organisms eaten by fish in this size class and larger varies little: shrimp, crabs, and fish with smaller red drum eating smaller individuals than larger red drum. Spotted seatrout are considered opportunistic visual foragers and rely almost entirely on nektonic organisms. Like red drum there are ontogenetic shifts in food consumption. In this study the smallest spotted seatrout were 300 mm; shrimp comprise the majority of the diet in warmer months and fish in cooler months for seatrout of this size and larger. Black drum are carnivorous throughout their lives. The most important prey targeted by black drum are (in order of importance): molluscs (mostly bivalves), decapod crustaceans (shrimp, crabs), annelids, and fish (Patillo et al. 1997).

Table 2. Summary of the total numbers of black drum (*Pogonias cromis*), red drum (*Sciaenops ocellatus*) and spotted seatrout (*Cynoscion nebulosus*) collected from Lavaca, San Antonio, and Nueces bays, with average length (mm) and length range (mm).

	Lavaca Bay	San Antonio Bay	Nueces Bay
Black Drum			
Number retained	50	51	22
Average length (mm)	310	248	362
Range (mm)	215–914	215–457	362–503
Red Drum			
Number retained	30	29	14
Average length (mm)	393	362	439
Range (mm)	346–439	337–402	249–463
Spotted Seatrout			
Number retained	33	33	41
Average length (mm)	499	370	483
Range (mm)	399–722	327–438	340–765

Mercury Concentrations

In this section we provide a general overview of mercury concentrations in organisms by bay, followed by a summary and comparison of mercury results across bays. Mercury in phytoplankton is represented by 1-2 samples/bay, zooplankton by 1 sample/bay, sediments by 4 samples/bay, benthos (including mollusks) by 1-3 samples/bay, and prey fish, shrimp and crabs, and bay squid by 1-3 samples/size class/bay; not all size classes were available for sampling in any given bay (Appendix 2). Game fish were generally represented by 4-6 samples/size class/bay.

Mercury Concentrations in Organisms by Bay

Lavaca Bay—At the base of the food web, MeHg was below detection limits (0.15 ng/g dw) in the phytoplankton (which also includes particulate organic matter [POM] and sediment particles) while MeHg in the zooplankton was much higher (Table 4). Mercury in the phytoplankton was dominated by inorganic Hg while mercury in the zooplankton was dominated by MeHg. Inorganic mercury also dominated mercury concentrations in the sediments (mean of 4 locations), polychaetes, gastropods, and oysters (*Crassostrea virginica*) which had very low concentrations of MeHg; MeHg and inorganic mercury concentrations in bivalves other than oysters were similar.

Methylmercury dominated mercury concentrations in all of the crustaceans, ranging from 83–95% of total mercury concentrations (Table 4). The bay squid (Teuthida) were similar in this regard, as were the prey/forage fishes with the exception of the filter feeding prey fishes, striped mullet (*Mugil cephalus*) and menhaden (*Brevoortia* sp.). On average, MeHg constituted just over half of total mercury concentrations in menhaden, and only around one-quarter of total mercury concentrations in striped mullet. In pinfish (*Lagodon rhomboides*) and bay squid proportion of

Table 3. Summary of the total numbers of nektonic/epibenthic prey organisms collected from Lavaca (LB), San Antonio (SAB), and Nueces (NB) bays. X = present but not enumerated.

Scientific Name	Common Name	LB	SAB	NB
Annelida				
Polychaeta	Unidentified polychaetes	X	X	X
Mollusca				
Lolliguncula sp.	Squid	56	1	10
Crassostrea virginica	Eastern oyster	X	X	X
Gastropoda	Unidentified gastropods	X	X	X
Bivalvia	Unidentified bivalves	X	X	X
Crustacea				
Callinectes sapidus	Blue crab	12	13	1
Callinectes similis	Lesser blue crab		1	
Micropanope scultipes	Sculptured mud crab			9
Libinia sp.	Spider crab	2		
Brachyura	Unidentified juvenile crab	2		
Farfantepenaeus aztecus	Brown shrimp	76	50	119
Litopenaeus setiferus	White shrimp	217	14	26
Palaemonetes spp.	Grass shrimp	6	36	35
Tozeuma carolinense	Arrow shrimp			1
Actinopterygii (fish)				
Anchoa mitchilli	Bay anchovy	69	12	70
Harengula jaguana	Scaled sardine			23
Brevoortia patronus	Gulf menhaden	1	1	133
Brevoortia gunteri	Finescale menhaden	1		
Mugil cephalus	Striped mullet	2		1
Menidia beryllina	Inland silverside	2	22	
Polydactylus octonemus	Atlantic threadfin	1		
Cyprinodon variegatus	Sheepshead minnow		190	
Sphoeroides parvis	Least puffer	1		
Chilomycterus schoepfii	Spiny boxfish	1		
Ariopsis felis	Hardhead catfish		8	
Siluriformes spp.	Catfish (juvenile)	4		
Synodus foetens	Inshore lizardfish	1		
Lagodon rhomboides	Pinfish	103	17	3
Sparidae spp.	Porgy (juvenile)	3		
Leistomus xanthurus	Spot croaker	194	6	3
Micropogonias undulatus	Atlantic croaker	15	4	12
Cynoscion arenarius	Sand seatrout (juvenile)	1		
Menticirrhus americanus	Southern kingcroaker (juvenile)	3		
Bairdiella chrysoura	American silver perch		4	
Paralichthys lethostigma	Southern flounder (juvenile)	6		
Caranx latus	Horse-eye jack (juvenile)	5		
Total		784	380	448
Number of taxa collected		25	15	14

Table 4. Mean and standard deviation (SD) of the dry weight (dw) concentration and percent (%) of methylmercury (MeHg), and inorganic mercury, and total mercury found in the game fishes, prey items, and sediments of Lavaca Bay.

Taxon/group	Size class	n	MeHg (ng/g dw [ppb])		Inorg. Hg (ng/g dw [ppb])		Total Hg (ng/g dw [ppb])		% MeHg		% Inorganic Hg	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Game fishes												
Pogonias cromis	200-299	5	553.00	173.077	16.60	5.727	569.40	178.144	97.00	0.000	3.00	0.000
Pogonias cromis	300-399	6	545.00	204.954	17.50	5.992	562.17	210.355	96.83	0.753	3.17	0.753
Pogonias cromis	400-999	4	1370.00	1273.444	41.00	42.024	1411.25	1315.924	97.25	0.500	2.75	0.500
Sciaenops ocellatus	300-399	6	886.67	213.771	27.00	7.071	914.17	219.991	96.83	0.408	3.17	0.408
Sciaenops ocellatus	400-999	4	1129.25	228.456	30.50	7.937	1159.25	234.159	97.50	0.577	2.50	0.577
Cynoscion nebulosus	300-399	5	1519.20	559.882	171.20	237.509	1690.20	429.287	88.20	17.527	11.80	17.527
Cynoscion nebulosus	400-999	5	1467.40	380.115	54.40	12.681	1521.40	391.267	96.40	0.548	3.60	0.548
Prey fishes and squid												
Anchoa mitchilli	0-50	2	51.82	5.233	2.04	0.759	53.86	4.473	96.13	1.731	3.87	1.731
Brevoortia spp.	101-150	2	18.07	3.369	16.85	7.357	34.92	10.726	52.74	6.554	47.26	6.554
Lagodon rhomboides	51-100	2	86.57	14.250	8.15	2.097	94.72	16.347	91.46	0.739	8.54	0.739
Lagodon rhomboides	101-150	2	172.20	22.948	26.10	5.895	198.30	28.843	86.92	1.070	13.08	1.070
Lagodon rhomboides	151-200	2	174.78	11.271	55.70	18.288	230.48	29.559	76.14	4.875	23.86	4.875
Leiostomus xanthurus	101-150	2	156.02	13.818	19.06	1.311	175.08	12.507	89.08	1.561	10.92	1.561
Micropogonias undulatus	51-100	2	88.74	2.568	18.41	2.125	107.15	4.693	82.85	1.232	17.15	1.232
Micropogonias undulatus	101-150	2	407.51	18.667	8.29	1.181	415.80	19.848	98.01	0.189	1.99	0.189
Mugil cephalus	151-200	2	11.30	10.302	33.43	26.671	44.73	36.973	23.91	3.269	76.09	3.269
Teuthida	0-50	2	52.60	2.934	6.50	1.019	59.09	3.953	89.04	0.991	10.96	0.991
Teuthida	51-100	2	48.67	0.509	14.34	0.521	63.01	0.012	77.25	0.823	22.75	0.823

Table 4. Continued.

Taxon/group	Size class	n	MeHg (ng/g dw [ppb])		Inorg. Hg (ng/g dw [ppb])		Total Hg (ng/g dw [ppb])		% MeHg		% Inorganic Hg	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Shrimps and crabs												
Farfantepenaeus aztecus	0-50	1	20.78		1.89		22.67		91.67		8.33	
Farfantepenaeus aztecus	51-100	2	64.36	9.830	5.61	1.021	69.97	10.850	92.00	0.218	8.00	0.218
Farfantepenaeus aztecus	101-150	2	65.72	2.139	7.21	3.398	72.93	5.536	90.26	3.919	9.74	3.919
Litopenaeus setiferus	0-50	2	71.71	9.030	5.04	1.264	76.75	10.294	93.48	0.772	6.52	0.772
Litopenaeus setiferus	51-100	2	44.78	1.774	2.98	0.773	47.76	1.000	93.74	1.750	6.26	1.750
Litopenaeus setiferus	101-150	2	63.01	6.743	6.49	3.103	69.49	9.846	90.89	3.175	9.11	3.175
Litopenaeus setiferus	151-200	2	58.58	1.381	3.07	0.873	61.65	2.254	95.04	1.235	4.96	1.235
Palaemonetes spp.	0-50	1	50.02		7.04		57.05		87.67		12.33	
Callinectes sapidus	0-50	2	66.17	5.622	13.28	2.818	79.45	8.440	83.38	1.782	16.62	1.782
Callinectes sapidus	51-100	1	144.97		27.71		172.68		83.85		16.15	
Benthos												
Polychaetes		1	0.61		53.09		53.71		1.12		98.88	
Gastropods		1	12.19		29.97		42.16		30.16		69.84	
Crassostrea virginica	0-50	1			23.06		23.08				100.00	
Crassostrea virginica	51-100	2	0.30	0.140	13.48	11.115	13.78	11.255	2.67	1.162	97.33	1.162
Crassostrea virginica	101-150	2			14.47	11.670	14.46	11.581	0.87		99.56	0.619
Other bivalves		2	8.12	5.842	11.39	10.186	19.51	4.344	46.11	40.215	53.89	40.215
Phytoplankton		2			144.55	98.262	144.65	98.204			100.00	0.000
Zooplankton		1	0.42		0.31		0.73		57.46		42.54	
Sediment		4	0.35	0.044	44.49	37.378	44.84	37.420	1.43	1.347	98.57	1.347

MeHg declined as size increased; for Atlantic croaker (*Micropogonias undulatus*) the opposite was true.

The proportion of MeHg in the game fishes exceeded 88% of total mercury for all size classes and species (Table 4). Many of the concentrations, particularly for red drum (*Sciaenops ocellatus*) and spotted seatrout (*Cynoscion nebulosus*) were above the 700 ng/g dw (700 ppb or 0.7 mg/kg) Texas Department of State Health Services (TDSHS) "action level" which indicates that fish with these concentrations of mercury in their tissues may "pose a threat to human health" (Mike Ordner, TDSHS Seafood and Aquatic Life Group, personal communication). Although concentrations of mercury (total and MeHg) generally increased as the sizes of black drum and red drum increased (Figure 11), the proportion of MeHg varied little (Table 4). The proportion of MeHg in spotted seatrout also varied little but the pattern of increase in tissues with increasing total length was not as clear.

San Antonio Bay—Overall, there were fewer organisms (both in abundance and taxonomically) available for testing from San Antonio Bay than from either of the other bays, with many groups/size classes represented by a single or only 2 data points.

Virtually all the mercury in phytoplankton (including POM and sediment particles) was inorganic whereas 100% of mercury in zooplankton was MeHg (note that there was only 1 sample available for testing of these two groups; Table 5). Inorganic mercury was also essentially the only species detected in polychaetes, gastropods, oysters, and sediments; only bivalves other than oysters had significant concentrations of MeHg, which comprised 35% of total mercury on average.

MeHg dominated mercury concentrations in all crustaceans ranging from an average of 71% in grass shrimp to 95% in 101-150 mm blue crabs (*Callinectes sapidus*) (Table 5). For the penaeid shrimp (*Farfantepenaeus aztecus*, *Litopenaeus setiferus*) average absolute concentrations of total mercury generally increased as size increased but proportions of MeHg tended to decline. For blue crabs, absolute concentrations also increased with size, with proportions of MeHg also increasing with size. Concentrations of mercury in bay squid and prey fishes were also dominated by MeHg. The proportion of total mercury in MeHg was lowest in menhaden. In those species for which more than one size class was tested, total mercury increased with size, but the increase was small, ranging from an increase of <4 ng/g dw in bay anchovy (*Anchoa mitchilli*) to ~5 ng/g dw in pinfish. Proportions of MeHg in these species varied little but exhibited opposite patterns, declining with size in bay anchovy and increasing slightly with size in pinfish.

Concentrations of mercury were much higher in game fishes than in all other organisms, with nearly all mercury measured as MeHg (Table 5). Concentrations of mercury did not exceed the 700 ppb limit set by TDSHS in any of the game fishes tested. Overall, mean mercury concentrations in black drum (*Pogonias cromis*) were lower than either spotted seatrout or red drum. Mercury concentrations generally increased with size in red drum and spotted seatrout but were often lower in black drum of similar size (Figure 12).

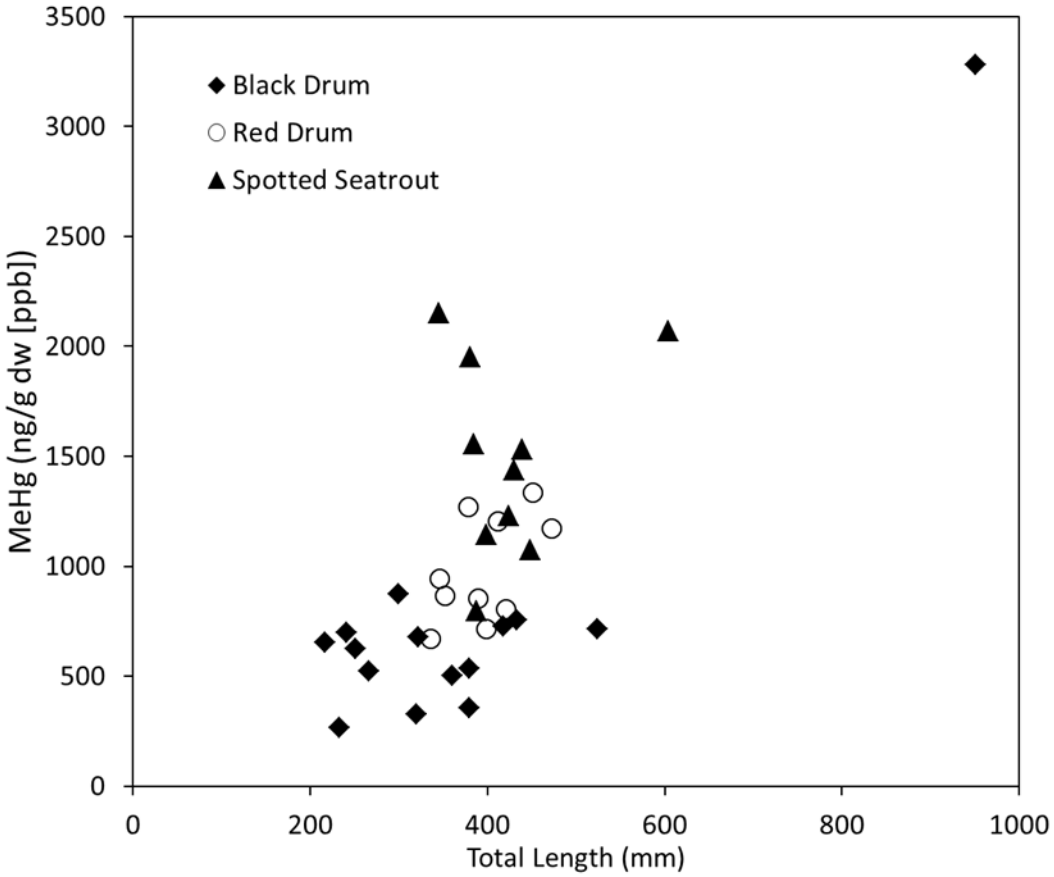

Figure 11. Relationship between total length (mm) and methylmercury concentration (MeHg, ppb) in black drum, red drum, and spotted seatrout from Lavaca Bay, Texas.

Nueces Bay—Inorganic mercury dominated total mercury concentrations in phytoplankton, zooplankton, and the benthos (Table 6). MeHg dominated mercury concentrations in the crustaceans and while total mercury concentrations increased with size in the brown shrimp (*Farfantepenaeus aztecus*), concentrations declined with size in both white shrimp (*Litopenaeus setiferus*) and blue crabs. The proportion of MeHg in blue crabs was lower than in the other members of this group but increased with size. The proportion of MeHg in prey fishes ranged from 76-96% and mean total mercury concentrations increased with size class. This was particularly noticeable in the 101-150 mm and 151-200 size classes of Atlantic croaker (*Micropogonias undulatus*) which showed a more than three-fold increase in average total mercury between the two size classes. Total mercury concentrations were relatively low in bay squid and the proportion of MeHg was not as high as in the prey fishes.

Mean total mercury concentrations exceeded the 700 ppb threshold set by TDSHS in the largest size class of black drum and in all size classes of red drum and spotted seatrout that were available for testing (no red drum or spotted seatrout 200-299 mm TL were collected or tested; Table 6). MeHg comprised more than 91% of total mercury in game fishes. Mercury

Table 5. Mean and standard deviation (SD) of the dry weight (dw) concentration and percent (%) of methylmercury (MeHg), and inorganic mercury, and total mercury found in the game fishes, prey items and sediments of San Antonio Bay.

Taxon/group	Size class	n	MeHg (ng/g dw [ppb]0		Inorganic Hg (ng/g dw [ppb])		Total Hg (ng/g dw [ppb])		% MeHg		% Inorganic Hg	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Game fishes												
Pogonias cromis	200-299	5	169.40	89.159	7.60	3.782	176.60	93.224	96.00	0.000	4.00	0.000
Pogonias cromis	300-399	4	116.25	29.748	5.00	1.414	121.25	30.729	96.00	0.816	4.00	0.816
Pogonias cromis	400-999	1	142.00		6.00		148.00		96.00		4.00	
Sciaenops ocellatus	300-399	5	328.20	101.478	11.80	2.490	339.80	103.541	96.40	0.894	3.60	0.894
Sciaenops ocellatus	400-999	5	544.80	90.140	14.00	3.391	558.80	93.339	97.60	0.548	2.40	0.548
Cynoscion nebulosus	300-399	5	216.20	68.478	10.20	2.775	226.80	70.553	95.20	0.837	4.80	0.837
Cynoscion nebulosus	400-999	5	437.60	275.612	49.80	57.547	487.40	243.672	84.00	24.668	16.00	24.668
Prey fishes and squid												
Anchoa mitchilli	0-50	1	18.38		1.28		19.66		93.49		6.51	
Anchoa mitchilli	51-100	2	20.80	8.402	2.42	1.290	23.22	7.112	88.17	9.178	11.83	9.178
Brevoortia patronus	51-100	2	14.51	0.157	1.83	0.761	16.35	0.604	88.87	4.245	11.13	4.245
Cyprinodon variegatus	0-50	2	5.19	2.458	3.41	0.852	8.60	1.605	58.73	17.619	41.27	17.619
Lagodon rhomboides	51-100	2	29.39	4.959	2.55	1.132	31.95	6.091	92.20	2.057	7.80	2.057
Lagodon rhomboides	101-150	2	34.98	2.288	2.36	0.117	37.34	2.171	93.65	0.682	6.35	0.682
Leiostomus xanthurus	101-150	2	28.50	2.494	2.29	0.916	30.78	1.577	92.48	3.362	7.52	3.362
Micropogonias undulatus	101-150	2	41.53	0.241	0.96	0.175	42.49	0.066	97.73	0.415	2.27	0.415
Teuthida	0-50	1	10.72		3.19		13.91		77.08		22.92	

Table 5. Continued.

Taxon/group	Size class	n	MeHg (ng/g dw [ppb])		Inorganic Hg (ng/g dw [ppb])		Total Hg (ng/g dw [ppb])		% MeHg		% Inorganic Hg	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Shrimps and crabs												
Farfantepenaeus aztecus	51-100	2	19.69	0.035	1.71	0.513	21.40	0.478	92.05	2.221	7.95	2.221
Farfantepenaeus aztecus	101-150	2	16.49	0.554	6.24	1.848	22.73	2.402	72.81	5.255	27.19	5.255
Litopenaeus setiferus	0-50	1	13.22		0.82		14.05		94.14		5.86	
Litopenaeus setiferus	51-100	2	13.38	0.698	2.53	0.221	15.91	0.477	84.08	1.864	15.92	1.864
Litopenaeus setiferus	101-150	2	18.47	0.992	3.21	0.515	21.69	1.508	85.24	1.350	14.76	1.350
Palaemonetes sp.	0-50	2	11.99	1.671	4.87	0.583	16.86	2.254	71.04	0.379	28.96	0.379
Callinectes sapidus	0-50	2	8.00	1.082	2.39	0.767	10.40	0.315	76.85	8.079	23.15	8.079
Callinectes sapidus	101-150	2	57.14	7.722	2.93	0.933	60.07	6.788	95.00	2.118	5.00	2.118
Benthos												
Polychaetes	NA	1			11.12		11.17				100.00	
Gastropods	NA	1	0.77		17.59		18.36		4.19		95.81	
Crassostrea virginica	0-50	1			7.60		7.69				100.00	
Crassostrea virginica	51-100	2			7.54	1.951	7.57	1.940	0.00	0.000	100.00	0.000
Crassostrea virginica	101-150	2			7.48	1.952	7.42	1.934	0.00	0.000	100.00	0.000
Other bivalves	NA	2	1.86	0.628	5.16	4.718	7.02	4.090	35.07	29.370	64.93	29.370
Phytoplankton	NA	1	1.35		248.62		249.97		0.54		99.46	
Zooplankton	NA	1	0.74				0.74		100.00			
Sediment	NA	4	0.22		4.77	3.838	4.88	3.912	0.68	1.354	99.32	1.354

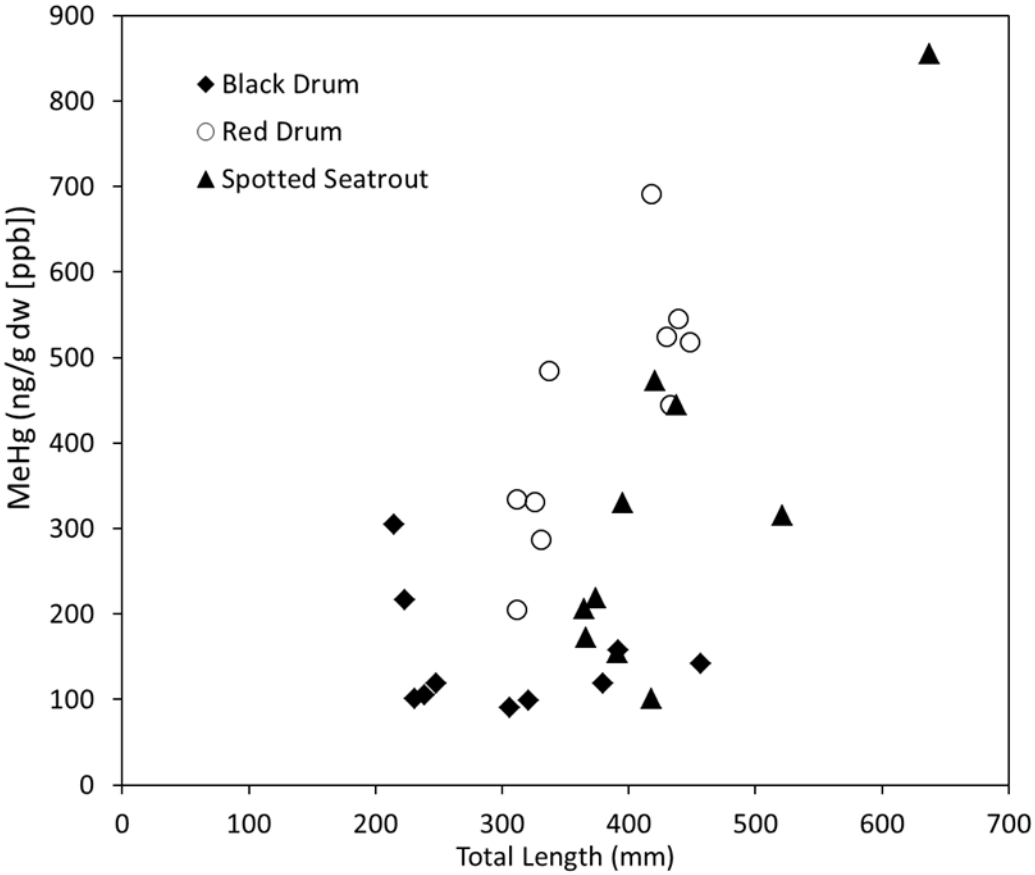

Figure 12. Relationship between total length (mm) and methylmercury concentration (MeHg, ppb) in black drum, red drum, and spotted seatrout from San Antonio Bay, Texas.

concentrations increased with size in black drum but decreased somewhat with size in red drum; mean concentrations varied greatly with the largest seatrout having one of the lowest concentrations of MeHg (Figure 13).

Summary and Comparison of Mercury Concentrations among Bays

Sediments—Inorganic mercury (Hg[II]) was the most abundant chemical species of mercury in all three bays (Figure 14) although very little of either species was present in sediments in San Antonio Bay. The average Hg(II) in Nueces Bay was somewhat higher than and Lavaca Bay although the concentrations in sediments in these bays was quite variable. Proportionally, methylmercury represented 1% or less of total mercury in sediments.

Phytoplankton—Inorganic mercury was also the most abundant chemical species of mercury in the phytoplankton collected from all three bays (Figure 15). MeHg represented less than 0.5% of total mercury in phytoplankton. Concentration of mercury was evident in the phytoplankton of

Table 6. Mean and standard deviation (SD) of the dry weight (dw) concentration and percent (%) of methylmercury (MeHg), and inorganic mercury, and total mercury found in the game fishes, prey items and sediments of Nueces Bay.

Taxon/group	Size class	n	MeHg (ng/g dw [ppb])		Inorganic Hg (ng/g dw [ppb])		Total Hg (ng/g dw [ppb])		% MeHg		% Inorganic Hg	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Game fishes												
Pogonias cromis	200-299	5	263.20	176.967	9.20	7.563	272.40	184.082	96.88	1.039	3.12	1.039
Pogonias cromis	300-399	5	510.20	320.487	14.60	8.849	524.80	329.116	97.13	0.668	2.87	0.668
Pogonias cromis	400-999	5	865.60	403.515	28.80	19.176	894.80	422.168	96.99	0.676	3.01	0.676
Sciaenops ocellatus	300-399	5	891.60	408.588	23.00	10.392	914.60	418.973	97.49	0.052	2.51	0.052
Sciaenops ocellatus	400-999	5	874.60	286.371	23.60	4.980	898.20	291.249	97.27	0.436	2.73	0.436
Cynoscion nebulosus	300-399	5	1489.00	432.254	69.00	71.323	1557.80	429.065	95.44	4.697	4.56	4.697
Cynoscion nebulosus	400-999	5	936.80	819.444	61.80	71.810	998.60	813.420	91.21	13.150	8.79	13.150
Prey fishes and squid												
Anchoa mitchilli	0-50	2	35.36	1.155	5.65	0.607	41.01	0.548	86.21	1.665	13.79	1.665
Anchoa mitchilli	51-100	1	82.48		3.70		86.17		95.71		4.29	
Lagodon rhomboides	51-100	2	21.52	16.715	4.70	4.353	26.22	21.068	83.39	3.252	16.61	3.252
Lagodon rhomboides	101-150	2	33.16	34.150	2.82	1.020	35.98	35.171	87.64	9.242	12.36	9.242
Leiostomus xanthurus	51-100	3	57.01	1.517	6.88	1.450	63.88	2.839	89.28	1.821	10.72	1.821
Leiostomus xanthurus	101-150	3	76.62	4.369	8.64	2.433	85.26	6.107	89.94	2.228	10.06	2.228
Leiostomus xanthurus	151-200	2	81.43	10.273	24.97	3.015	106.40	7.259	76.38	4.444	23.62	4.444
Micropogonias undulatus	101-150	2	92.01	1.497	4.71	1.332	96.72	0.165	95.13	1.386	4.87	1.386
Micropogonias undulatus	151-200	2	298.38	60.670	27.81	0.535	326.19	61.205	91.34	1.462	8.66	1.462
Teuthida	0-50	3	10.68	7.477	8.76	6.164	19.44	4.578	52.90	31.774	47.10	31.774
Teuthida	51-100	2	7.52	2.946	14.18	1.117	21.70	1.829	36.85	14.438	63.15	14.438

Table 6. Continued.

Taxon/group	Size class	n	MeHg (ng/g dw [ppb])		Inorganic Hg (ng/g dw [ppb])		Total Hg (ng/g dw [ppb])		% MeHg		% Inorganic Hg	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Shrimps and crabs												
Farfantepenaeus aztecus	0-50	3	18.78	3.069	4.80	6.496	23.58	3.918	82.00	22.610	18.00	22.610
Farfantepenaeus aztecus	51-100	2	32.75	0.238	4.87	0.100	37.62	0.137	87.05	0.314	12.95	0.314
Litopenaeus setiferus	0-50	1	16.67		1.12		17.79		93.73		6.27	
Litopenaeus setiferus	51-100	3	13.58	6.256	2.99	3.572	16.57	9.751	85.77	9.987	14.23	9.987
Palaemonetes sp.	0-50	2	9.78	1.094	2.36	0.366	12.14	1.460	80.62	0.686	19.38	0.686
Callinectes sapidus	0-50	2	60.52	70.054	11.11	2.355	71.63	72.409	71.68	25.341	28.32	25.341
Callinectes sapidus	51-100	3	24.49	8.799	19.67	6.861	44.15	15.519	55.43	2.000	44.57	2.000
Callinectes sapidus	101-150	2	18.76	5.787	9.17	9.530	27.93	3.743	69.17	29.988	30.83	29.988
Benthos												
Polychaetes		2			32.57	8.932	32.64	8.800	0.30	0.423	99.70	0.423
Gastropods	NA	1	3.44		18.11		21.55		15.96		84.04	
Crassostrea virginica	0-50	3	0.39	0.232	19.56	0.524	19.83	0.579	1.97	1.094	98.69	1.375
Crassostrea virginica	51-100	3			27.95		27.97				99.98	
Other bivalves		1	1.21		13.17		14.38		8.43		91.57	
Phytoplankton		1	2.00		429.32		431.32		0.46		99.54	
Zooplankton		2	0.50	0.037	2.10	1.637	2.61	1.674	23.80	13.878	76.20	13.878
Sediment		4	0.36	0.124	58.88	37.129	59.17	37.190	0.43	0.383	99.57	0.383

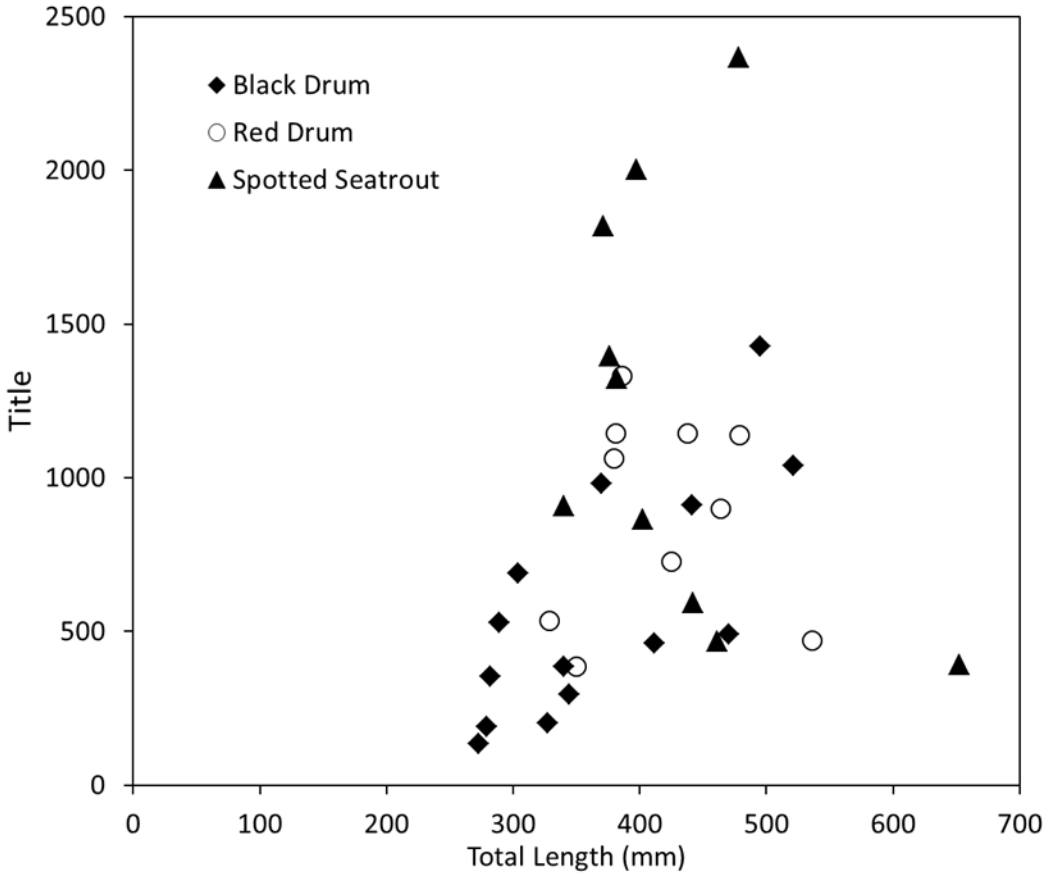

Figure 13. Relationship between total length (mm) and methylmercury concentration (MeHg, ppb) in black drum, red drum, and spotted seatrout from Nueces Bay, Texas.

all three bays, with Hg(II) concentrations ranging from ~3 times the sediment concentration in Lavaca Bay to nearly 50 times the sediment concentration in San Antonio Bay. MeHg was also concentrated in phytoplankton in Nueces Bay and San Antonio Bay ranging from ~28 times the sediment value in San Antonio Bay to ~8 times the sediment value in Nueces Bay; MeHg concentrations were below detectable limits in Lavaca Bay.

Zooplankton—Inorganic mercury was below detectable limits in zooplankton collected from San Antonio Bay and MeHg concentrations were greater than in zooplankton collected from the other bays (Figure 16). Inorganic mercury concentrations were greatest in Nueces Bay where it made up 81% of total mercury. In zooplankton, neither Hg(II) nor MeHg were concentrated compared to either the environment or to the phytoplankton; concentrations of both chemical species were less than those measured in both sediments and phytoplankton in all three bays.

Polychaetes—Inorganic mercury was the majority of mercury detected in polychaetes (Figure 17). MeHg was 1.1% of total mercury in polychaetes collected from Lavaca Bay and was below

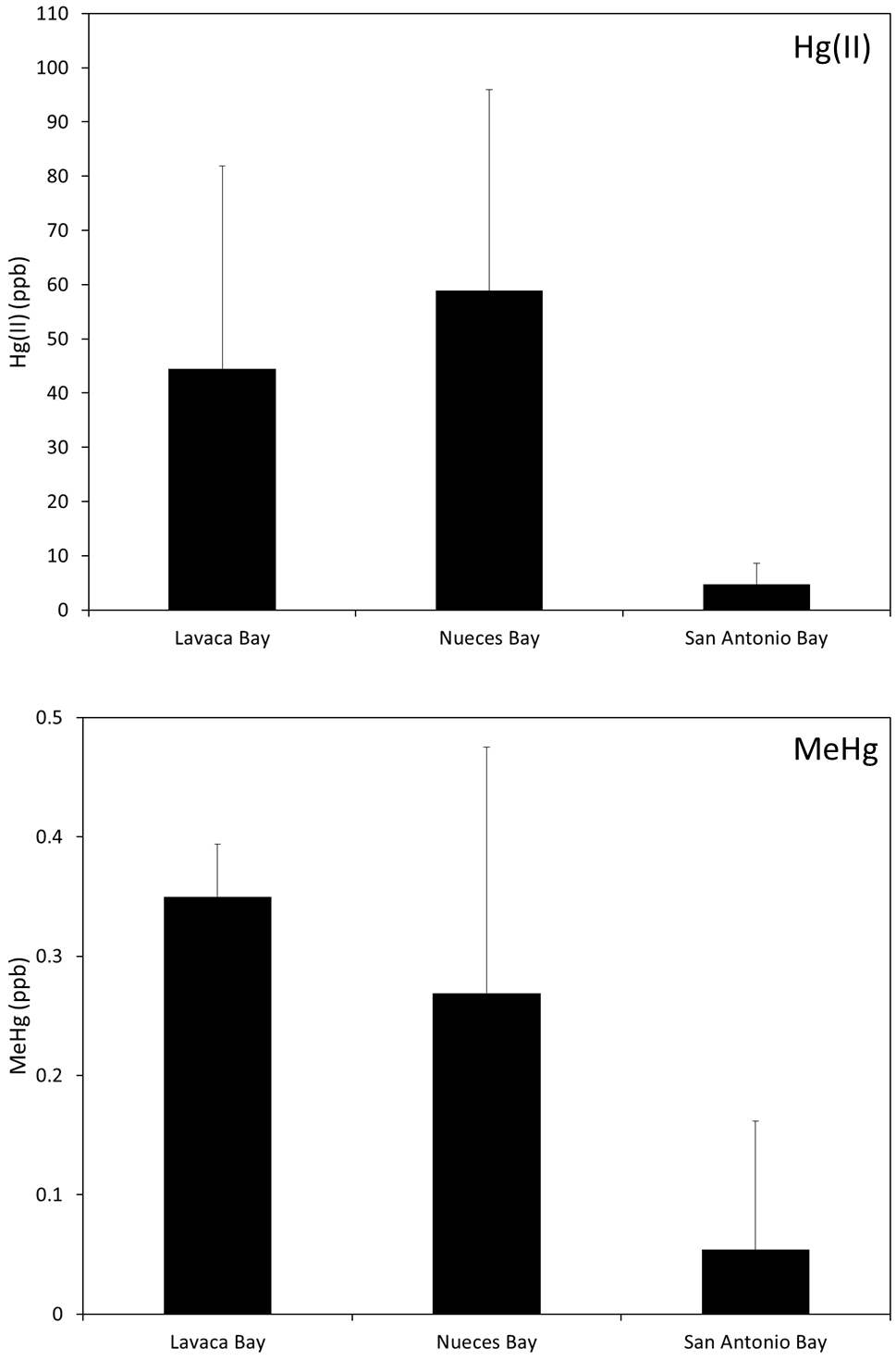

Figure 14. Mean inorganic mercury (Hg[II], ppb, top) and methylmercury (MeHg, ppb, bottom) in sediments. Note the differences in scaling on the y-axis of each graph.

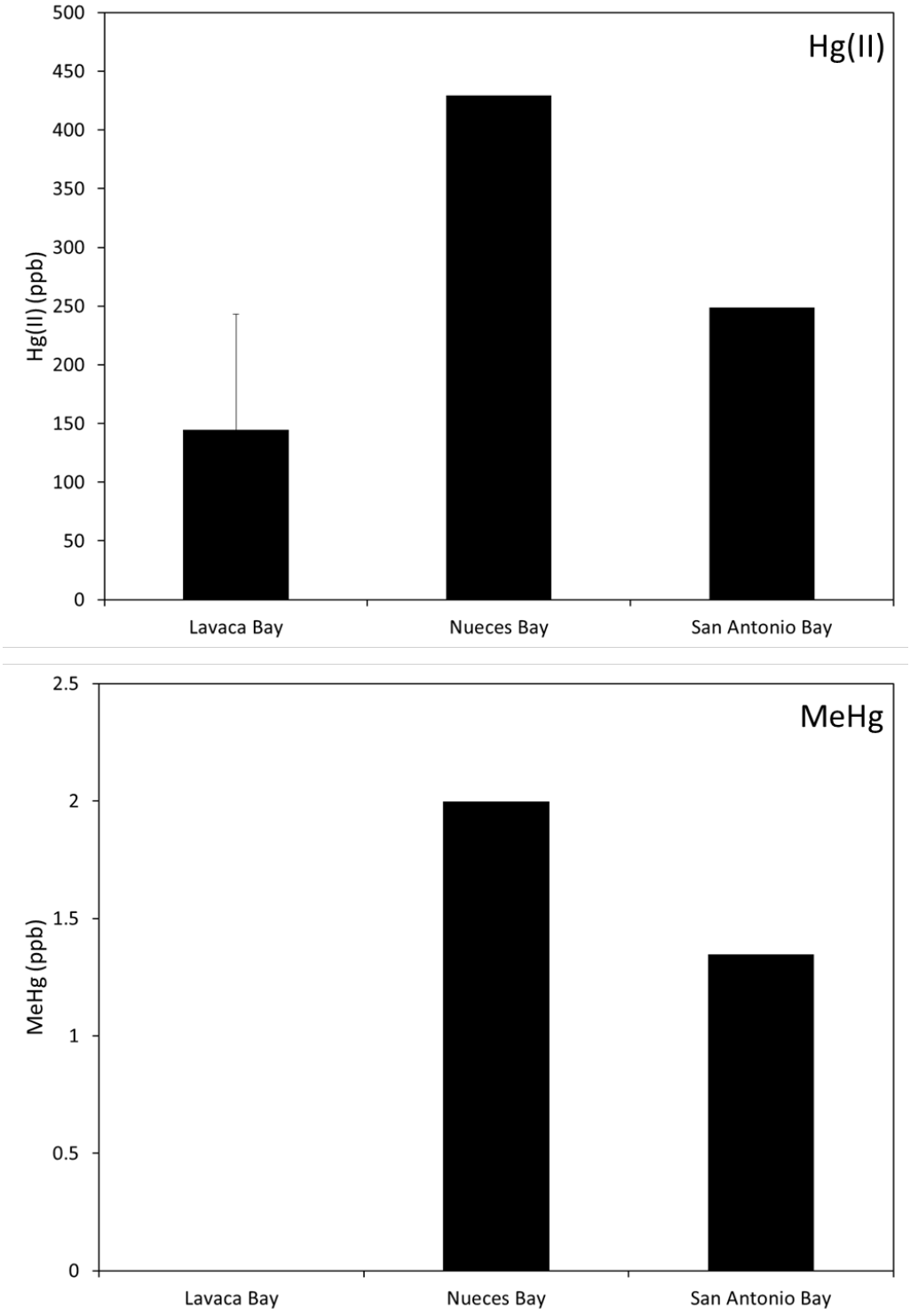

Figure 15. Mean inorganic mercury (Hg[II], ppb, top) and methylmercury (MeHg, ppb, bottom) in phytoplankton. Note the differences in scaling on the y-axis of each graph.

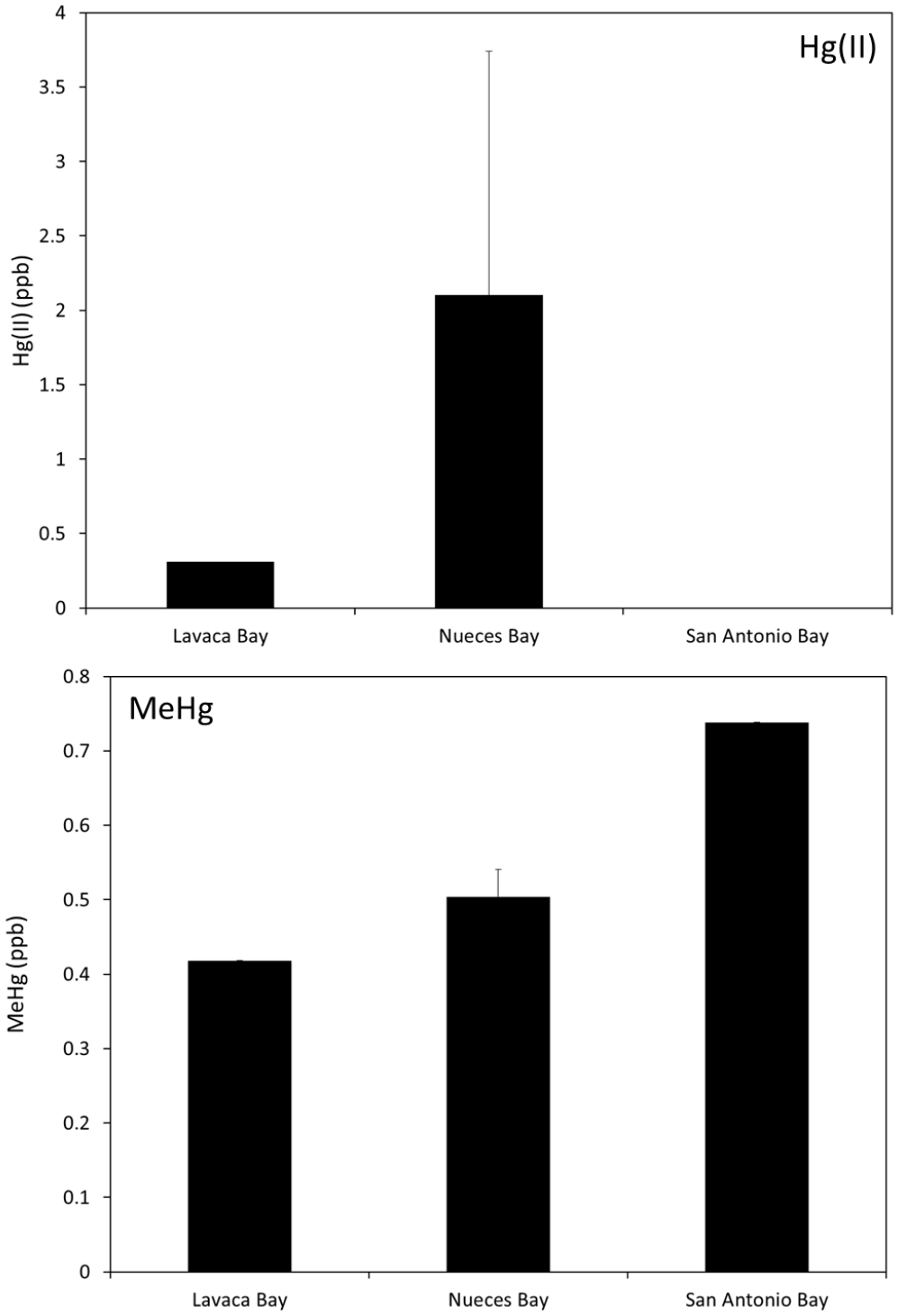

Figure 16. Mean inorganic mercury (Hg[II], ppb, top) and methylmercury (MeHg, ppb, bottom) in zooplankton. Note the differences in scaling on the y-axis of each graph.

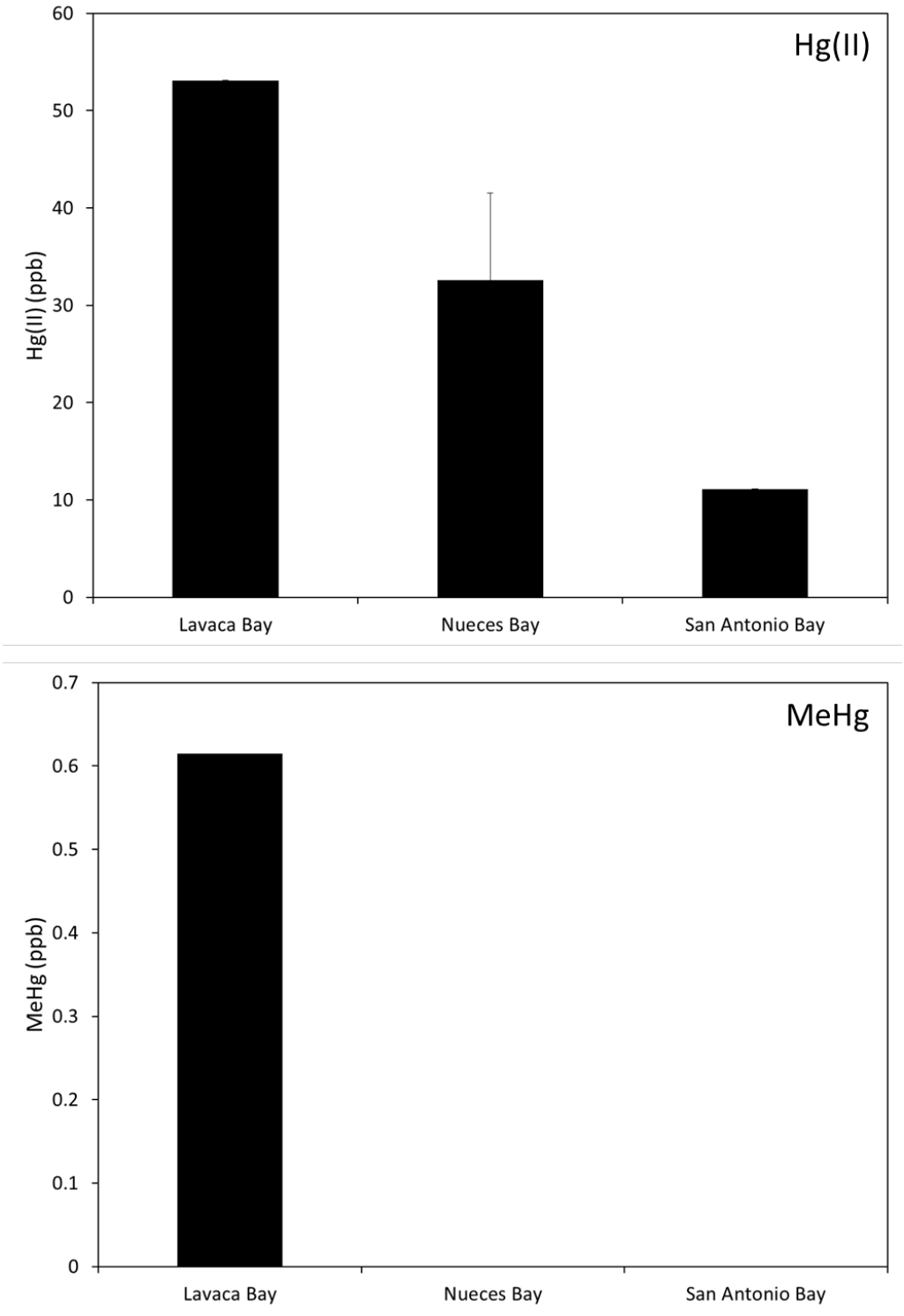

Figure 17. Mean inorganic mercury (Hg[II], ppb, top) and methylmercury (MeHg, ppb, bottom) in polychaetes. Note the differences in scaling on the y-axis of each graph.

detectable concentrations in polychaetes from the other two bays. The concentration of inorganic mercury in polychaetes was slightly higher than the mean concentration in sediments in Lavaca Bay(53 ppb vs 44 ppb), but was lower than sediments in both Nueces Bay (32 ppb vs 58 ppb) and San Antonio Bay (5 ppb vs 11 ppb).

Mollusks—The concentration of MeHg in mollusk tissues varied greatly within the group with the lowest concentrations measured in eastern oysters (*Crassostrea virginica*) in any bay and the highest concentrations in squid (Order Teuthida) in Lavaca Bay (Figure 18). MeHg constituted less than 1% of total mercury in oysters, up to 42% in other bivalves, up to 28% in gastropods, and 47-80% in squid. The general trend of greater concentrations of MeHg in organisms in Lavaca Bay and less in San Antonio Bay continues with this group. The differences in concentrations reflect accumulation due to the diets of the organisms, particularly the scraping foraging behavior of the gastropods and their focus on epiphytes and/or epibenthic algae, and predation by squid.

Crustaceans—Mean tissue concentrations of MeHg were similar across crustacean groups, although blue crab concentrations were higher than other crustaceans in Lavaca Bay (Figure 19). In particular, the concentrations in shrimp tissue in Lavaca Bay were very similar regardless of taxon. Mean concentrations of MeHg were up to twice as high in brown shrimp (*Farfantepenaeus aztecus*) in Nueces and San Antonio bays when compared to grass shrimp (*Palaemonetes* spp.) or white shrimp (*Litopenaeus setiferus*) in the same bays. MeHg made up the vast majority of total Hg in shrimp, ranging from 67-90% of total Hg. MeHg was 50-67% of total Hg in blue crabs. Blue crabs are largely scavengers, while shrimp have a somewhat more varied diet that includes both scavenging and grazing, primarily on epiphytic algae. MeHg concentrations in these groups also reflect dietary accumulation as well as the general pattern of greatest concentrations in Lavaca Bay and lowest concentrations in San Antonio Bay.

Prey/Forage Fish—Concentrations of MeHg in bay anchovy (*Anchoa mitchelli*) tissues are similar in Lavaca and Nueces bays, and lower than concentrations in the tissues of other forage fishes in Lavaca Bay (Figure 20). MeHg constitutes 88-99% of total mercury in these fish. Bay anchovies are primarily planktivores, so dietary accumulation is not as marked in this species as in the others, which are largely predatory. MeHg concentrations in Atlantic croaker (*Micropogonias undulatus*), spot (*Leistomus xanthurus*), and pinfish (*Lagodon rhomboides*) collected from Lavaca Bay are 2 to 10 times greater than concentrations in the same fish species collected from the other bays.

Black Drum— Black drum (*Pogonias cromis*) was the only predatory fish for which sufficient individuals in the 200-299 mm size class were collected for mercury analysis. MeHg concentrations in black drum tissue increased with size class in Lavaca and Nueces bays, but were variable in San Antonio Bay, with the greatest concentrations in tissues of fish in the 200-299 mm size class and lower concentrations in the 300-399 mm size class (Figure 21). There was a great deal of variability in MeHg concentrations in the largest black drum in Lavaca bay, with concentrations ranging from 737 ppb to 3280 ppb. Predictably, tissue concentrations in black drum were greatest in Lavaca Bay and least in San Antonio Bay. Inorganic mercury averaged 3-4% of total in all size classes from each bay.

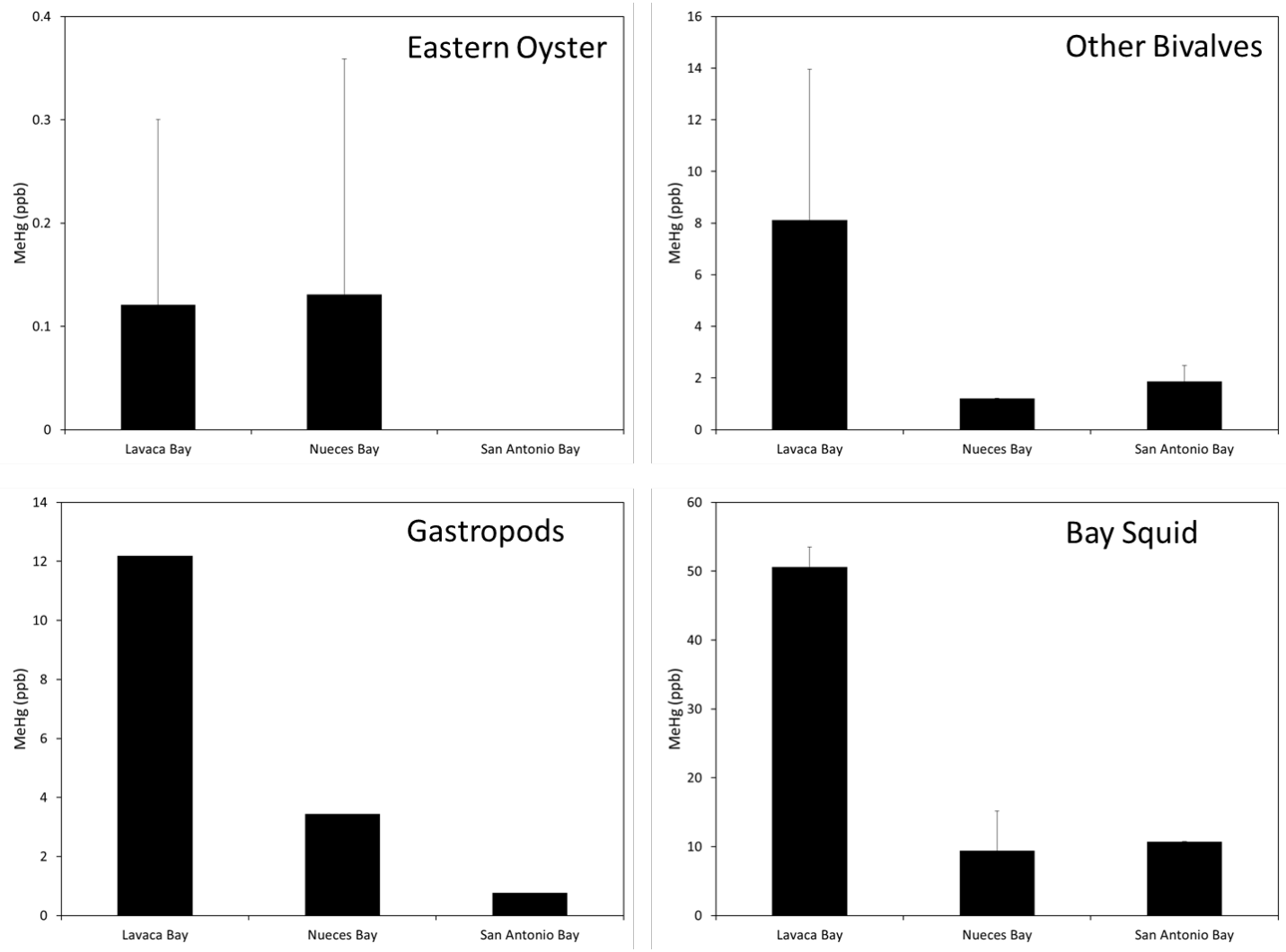

Figure 18. Mean MeHg (ppb) with standard deviation in eastern oyster (*Crassostrea virginica*); other bivalves, gastropods, and bay squid (Teuthida). Note the differences in scaling on the y-axis of each graph.

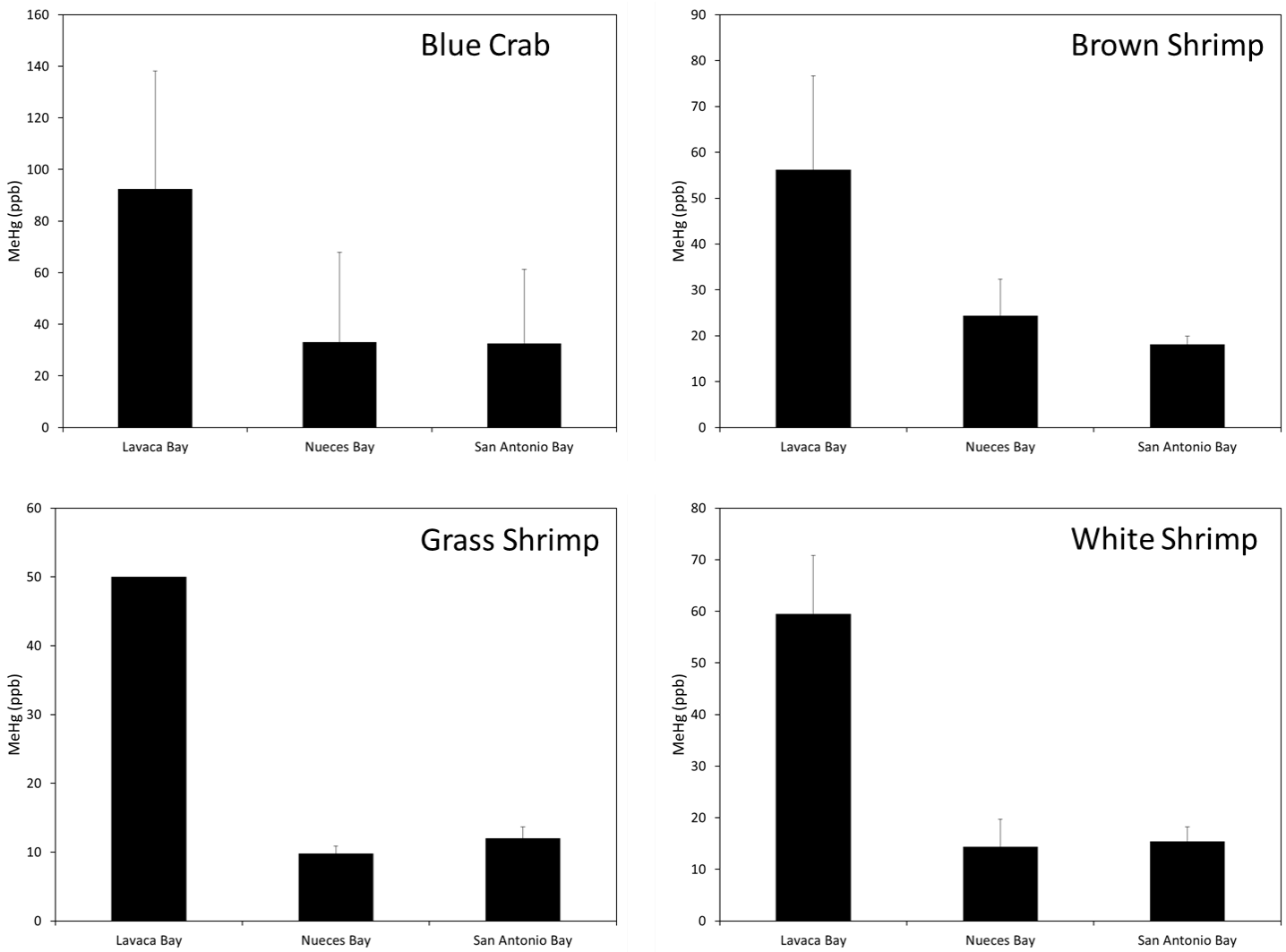

Figure 18. Mean MeHg (ppb) with standard deviation in blue crab (*Callinectes sapidus*), brown shrimp (*Farfantepenaeus aztecus*), grass shrimp (*Palaemonetes* spp.), white shrimp (*Litopenaeus setiferus*). Note the differences in scaling on the y-axis of each graph.

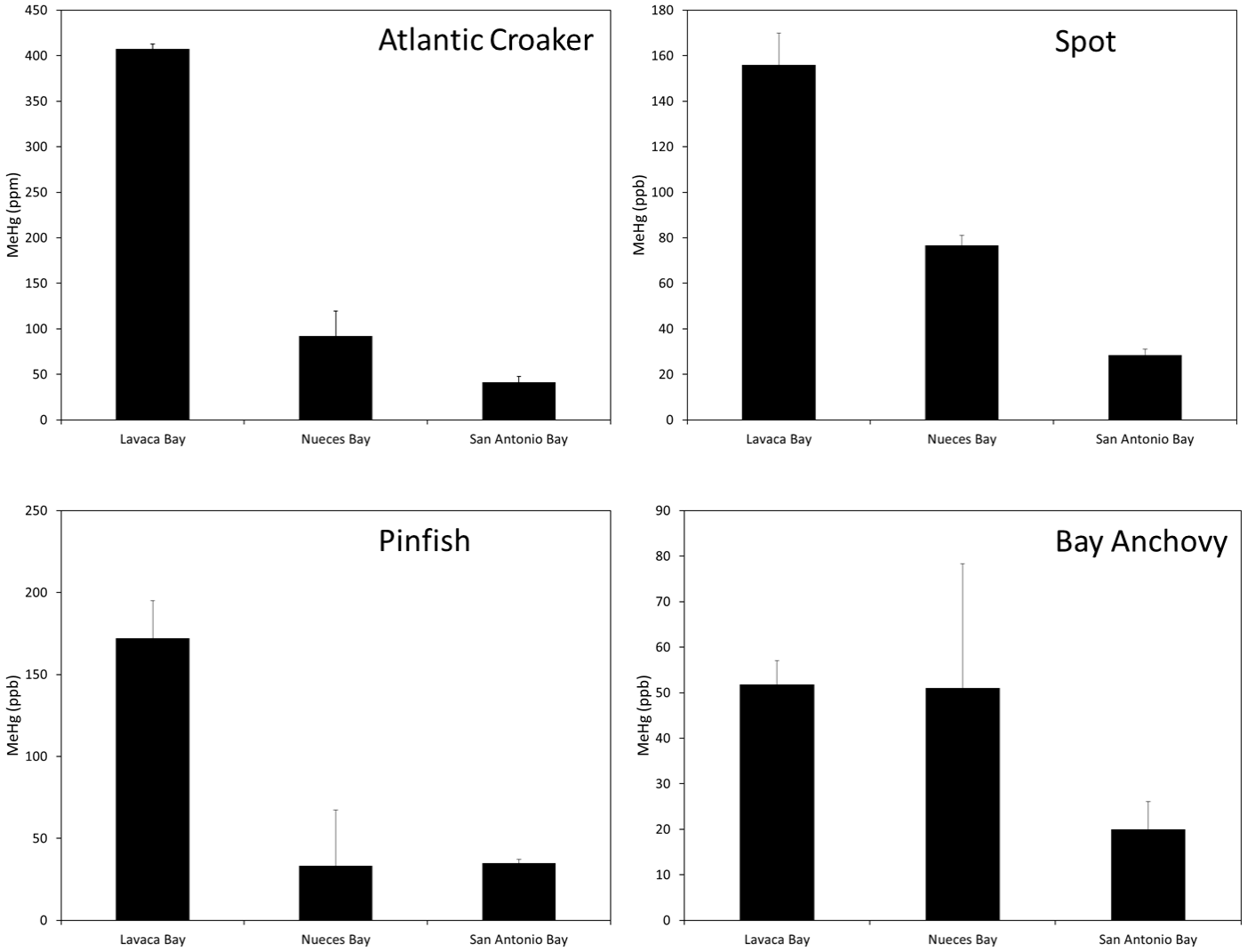

Figure 20. Mean MeHg (ppb) with standard deviation in Atlantic croaker (*Micropogonias undulatus*, 101-150 mm); spot croaker (*Leistomus xanthurus*, 101-150 mm); pinfish (*Lagodon rhomboides* 101-150 mm); and bay anchovy (*Anchoa mitchelli*, <100 mm). Note the differences in scaling on the y-axis of each graph.

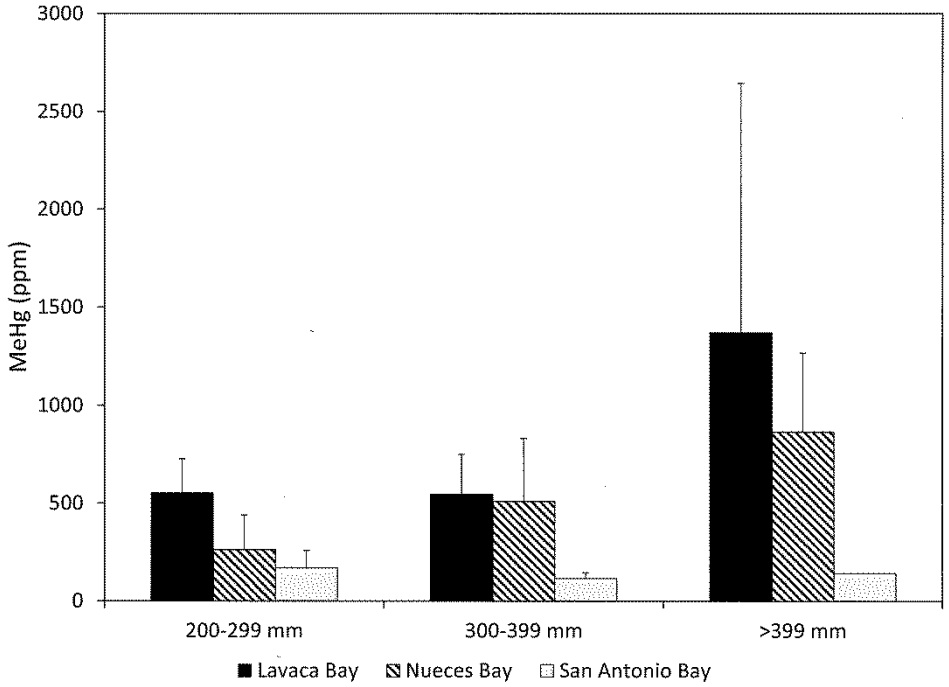

Figure 21. Mean concentration (ppb) of MeHg in black drum (*Pogonias cromis*) tissue by size class in Lavaca, Nueces, and San Antonio bays.

Red Drum—Mean tissue concentrations of MeHg in red drum (*Scieanops ocellatus*) were similar in Nueces Bay in both size classes (Figure 22). Tissue concentrations by size class increased modestly in Lavaca Bay, but differences were more substantial between size classes in San Antonio Bay. Inorganic mercury ranged from 2.5-3.2% of total mercury. Mean tissue concentrations of MeHg in red drum were similar to those of black drum in the same size classes. As noted in black drum, concentrations generally decline from Lavaca Bay to San Antonio Bay.

Spotted Seatrout— Mean tissue concentrations of MeHg in spotted seatrout (*Cynoscion nebulosus*) tissue of larger fish was less than smaller fish in Lavaca and Nueces bays, while increasing in larger fish in San Antonio Bay (Figure 23). The pattern of declining concentrations from Lavaca Bay to San Antonio Bay remained. Generally, mean concentrations of MeHg in spotted seatrout from Lavaca and Nueces bays were greater than in either black or red drum; concentrations in San Antonio Bay seatrout, red drum, and black drum were similar. The percentage of Hg(II) was much more variable in seatrout and was as high as 10% in 300-399 mm fish in Lavaca Bay and >399 mm fish in San Antonio Bay to 3.5 % in >399 mm fish in Lavaca Bay.

Discussion

The entry of mercury into the food webs of Lavaca, San Antonio, and Nueces bays, and specifically the bioaccumulation MeHg, is not completely clear based on the data we present here. Inorganic mercury was the only or primary species in the phytoplankton whereas the

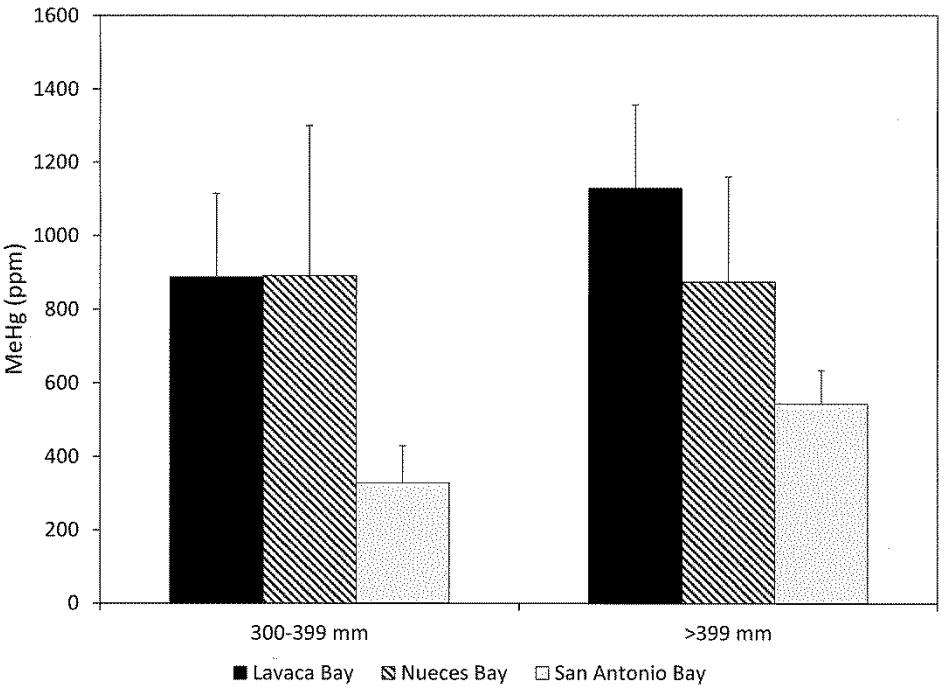

Figure 22. Mean concentration (ppb) of MeHg in red drum (*Scieanops ocellatus*) tissue by size class in Lavaca, Nueces, and San Antonio bays.

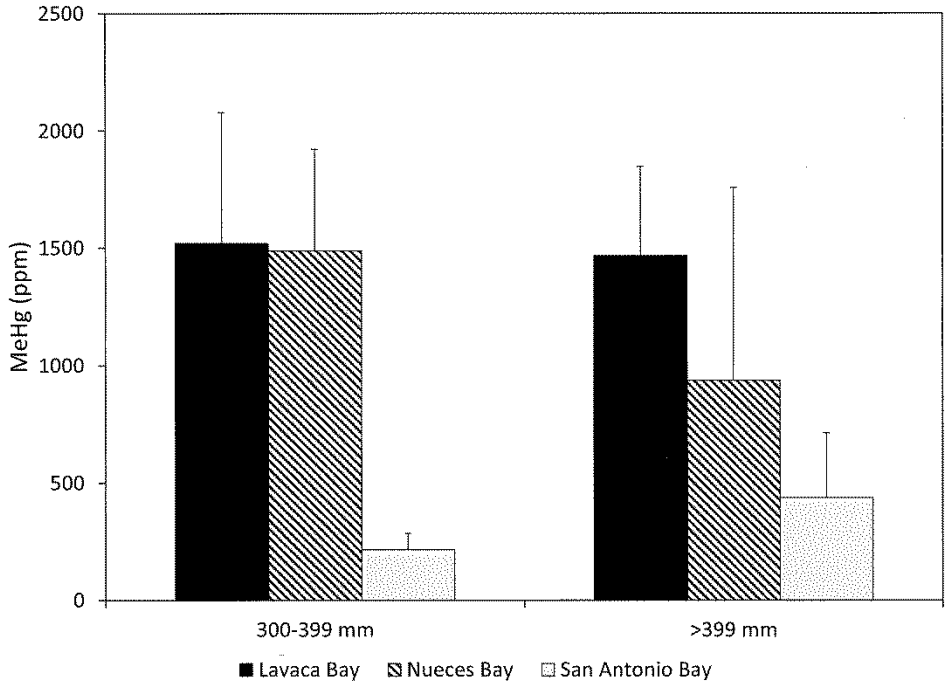

Figure 23. Mean concentration (ppb) of MeHg in spotted seatrout (*Cynoscion nebulosus*) tissue by size class in Lavaca, Nueces, and San Antonio bays.

proportion of MeHg tended to be higher in the zooplankton. Likewise, inorganic mercury was the predominant species in the sediments (although there is quite a bit of variability) as well as the polychaetes and oysters but the proportion of MeHg was higher in the other bivalves and the gastropods. For the most part, MeHg predominates in the higher trophic levels. So where is the inorganic mercury within the bay systems being methylized and moved into the food web since it is clearly not through the grazing pathway (phytoplankton to zooplankton)? The likely pathway is through the microbial food web, which was not specifically sampled for this study.

Heterotrophic bacteria, such as sulfate-reducing bacteria, are often the dominant methylating organisms in estuaries (Jackson 1998); these bacteria are also important components of energy flow and nutrient cycling in marine ecosystems (Fukami et al. 1996). These bacteria are important not just in the methylization of mercury but also its movement into food webs (Colwell and Nelson 1975). Heterotrophic nanoflagellates, ubiquitous protozoan zooplankton, are one of the most important bacterial consumers and, with the heterotrophic bacteria, play important roles in the movement of materials into higher trophic levels (Fukami et al. 1996). The lack of MeHg in the phytoplankton in this study indicates that source of the MeHg in the rather large zooplankton that we collected ($\geq$400 μm) is likely the heterotrophic nanoflagellates in the plankton, with MeHg in bivalves other than oysters and the gastropods coming directly from the hetertrophic bacteria in the former and from a mix of epibenthic sources (bacteria, POM, benthic microalgae) in the latter. Why MeHg is found in such low proportions in the oysters is unknown. In an experiment by Colwell and Nelson (1975), oysters readily bioaccumulated MeHg when fed mercury-accumulating bacteria demonstrating an important link between heterotrophic bacteria and filter-feeding mollusks. However, Colwell and Nelson (1975) also found some indications that oysters actively metabolize mercury, reducing concentrations in their tissues, which may account for the low MeHg proportions measured in this study.

Shrimps and crabs tend to be omnivorous but their diet is often focused primarily on animal components that are sized appropriately for the size of the animal feeding. For example, brown shrimp (*Farfantepenaeus aztecus*) larvae are omnivorous feeding on both phytoplankton and zooplankton, but as they grow they become more carnivorous while still including some detritus and plant material in their diets (Patillo et al. 1997). White shrimp (*Litopenaeus setiferus*) are more reliant on plant matter throughout their lives, combining predation with scavenging. The diet of grass shrimp (*Palaemonetes* spp.) is similar to white shrimp with the addition of epiphytic organisms, especially on seagrasses. Blue crabs are omnivorous with food items varying with size class, as well as the season and food availability. Larvae are primarily planktivorous while juveniles and adults feed on whatever is available. In the crustaceans, MeHg predominated mercury concentrations and the carnivorous/scavenging components of their diets are the likely sources of the MeHg.

Methylmercury also dominated mercury concentrations in the majority of the forage/prey fish as well as bay squid. With the exception of menhaden (*Brevoortia* sp.) and striped mullet (*Mugil cephalus*) which are primarily filter feeders, these organisms are generally carnivorous, feeding largely on organisms such as shrimp and crabs (Patillo et al. 1997). The game fishes feed on both the crustaceans as well as the forage/prey fish, with black drum also including a significant molluscan component in its diet. The bioaccumulation of MeHg from the prey species (forage fish, crustaceans, and bay squid) to the game fishes is clearly shown in the data.

The age of the black drum in the largest size class can be quite variable which directly relates to the amount of mercury that accumulates in tissues. The largest fish in the size class from Lavaca Bay was 951 mm (37 in) and weighed nearly 28 lbs. The largest in Nueces Bay was 521 mm (20 in) and weighed only 4 lbs and the largest from San Antonio Bay was 457 mm (18 in) and weighed 2.4 lbs. Texas black drum are typically 400-430 mm by the end of their third year after which growth rate decreases markedly (Pattillo et al. 1997). Growth after the third year decreases to 25-50 mm/year with estimated maximum ages ranging from 35-60 years. Thus, based on their lengths, the age of the largest black drum from Nueces Bay might be 5-9 years old, while the largest black drum from San Antonio Bay might be 4-5, but the largest from Lavaca Bay could be from 13-24 years old. The length of time that these fish have had to biomagnify mercury in their tissues is also extremely variable, with the largest fish in Lavaca Bay perhaps living during a time when overall mercury contamination in the bay was much higher. The fish in the other size classes in Lavaca Bay are probably very close to the same ages which accounts for both the lower concentrations of MeHg as well as the more modest variability in concentrations.

Red drum are long-lived (up to 37 years old) and grow rapidly until they are 4-5 years old (Patillo et al. 1997). Red drum of 700-800 mm total length are considered sexually mature athough sexually mature fish as young as 3 years old and as small as 425 mm (females) and 320 mm (males) have been reported. Five-year-old fish make up the bulk of spawning individuals and all fish are sexually mature by the time they are 6 years old. The red drum analyzed in this ranged from 336-472 mm in Lavaca Bay, 329-536 in Nueces Bay, and 312-448 in San Antonio Bay. In general, these fish are likely still within the rapid growth stage.

Spotted seatrout mature at lengths from 200-300 mm and by the end of their second year (Patillo et al. 1997). Growth is rapid during the first year and then declines, with fish reported to grow 13-18 mm/month and reaching 300-337 mm total length at the end of the first year. These fish are short-lived compared to red and black drum, generally only 5-9 years, although adults up to 15 years-old have been reported. All of the fish collected for this study were mature and likely past their rapid growth stage.

Life stage of all organisms affects bioaccumulation and biomagnification (Kidd et al. 2012). Growth rates can be negatively correlated with Hg concentrations (growth dilution) particularly in very productive areas; in areas with low primary productivity and low nutrients the opposite is generally true with slower growth rates (due to lower food availability) resulting in higher concentrations of mercury, especially at the top trophic levels. Long-lived organisms tend to have much higher concentrations of mercury due to bioaccumulation since even if they undergo a rapid growth phase, growth generally slows and levels off after they reach a certain age or size class. This is seen in the concentrations of mercury in the game fishes in this study. The red drum may still be growing relatively rapidly for their species, but since they are likely all at least 5 years old, their growth should be leveling off as they approach sexual maturity. The higher mercury concentration, and particularly the greater proportions of inorganic mercury, in some spotted seatrout, which are rather short-lived compared to the drum, may be due to direct uptake via exposure of their skin and gills to mercury in the water column. Seatrout have very thin scales and skin compared to the other drum species, so the possibility for direct uptake is greater.

Stable Isotopes

In this section we provide a general overview of nitrogen and carbon isotopes in organisms by bay with a focus on the information they provide on the trophic levels of the various organisms, followed by a comparison of stable isotope results across bays, again focusing on trophic level. Isotopic composition in the phytoplankton and most organisms except game fishes was determined in 2-3 samples in most cases; zooplankton determinations were made only in Nueces Bay (Appendix 3). Numbers of samples from game fish that were analyzed per size class varied greatly from a single sample to 13 or 14 samples per bay depending on species. Eight sediment samples were analyzed from each bay.

Carbon and Nitrogen Stable Isotopic Composition of Organisms by Bay

Lavaca Bay—Mean values for $\delta^{13}C$ and $\delta^{15}N$, with C:N ratios and calculated trophic levels for most taxa and size classes (no phytoplankton or zooplankton values) are shown in Table 7. A scatterplot plot of $\delta^{13}C$ vs $\delta^{15}N$ shows a spread of $\delta^{13}C$ from about -15 to -24‰, while the $\delta^{15}N$ ranges from ~9–16‰ (Figure 24). While the overall range of $\delta^{13}C$ or $\delta^{15}N$ is fairly large, within any given group of organisms there is typically little variability in the values either within a species (i.e., low standard deviation) or among the members of the group. For example, within the forage/prey fishes, $\delta^{13}C$ varies from ~18‰ to 21‰ while the crustaceans vary from ~16‰ to 19‰. The greatest variability in $\delta^{13}C$ both within and between species or species categories is for the game fishes. Variability within game fish species tends to increase with the size of the fish. A similar pattern is exhibited by $\delta^{15}N$ although with the exception of the smaller sizes classes of black drum, within species variability is also low within the game fishes. Values of $\delta^{15}N$ suggest that all the organisms tested are secondary consumers or higher (all organisms >7‰ $\delta^{15}N$); however calculated trophic levels range from primary consumer (2; the lowest calculated value was 1.941 for 0-50 mm white shrimp) to tertiary consumer (4; 4 was the highest calculated value and was mostly confined to the game fish).

San Antonio Bay—Mean $\delta^{13}C$ values range from about -15 to -25‰; mean $\delta^{15}N$ generally ranges from ~13‰ to ~20‰ (Table 8). The outlying values seen on the scatterplot (Figure 25) are for sheepshead minnows (*Cyprinodon variegatus*) which had ~7.7‰ $\delta^{15}N$ and a calculated trophic level of only 1.5, the lowest calculated trophic level of any organism in any bay. Variability within and between groups is lower than the overall range with the greatest variability (i.e., standard deviation) of both $\delta^{13}C$ and $\delta^{15}N$ within the game fishes. Including sheepshead minnows, $\delta^{15}N$ values suggest that all organisms are secondary consumers or higher (>7 ‰); calculated trophic levels range from 1.5 to 5 (most of the game fish and some of the prey/forage fish, such as Atlantic croaker [*Micropogonias undulatus*]).

Nueces Bay—The range of mean $\delta^{13}C$ values was similar to the other bays (~-14‰–24‰) as was the range of mean $\delta^{15}N$ (~11–17‰); patterns of variability within groups and among species were also similar (Table 9). On the scatterplot, the two outlying values are for white shrimp (51-100 mm) and grass shrimp (Figure 26). These species/size classes had the lowest mean $\delta^{15}N$ values with the white shrimp yielding the lowest calculated trophic level (2.4). Both eastern oyster and other bivalves also had relatively low mean $\delta^{15}N$ values (11.4 ‰, 11.3‰ respectively) but much higher mean $\delta^{13}C$ values resulting in trophic level calculations of secondary consumer

Table 7. Mean and standard deviation (SD) of nitrogen and carbon stable isotopes and trophic level calculated from nitrogen isotope data for all taxon groups and sediments from Lavaca Bay.

Taxon/Group	Size Class	n	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		C:N Ratio		Trophic Level	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Game fishes										
Pogonias cromis	200-299	14	-19.466	2.4704	12.434	1.5641	3.189	0.0268	2.959	0.4740
Pogonias cromis	300-399	5	-19.494	1.4651	14.170	1.4715	3.168	0.0277	3.485	0.4459
Pogonias cromis	400-999	9	-20.468	0.8682	12.568	0.5512	3.200	0.0245	2.999	0.1670
Sciaenops ocellatus	300-399	13	-19.022	0.6410	14.095	0.8660	3.191	0.0328	3.462	0.2624
Sciaenops ocellatus	400-999	5	-17.108	0.3125	16.068	0.3373	3.192	0.0084	4.060	0.1022
Cynoscion nebulosus	300-399	8	-19.908	0.7692	15.245	0.2682	3.295	0.0424	3.811	0.0813
Cynoscion nebulosus	400-999	13	-20.302	1.0370	14.865	0.4049	3.340	0.1425	3.696	0.1227
Prey fishes and squid										
Anchoa mitchilli	0-50	3	-19.880	0.1873	14.267	0.5424	3.347	0.0603	3.514	0.1644
Lagodon rhomboides	51-100	3	-19.690	0.4107	12.550	0.2751	3.210	0.0436	2.994	0.0834
Lagodon rhomboides	151-200	3	-20.677	0.1106	12.723	0.0833	3.263	0.0115	3.046	0.0252
Leiostomus xanthurus	101-150	3	-19.727	0.2397	13.340	0.0265	3.437	0.0503	3.233	0.0080
Micropogonias undulatus	51-100	3	-18.547	0.3029	13.280	0.1323	3.213	0.0321	3.215	0.0401
Micropogonias undulatus	101-150	3	-17.803	0.1185	15.003	0.0208	3.570	0.1179	3.737	0.0063
Teuthida	0-50	3	-19.447	0.1550	14.200	0.3659	3.780	0.0700	3.494	0.1109
Teuthida	51-100	3	-21.470	0.0954	12.540	0.2339	3.943	0.0379	2.991	0.0709
Crustaceans										
Farfantepenaeus aztecus	0-50	3	-16.090	0.0781	11.293	0.1172	3.283	0.0503	2.613	0.0355
Farfantepenaeus aztecus	51-100	3	-17.767	0.1168	11.663	0.2250	3.263	0.0252	2.725	0.0682
Farfantepenaeus aztecus	101-150	3	-17.173	0.0764	12.440	0.0900	3.203	0.0321	2.961	0.0273
Litopenaeus setiferus	0-50	3	-15.780	0.0173	9.077	0.0839	3.430	0.0300	1.941	0.0254
Litopenaeus setiferus	51-100	3	-18.107	0.2155	10.693	0.1320	3.250	0.0300	2.431	0.0400
Litopenaeus setiferus	101-150	3	-19.200	0.2884	11.207	0.1850	3.247	0.0231	2.587	0.0561

Table 7. Continued.

Taxon/Group	Size Class	n	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		C:N Ratio		Trophic Level	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Palaemonetes sp.	0-50	2	-16.005	0.0636	10.075	0.0212	3.630	0.0707	2.244	0.0064
Callinectes sapidus	0-50	3	-18.450	0.1637	12.363	0.1436	3.340	0.0173	2.937	0.0435
Callinectes sapidus	51-100	3	-18.370	0.0624	12.377	0.2417	3.253	0.0451	2.941	0.0733
Benthos										
Polychaetes		3	-18.360	0.7104	10.533	0.2113			2.383	0.0640
Gastropods		2	-19.490	0.2546	13.550	0.4525	4.587	0.4692	3.297	0.1371
Crassostrea virginica	0-50	3	-22.053	0.0862	9.420	0.2007	5.033	0.3656	2.045	0.0608
Crassostrea virginica	51-100	3	-21.113	0.1172	9.583	0.1250	5.010	0.0600	2.095	0.0379
Crassostrea virginica	101 - 150	3	-22.330	0.1493	10.763	0.1531	4.487	0.1097	2.453	0.0464
Other bivalves		3	-22.317	1.0693	9.910	0.1217	4.160	0.2970	2.194	0.0369
Sediment		8	-20.788	0.7259	nd	nd			nd	nd

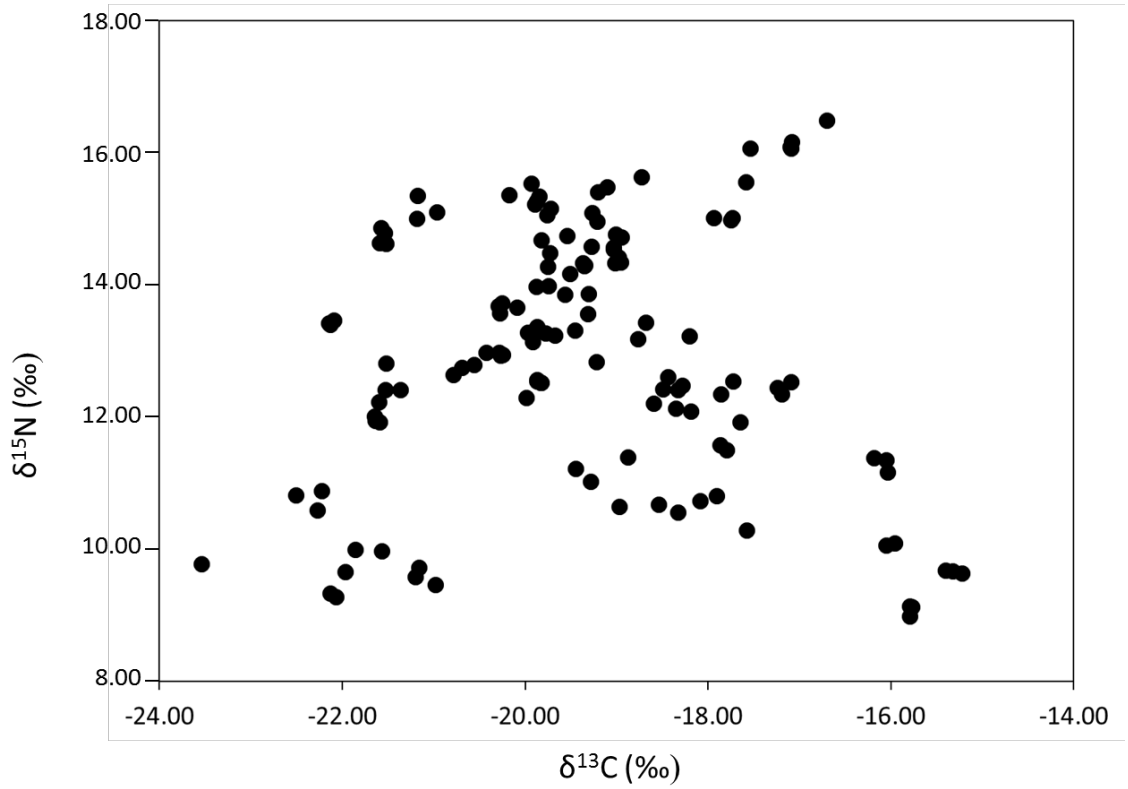

Figure 24. Scatterplot of $\delta^{13}C$ vs $\delta^{15}N$ for all species and species-categories from Lavaca Bay listed in Table 7.

(3). Mean $\delta^{15}N$ values suggest that all organisms are secondary consumers or higher (>7 ‰); calculated values range from ~2 (primary consumer) to 4 (tertiary consumer; most game fish and forage/prey fishes).

Trophic Level as Inferred from $\delta^{15}N$ Among the Bays

The relative trophic level ($\delta^{15}N$) of 18 organism categories (species and/or species by size class) that were common to all three bay systems and which should represent different trophic levels were determined: polychaetes (Poly), gastropods (Gast), eastern oyster (Oyst2, 51-100 mm), other bivalves (Bivalves), brown shrimp (BS2, 51-100 mm), white shrimp (WS2, 51-100 mm), grass shrimp (GS1, <50 mm), blue crab (BC1, <50 mm), bay anchovy (AM1, <50 mm), pinfish (PIN2, 51-100 mm), Atlantic croaker (AC1, 51-100 mm), black drum (BD1, 200-299 mm; BD2, 300-399 mm; BD3, >399 mm), red drum (RD2, 200-299 mm; RD3, 300-399 mm), and spotted seatrout (ST2, 200-299 mm; ST3, 300-399 mm). Biomass of the phytoplankton or zooplankton collected from the bays was insufficient to be included in this comparison.

In Lavaca Bay, and to a somewhat lesser extent, Nueces Bay, food chains appear to be short with most higher organisms feeding at a similar trophic level (Figure 27). For example in Lavaca Bay, while red drum (>399 mm; RD3) sits at a slightly higher trophic level, the remainder of the game fishes (BD, RD2, ST) are at a lower trophic level and overlap greatly with the forage/prey

Table 8. Mean and standard deviation (SD) of nitrogen and carbon stable isotopes and trophic level calculated from nitrogen isotope data for all taxon groups and sediments from San Antonio Bay.

Taxon/Group	Size Class	n	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		C:N Ratio		Trophic Level	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Game fishes										
Pogonias cromis	200-299	9	-21.137	0.4813	16.048	2.0991	3.217	0.0716	4.054	0.6361
Pogonias cromis	300-399	10	-21.084	2.3904	16.483	1.4804	3.201	0.0549	4.186	0.4486
Pogonias cromis	400-999	1	-21.870		19.200		3.160		5.009	
Sciaenops ocellatus	300-399	11	-17.760	1.1970	18.155	0.8286	3.219	0.0302	4.692	0.2511
Sciaenops ocellatus	400-999	9	-15.256	0.3235	16.630	0.6311	3.203	0.0377	4.230	0.1912
Cynoscion nebulosus	300-399	11	-20.078	0.2941	19.995	0.3442	3.290	0.0728	5.250	0.1043
Cynoscion nebulosus	400-999	9	-19.103	1.4789	18.960	0.9463	3.354	0.1897	4.936	0.2868
Prey fishes										
Anchoa mitchilli	0-50	3	-22.853	0.0666	19.187	0.1069	3.343	0.0252	5.005	0.0324
Anchoa mitchilli	51-100	3	-22.037	0.0153	19.977	0.0611	3.370	0.0265	5.244	0.0185
Cyprinodon variegatus	0-50	3	-19.327	0.1656	7.683	0.1124	3.610	0.0265	1.519	0.0341
Lagodon rhomboides	51-100	3	-19.677	0.3190	12.787	0.5300	3.343	0.0058	3.066	0.1606
Lagodon rhomboides	101-150	3	-23.087	0.0666	19.067	0.0416	3.267	0.0153	4.969	0.0126
Leiostomus xanthurus	101-150	3	-21.117	0.0462	16.757	0.1021	3.270	0.0100	4.269	0.0310
Micropogonias undulatus	101-150	3	-23.997	0.2021	19.217	0.0850	3.293	0.0321	5.014	0.0258
Crustaceans										
Farfantepenaeus aztecus	51-100	3	-18.337	4.2588	14.657	0.3024	3.260	0.0200	3.632	0.0916
Farfantepenaeus aztecus	101-150	3	-20.527	0.1756	16.283	0.5301	3.273	0.0208	4.125	0.1606
Litopenaeus setiferus	0-50	3	-17.213	0.0513	14.267	0.1656	3.333	0.0404	3.514	0.0502
Litopenaeus setiferus	51-100	3	-18.690	0.0520	16.197	0.0493	3.290	0.0200	4.099	0.0149
Litopenaeus setiferus	101-150	3	-21.353	0.0321	17.087	0.1380	3.323	0.0666	4.369	0.0418
Callinectes sapidus	0-50	3	-22.570	0.0436	16.967	0.1320	3.290	0.0141	4.332	0.0400

Table 8. Continued.

Taxon/Group	Size Class	n	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		C:N Ratio		Trophic Level	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Callinectes sapidus	101-150	3	-20.993	0.0577	12.710	0.1758	3.463	0.0153	3.042	0.0533
Palaemonetes sp.	0-50	3	-17.530	0.1562	15.390	0.2291	3.413	0.0115	3.855	0.0694
Benthos										
Polychaetes		3	-19.153	0.0850	13.300	0.1442	4.843	0.0850	3.221	0.0437
Gastropods		2	-20.640	0.6081	16.530	0.1980	4.755	0.1202	4.200	0.0600
Crassostrea virginica	0-50	2	-24.460	0.0707	13.620	0.3111	6.435	0.4596	3.318	0.0943
Crassostrea virginica	51-100	3	-25.470	0.3404	14.280	0.1229	5.650	0.0200	3.518	0.0372
Crassostrea virginica	101-150	3	-25.307	0.1266	13.810	0.0600	6.273	0.0569	3.376	0.0182
Other bivalves		3	-22.750	0.0954	14.147	0.2532	4.400	0.0529	3.478	0.0767
Sediment		8	-20.788	0.6034	nd	nd			nd	nd

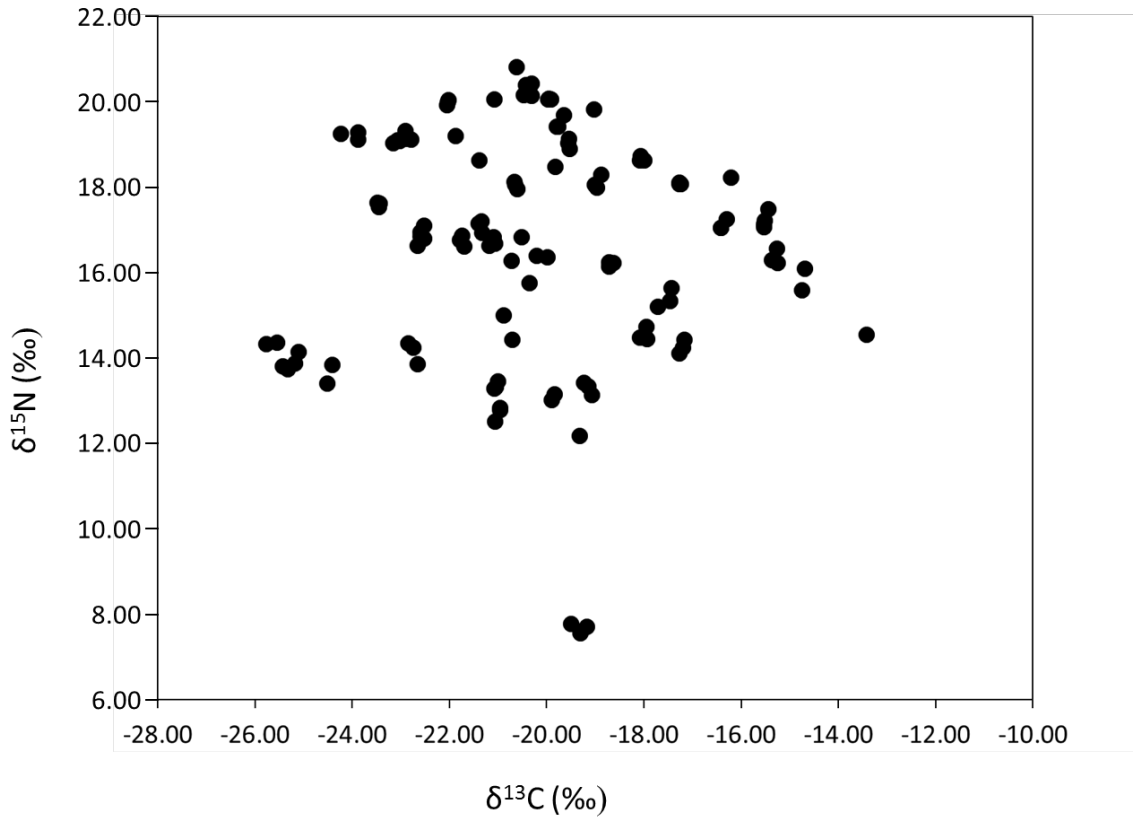

Figure 25. Scatterplot of $\delta^{13}C$ vs $\delta^{15}N$ for all species and species-categories from San Antonio Bay listed in Table 8.

fishes (AC, PIN). A similar pattern is seen in Nueces Bay with spotted seatrout (200-299 mm; ST2) and both size classes of red drum overlapping at a slightly higher trophic level than the black drum (BD), the larger spotted seatrout (>399 mm; ST3), and the forage/prey fishes and some of the crustaceans. Carbon sources also tend to be more constrained since the cluster of organisms is in the middle of the range of carbon on the x-axis. In contrast, the food web structure in San Antonio Bay is characterized by distinct positions for each of species or species category, and much clearer distinctions between the carbon sources used by each.

Discussion

The trophic level represented by the $\delta^{15}N$ values for each species or species category was consistently lower in Lavaca Bay, generally followed by Nueces Bay and then San Antonio Bay (Table 10). Exceptions to this pattern are seen in pinfish, large black drum (>399 mm), and large red drum (>399 mm). Benthic diatoms ($\delta^{15}N$ ~18-20‰) appear to be the most likely source of carbon for most organisms; very few consumers appeared to depend solely on carbon derived from phytoplankton. This is similar to the pattern reported for saltmarsh food webs (Sullivan and Moncreiff 1990).

Table 9. Mean and standard deviation (SD) of nitrogen and carbon stable isotopes and trophic level calculated from nitrogen isotope data for all taxon groups and sediments from Nueces Bay.

Taxon/group	Size class	n	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		C:N Ratio		Trophic Level	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Game fishes										
Pogonias cromis	200-299	8	-19.743	1.0357	14.805	1.6964	3.242	0.0268	3.677	0.5141
Pogonias cromis	300-399	11	-18.520	1.8301	13.665	0.9672	3.216	0.0369	3.332	0.2931
Pogonias cromis	400-999	9	-19.196	0.8686	14.576	0.8367	3.198	0.0367	3.608	0.2535
Sciaenops ocellatus	300-399	13	-17.408	0.7444	16.750	1.0900	3.240	0.0311	4.267	0.3303
Sciaenops ocellatus	400-999	7	-17.434	1.2964	16.523	1.1003	3.193	0.0395	4.198	0.3334
Cynoscion nebulosus	300-399	11	-17.678	0.9801	16.551	0.6580	3.230	0.0309	4.206	0.1994
Cynoscion nebulosus	400-999	9	-16.090	1.3762	14.870	0.8485	3.344	0.1662	3.697	0.2571
Prey fishes and squid										
Anchoa mitchilli	0-50	3	-20.203	0.1787	16.742	0.1845	3.345	0.0261	4.264	0.0559
Lagodon rhomboides	51-100	3	-18.040	0.0432	14.847	0.1620	3.249	0.0358	3.690	0.0491
Lagodon rhomboides	101-150	3	-17.026	1.1507	12.422	1.2016	3.326	0.0355	2.955	0.3641
Leiostomus xanthurus	51-100	3	-16.176	0.1150	14.277	0.1360	3.247	0.0345	3.517	0.0412
Leiostomus xanthurus	151-200	5	-19.932	0.1209	15.565	0.2212	3.351	0.0412	3.907	0.0670
Micropogonias undulatus	101-150	3	-18.711	0.0581	13.263	0.1482	3.274	0.0369	3.210	0.0449
Teuthida	0-50	3	-18.536	0.5675	15.633	0.5466	3.703	0.0705	3.928	0.1656
Teuthida	51-100	3	-18.812	0.4100	14.409	0.3555	3.955	0.0316	3.557	0.1077
Crustaceans										
Farfantepenaeus aztecus	0-50	1	-16.174		12.841		3.366		3.082	
Farfantepenaeus aztecus	51-100	4	-18.326	1.2450	14.175	0.2815	3.279	0.0580	3.486	0.0853
Litopenaeus setiferus	51-100	4	-18.601	0.3033	10.509	0.6045	3.234	0.0113	2.376	0.1832
Palaemonetes sp.	0-50	5	-13.793	0.1292	11.296	0.2012	3.493	0.0383	2.614	0.0610

Table 9. Continued.

Taxon/group	Size class	n	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		C:N Ratio		Trophic Level	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Callinectes sapidus	0-50	3	-17.098	1.2704	13.558	0.7970	3.762	0.6023	3.299	0.2415
Callinectes sapidus	51-100	4	-19.990	2.2241	13.458	1.1860	3.474	0.0153	3.269	0.3594
Callinectes sapidus	101-150	2	-17.659	0.0842	13.984	0.0169	3.330	0.0143	3.428	0.0051
Benthos										
Polychaetes		3	-18.017	0.2384	12.808	0.0895	4.975	0.0431	3.072	0.0271
Gastropods		3	-18.685	0.6711	13.746	0.4121	4.551	0.3372	3.356	0.1249
Crassostrea virginica	51-100	3	-23.540	2.5700	11.452	0.6846	5.640	1.3315	2.661	0.2074
Other bivalves		3	-21.936	0.1250	11.311	0.1531	4.562	0.0831	2.619	0.0464
Zooplankton		3	-20.105	0.2059	12.179	0.0440	5.333	0.0576	2.882	0.0133
Sediment		8	-20.434	1.3110						

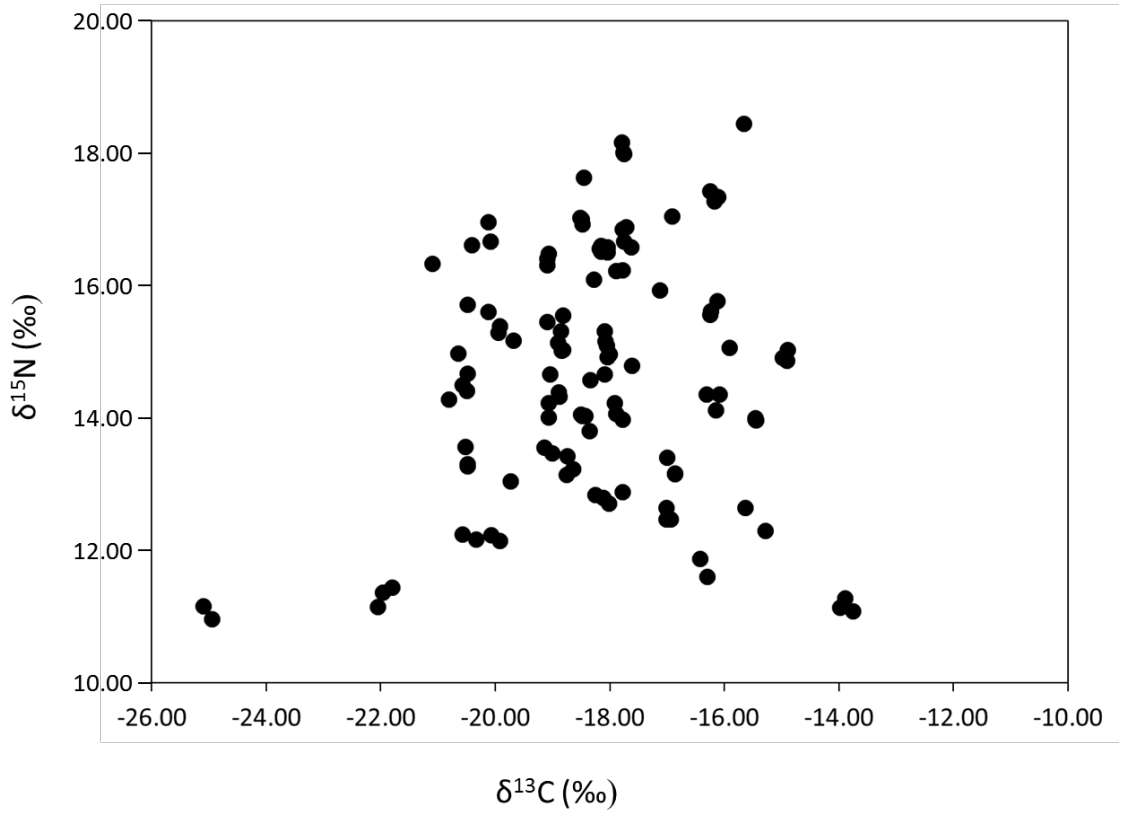

Figure 26. Scatterplot of $\delta^{13}C$ vs $\delta^{15}N$ for all species and species-categories from Nueces Bay listed in Table 9.

Generally, an approximate increase in $\delta^{15}N$ of 3.4‰ indicates an increase in trophic level (Page et al. 2013). Baseline (producer) $\delta^{15}N$ values in estuarine ecosystems range from ~6‰ for *Juncus/Spartina*, edaphic algae (Sullivan and Moncreiff 1990), and seagrasses and epiphytic algae (Moncreiff and Sullivan 2001) to ~7–10‰ for phytoplankton and macroalgae (Moncreiff and Sullivan 2001). In this study, values for the lowest consumer levels were just above the estimated phytoplankton baseline (10‰) in both Lavaca and Nueces bays whereas there is a clear increase in trophic level in San Antonio Bay between the estimated phytoplankton baseline and the lowest consumer levels (~13–14‰). Looking at all organisms tested in Lavaca and Nueces bays (see Tables 7–9), the differences between the highest and lowest mean $\delta^{15}N$ is 7‰ and 6.2‰, respectively, or a maximum of 2 trophic levels. On the other hand, in San Antonio Bay, the difference between the highest and lowest mean $\delta^{15}N$ is 12.3‰, or nearly 4 trophic levels.

Omnivory appears to be the feeding mode for most organisms in Lavaca and Nueces bays whereas food resources appear to be more distinct and species- or species category-specific in San Antonio Bay. Omnivory has a destabilizing effect on food webs and while it should be rare, it is fairly common in aquatic communities (Vander Zanden and Rasmussen 1996). Similar to all niche theory, while there is a potential (or maximum) trophic level for any given organism, the realized trophic level may be lower (Kling et al. 1992). Interactions between predatory/carnivorous organisms and herbivores may or may not be realized and organisms

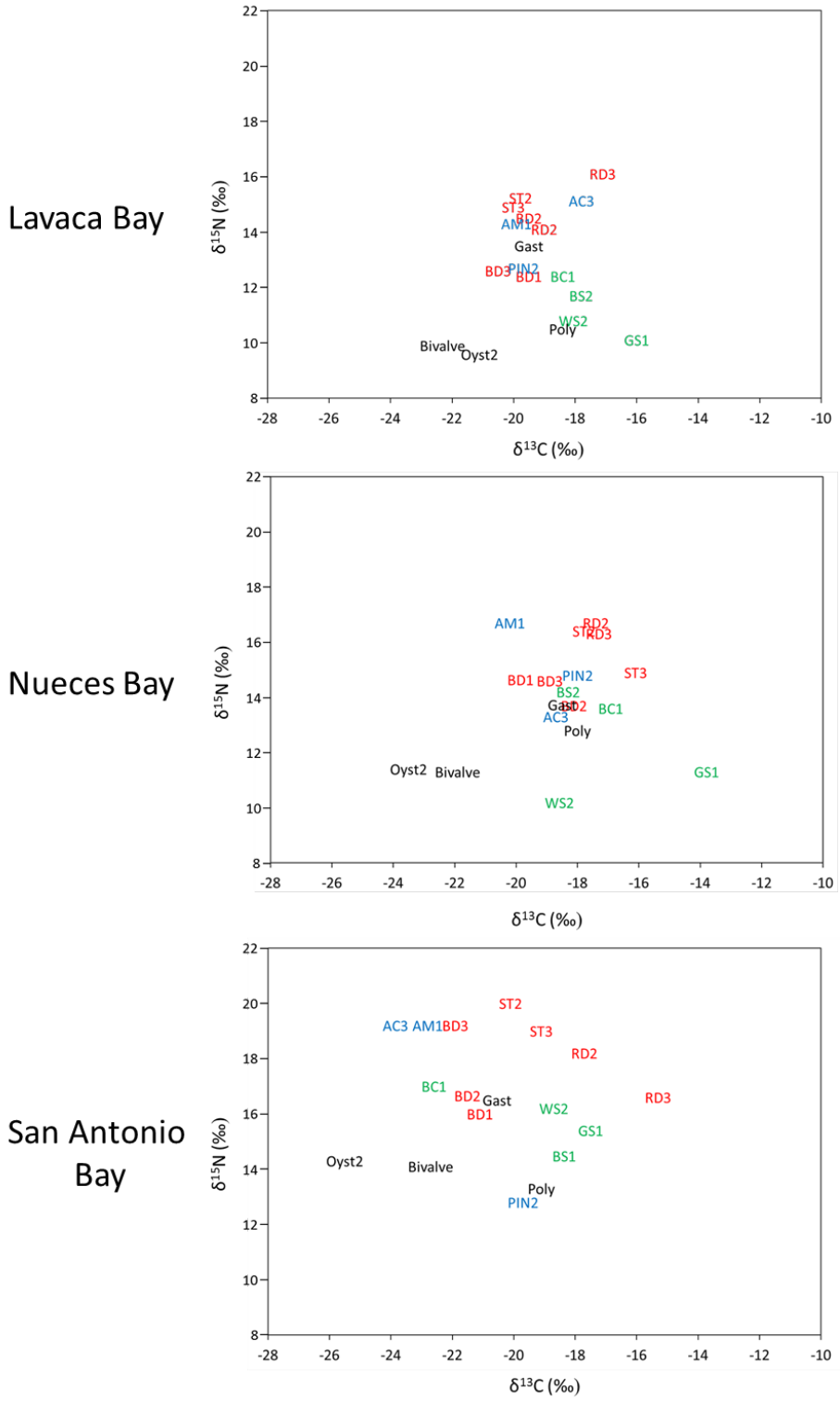

Figure 27. Comparison of estimated trophic position (from $\delta^{15}N$) of 18 species or species-categories common to Lavaca, Nueces, and San Antonio bays. See text for explanation of abbreviations. Red= presumed highest trophic level; blue=next lowest trophic level; green = next lowest trophic level; black = lowest trophic level.

Table 10. Between bay comparisons of trophic levels inferred from $\delta^{15}N$ values and carbon sources inferred from $\delta^{13}C$ values.

Species or Species Category	Relative Trophic level	Carbon source
Polychaetes	LB<SAB=NB	Benthic diatoms (C3-C4)
Eastern Oyster (51-100 mm)	LB<NB<SAB	Phytoplankton(C3)
Other bivalves	LB<NB<SAB	Phytoplankton (C3)
Gastropods	LB=NB<SAB	Benthic diatoms (C3-C4)
Brown shrimp (51-100 mm)	LB<SAB=NB	Benthic diatoms (C3-C4)
White shrimp (51-100 mm)	LB=NB<SAB	Benthic diatoms (C3-C4)
Grass shrimp (<50 mm)	LB<NB<SAB	Benthic diatoms (C3-C4)
Blue crab (<50 mm)	LB<NB<SAB	LB, NB = benthic diatoms (C3-C4); SAB = phytoplankton (C3)
Bay anchovy (<50 mm)	LB<NB<SAB	Phytoplankton (C3)
Pinfish (51-100 mm)	LB=SAB<NB	Phytoplankton and/or benthic diatoms (C3-C4)
Atlantic croaker (>100 mm)	NB<LB<SAB	LB, NB = benthic diatoms (C3-C4); SAB = phytoplankton (C3)
Black drum (200-299 mm)	LB<NB<SAB	Phytoplankton and/or benthic diatoms (C3-C4)
Black drum (300-399 mm)	NB<LB<SAB	Phytoplankton and/or benthic diatoms (C3-C4)
Black drum (>399 mm)	LB<NB<SAB	Phytoplankton and/or benthic diatoms (C3-C4)
Red drum (300-399 mm)	LB<NB<SAB	Benthic diatoms (C3-C4)
Red drum (>399 mm)	LB=NB=SAB	Benthic diatoms (C3-C4)
Spotted seatrout (300-399 mm)	LB<NB<SAB	Benthic diatoms (C3-C4)
Spotted seatrout (>399 mm)	LB<NB<SAB	Benthic diatoms (C3-C4)

that are considered strict predators are often omnivorous instead. The minimal number of trophic levels above the baseline in Lavaca and Nueces bays are indicative of omnivory and signal food webs that have been destabilized with few organisms reaching their potential trophic level. The more “normal” number of trophic levels above the baseline in San Antonio Bay indicates a more stable system, with less omnivory and more organisms feeding at their potential trophic level.

Relationship of Methylmercury Concentrations to Trophic Level

Because MeHg bioaccumulates and biomagnifies, the expectation is that MeHg concentrations in organisms should increase as trophic level increases. Figure 28A is a scatterplot of the calculated trophic level (see Tables 7-10) and MeHg concentrations (see Tables 4-6) for the values for the 18 species and species-categories that were common to Lavaca, San Antonio, and Nueces bays

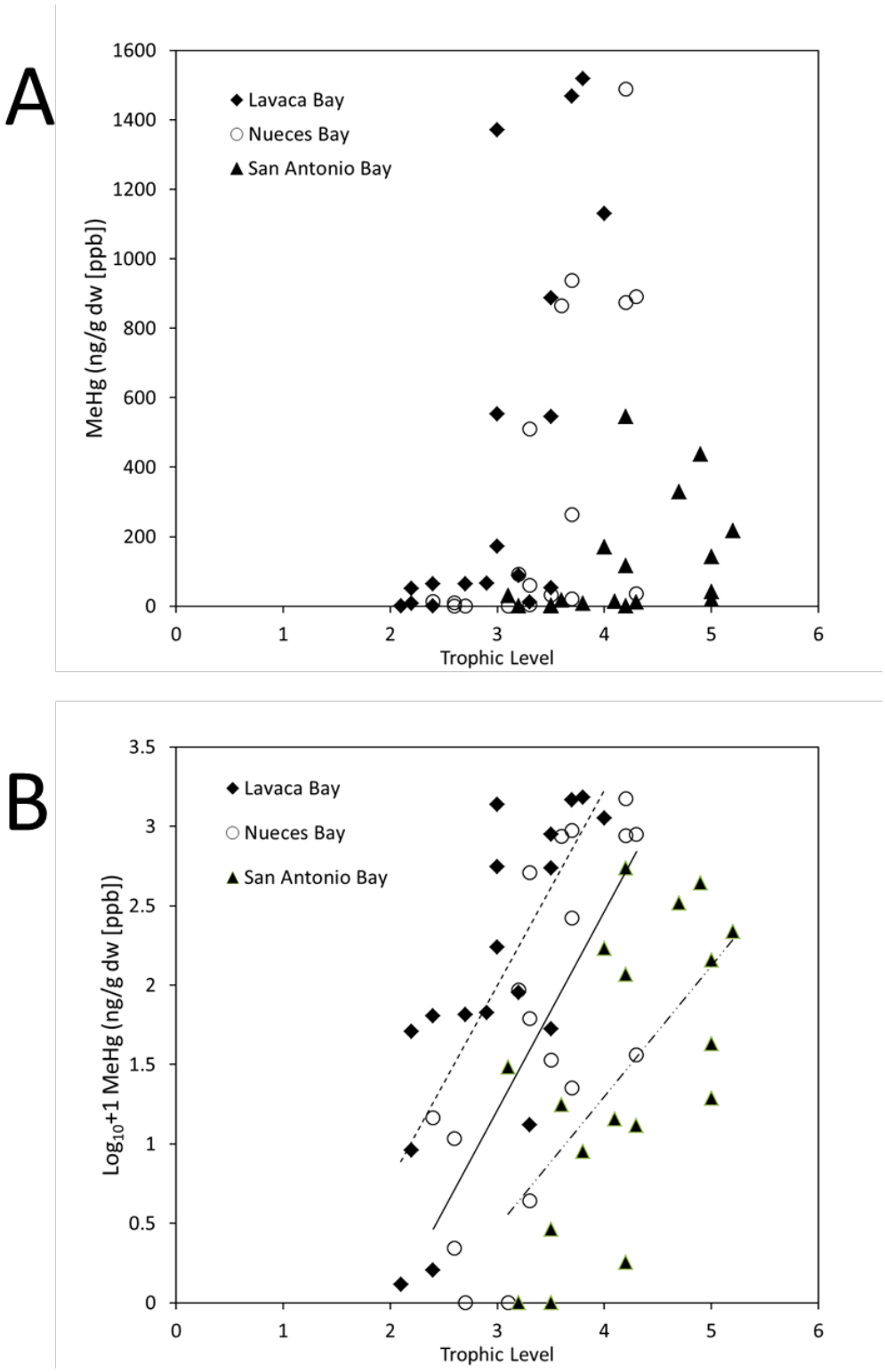

Figure 28. A) Scatterplot of untransformed MeHg concentrations vs calculated trophic level for the 18 species or species categories that were common to Lavaca, San Antonio, and Nueces bays. B) Log-transformed (log_{10}+1) MeHg concentrations vs calculated trophic level with trendlines from regression analysis. Lavaca Bay – even dashes; Nueces Bay – solid line; San Antonio Bay – long and short dashes.

(see Table 10). The small number of trophic levels in Lavaca and Nueces bays results in very steep increases from low to high and very high concentrations in some organisms. In San Antonio Bay, MeHg concentrations also increase with trophic level, but the rate of increase is less rapid, largely due to the overall lower concentrations of mercury in organisms, but also because the food chain is longer. Using the same trophic level data and log-transformed ($\log_{10}$+1) MeHg concentrations as suggested by Kidd et al. (2012), linear regressions were run to test the hypothesis that MeHg was positively related to calculated trophic level (Figure 28B). There was a significant positive relationship between MeHg and trophic level in all three bays (df=1,17; Lavaca Bay–P <0.0001, R^2 = 0.90; San Antonio Bay–P <0.0001, R^2 = 0.80; Nueces Bay–P<0.0001, R^2 = 0.82) strongly supporting the hypothesis.

Discussion

It is unremarkable that we find a significant correlation between trophic level and MeHg concentrations since this fact is widely reported in the literature, and is expected based on the history of contamination, especially in Lavaca Bay. More interesting is the very steep increases seen in the Lavaca and Nueces bays where food chains are short. Mercury is accumulating rapidly in the top predators in these bays despite being relatively low at the lowest trophic levels. The trendlines for Lavaca Bay and Nueces Bay are parallel indicating that there are different bioavailabilities or baseline concentrations in the two bays as illustrated by Kidd et al. (2012; see Figure 4). The slightly lower slope of the trendline for San Antonio Bay is indicative of slower bioaccumulation rates in the bay; this line also extends to beyond trophic level 5 illustrating the longer food chain within the bay (Kidd et al. 2012; see Figure 4). Omnivory in Lavaca and Nueces bays seems to be concentrating mercury in the higher trophic levels faster despite the fact that there is little difference in MeHg concentrations at lower trophic levels among the three bays.

Conceptual Food Web Model

To establish the food web relationships of the resulting diagram, we downloaded from GoMexSI all available diet data for the three game fishes. This resulted in approximately 1000 lines of data for each species. These data were then sorted and grouped into about eight categories, of which six (Annelida, Mollusca, Crustacea, Actinopterygii [fish], Plantae, detritus) were used to establish the relative frequency of occurrence of the food items and groups in the diets of the game fishes (Figure 29). Three of the groups, Annelida, Plantae, and detritus were never more than 10% of the diet items for any of the game fishes. The Mollusca occurred much more frequently (about 37%) in the diet of black drum but was not important in the diets of either red drum or spotted seatrout. Crustaceans were the most frequently occurring food item ranging from about 32% to 47%. Fish were most frequent item in the diet of spotted seatrout (~43%) and were important in the diet of red drum but were infrequent in the diet of black drum. There was no food item that constituted more than 50% of the diet of any of the three game fishes based on the data available in the GoMexSI database.

These data were used to construct a composite food web for the three bays (Figure 30), using the spatial location of the predators and prey from the Lavaca Bay data set. The rectangles representing each of the predators and prey are plotted according to the calculated trophic level along the y-axis, and according to their $\delta^{13}C$ value along the x-axis. The rectangles are scaled to

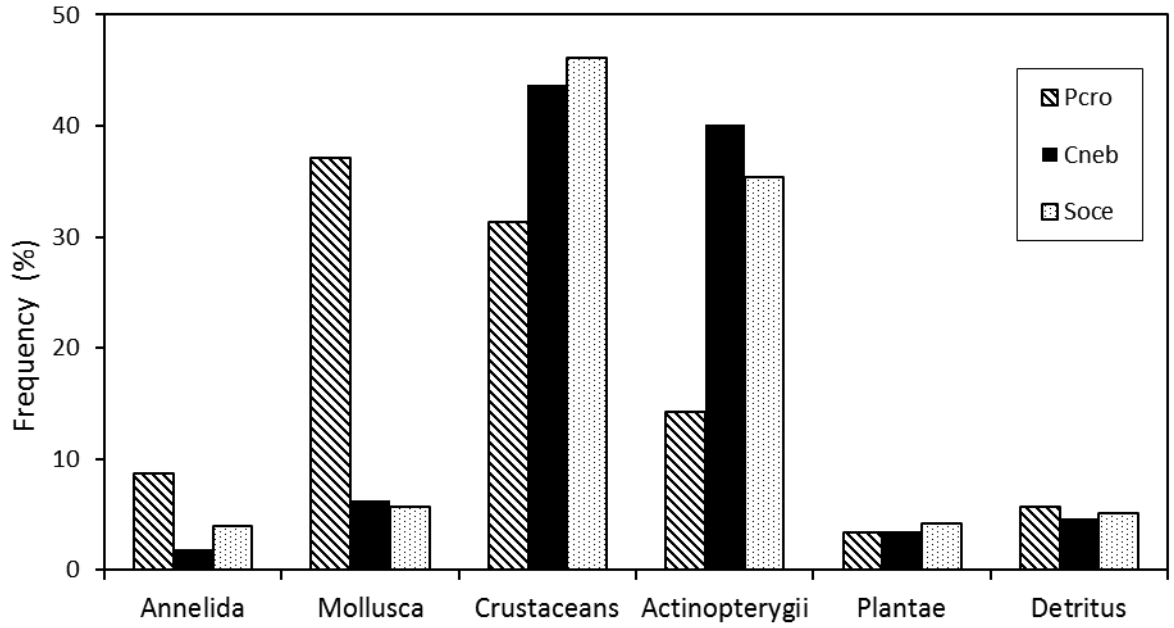

Figure 29. Frequency of major food groups for black drum (*Pogonias cromis*, Pcro), red drum (*Scieanops ocellatus*, Soce) and spotted seatrout (*Cynoscion nebulosus*, Cneb) based on data compiled from the GoMexSI database.

total mercury concentration. Lines connecting the game fishes to their prey are scaled so that the thinnest lines represent relatively rare food items (10% frequency), the slightly heavier line represents somewhat more common groups (11–25%), and the thickest lines (2pt) represent the most common food groups (26–50%).

Discussion

The diagram immediately conveys the complexity of the Texas coastal estuarine food webs. The diagram is also not complete, because many minor connections are left out. A few species for which we did not have Hg data, but did have stable isotope data (or found it in literature for the local area) are included if they are major part of the food web. The primary producers include the emergent marsh vegetation and submerged aquatic vegetation (seagrasses), benthic algae/organic matter, and phytoplankton. The stable carbon isotope clearly separates the primary producers, and that signature can be seen in the consumers in the food web. Because black drum feed heavily on bivalves, and bivalves feed heavily on phytoplankton and POM, black drum tended to have a $\delta^{13}C$ signature close to the phytoplankton/POM signature. Due to the resulting low trophic level of the bivalves, black drum were generally positioned at a somewhat lower trophic level (3-4) than either spotted seatrout or red drum (4-5). In addition, the generally lower concentrations of mercury in the bivalves tended to keep the mercury concentrations in black drum lower than that in the other game fishes. Both red drum and spotted seatrout feed heavily on crustaceans and fish with seatrout positioned slightly higher than red drum. Fish are most frequent in the diet of

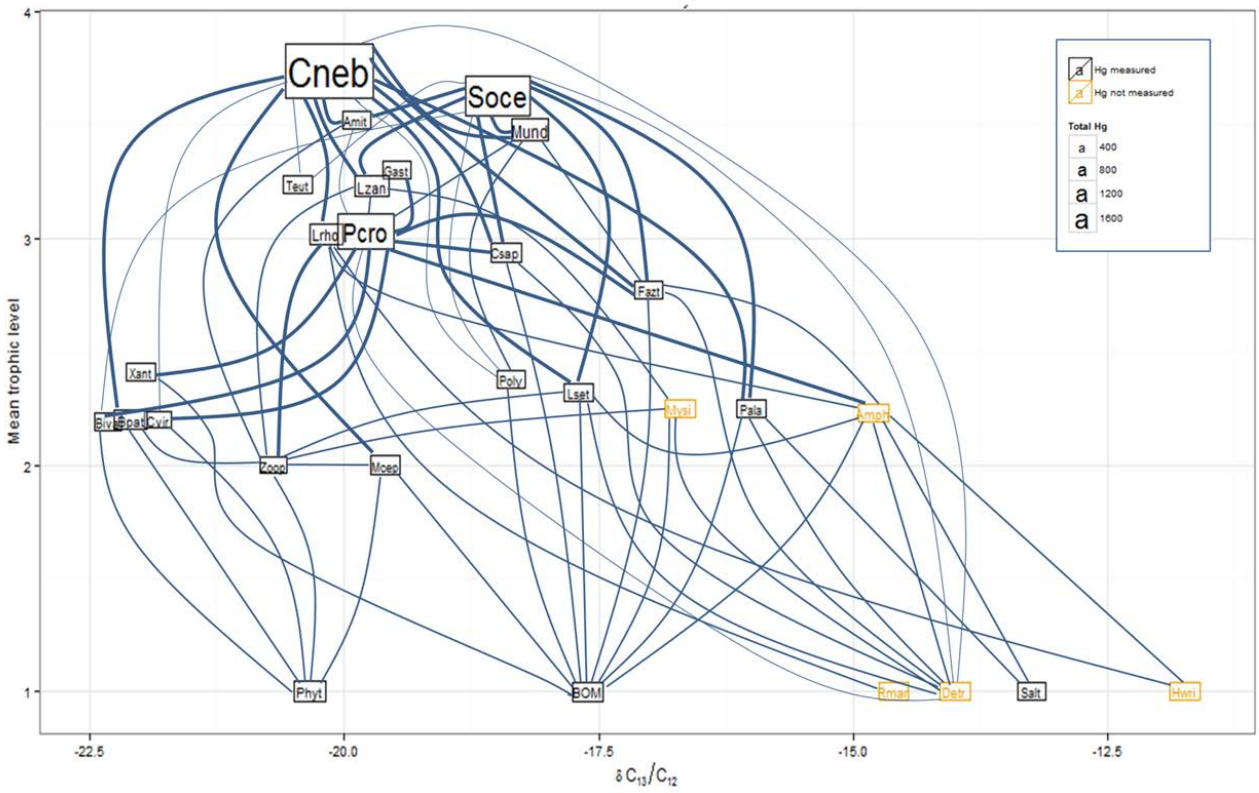

Figure 30. Composite food web diagram for Lavaca Bay, San Antonio Bay, and Nueces Bay. The plot uses the data from Lavaca Bay, but the diet data is a compilation from the entire coast of Texas. The mercury scale is in ng/g dw (ppb). Yellow rectangles represent groups or species for which no mercury data was collected in this project. A list of the species/group abbreviations used in the diagram, with their associated common and scientific names is in Appendix 4.

seatrout which is shown in its slightly higher trophic level, mercury concentration, and greater $\delta^{13}C$ enrichment when compared with red drum. A more detailed examination of the species of fishes consumed seatrout and red drum may also reveal that some fish with higher concentrations of mercury in their tissues may be preferred by seatrout. For example, mercury concentrations in Atlantic croaker (*Micropogonias undulatus*) and spot croaker (*Leiostomus xanthurus*) were higher than those of Gulf menhaden (*Brevoortia patronus*) and striped mullet (*Mugil cephalus*).

SUMMARY AND CONCLUSIONS

Many of the organisms in Lavaca, San Antonio, and Nueces bays, especially the fish, show evidence of mercury contamination. Inorganic mercury is usually the primary species in the lowest trophic levels (e.g., phytoplankton, zooplankton polychaetes) while methylmercury (MeHg) is the primary species at the higher trophic levels, particularly in the fish. Organisms in San Antonio Bay have overall lower loads of mercury and while proportionally MeHg constituted the majority of total mercury in the fish, overall concentrations were much lower in the fish than in the other two bays. Concentrations of total mercury in the largest size class of black drum and both size classes of red drum and spotted seatrout exceeded TDSHS action levels

(700 ng/g dw or 700 ppb) in both Lavaca and Nueces bays; no fish exceeded TDSHS action levels in San Antonio Bay. In all bays, mercury concentrations in game fish generally increased with size. This pattern of mercury contamination generally conforms to our expectations that Lavaca Bay organisms would show the greatest concentrations due to historical inputs and that San Antonio Bay would show the least due to the lack of inputs; however the amount of mercury in game fishes in Nueces Bay was somewhat higher than might be expected given the lack of specific historical sources. Stunz and Robillard (2011) reported lower total mercury concentrations in Nueces Bay for similarly sized fish for all three species; and while they did note the relationship between size and concentration, they did not report concentrations by size classes as we do here.

Stable isotope analyses revealed that the food webs in Lavaca and Nueces bays are constrained by omnivory, resulting in fewer trophic levels when compared with San Antonio Bay. Food webs in these bays are destabilized as a result of omnivory and reflect the perturbations and disturbances of the system. These disturbances may be due to long-term mercury contamination, at least in Lavaca, but both Nueces and Lavaca bays have histories of anthropogenic disturbances as a result of industrial activity, oil and gas production and refining (e.g., brine disposal), and shell dredging to name a few. San Antonio Bay has also experienced shell dredging (stopped in 1982) but is otherwise relatively undisturbed with the exception of the oyster fishery. While all three bays show increased methylmercury concentrations with trophic level, methylmercury is accumulating much more rapidly via the short food chains in Lavaca and Nueces bays. Texas estuarine food webs are complex but it is clear that the bioaccumulation and biomagnification of mercury increases as the trophic level and size of organisms increases. The differences among and between the three bays in this study are due to the relative importance of omnivory in the food chains that make up the food web which reflects the disturbance within the bay system. This disturbance may be due to contaminants, such as mercury, or to natural factors, such as fluctuating salinities.

EDUCATION/OUTREACH

Some of the results and concepts from the Coastal Management Program project “Assessment of Mercury in Selected Game Fish Food Webs in the Texas Coastal Zone” are currently being integrated into various programs within the Aquatic Education Program at the Center for Coastal Studies. Most educational programs in the Aquatic Education Program involve intensive outdoor field experiences that allow the students to become immersed in their environment. This project provides an opportunity to add additional depth to the program by focusing on a specific contaminant of concern that serves as a platform for the exploration of pollution and the effects of pollution on aquatic resources. Slides that give an overview of mercury contamination and its effects on humans and an original lab developed demonstrate the broad concept of bioaccumulation and biomagnification and the flow of mercury (or other persistent contaminants) are in Appendix 5.

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Appendix 1: Dates, Location Details, and Physicochemical Measurements during Specimen Collections

Appendix 1.1. Dates, locations, and physico-chemical data at the Texas Parks and Wildlife Department (TPWD) gillnet sampling sites where game fishes were collected.

Bay	Date	TPWD Site Number	Latitude	Longitude	Water Temperature (°C)	Salinity (psu)	Dissolved Oxygen (mg/L)
Lavaca Bay	30 May 13	4-190-85	28 40 37	96 34 01	26.1	27.3	6.1
Lavaca Bay	30 May 13	4-190-86	28 41 02	96 33 40	26.1	27.3	6.1
Lavaca Bay	12 Jun 13	4-190-81	28 40 32	96 38 33	28.4	25.9	5.4
Lavaca Bay	12 Jun 13	4-190-105	28 39 16	96 38 02	28.4	28.6	5.7
Lavaca Bay	23 Oct 13	4-190-30	28 43 18	96 36 31	20.3	27.9	6.6
Lavaca Bay	23 Oct 13	4-190-108	28 39 36	96 35 03	19.8	26.9	7.5
Lavaca Bay	23 Oct 13	4-190-171	28 37 45	96 37 07	20.3	27.6	6.5
San Antonio Bay	4 Jun 13	4-200-32	28 24 52	96 48 13	28.2	10.8	5.4
San Antonio Bay	4 Jun 13	4-200-24	28 24 31	96 46 21	27.6	4.1	5.1
San Antonio Bay	5 Jun 13	4-190-27	28 25 35	96 45 55	27.4	1.3	6.6
San Antonio Bay	5 Jun 13	4-190-12	28 27 10	96 46 46	30.0	0.3	5.7
San Antonio Bay	30 Oct 13	4-200-30	28 24 05	96 50 59	24.9	19.4	5.9
San Antonio Bay	30 Oct 13	4-200-39	28 23 45	96 50 40	25.1	19.9	6.8
San Antonio Bay	5 Nov 13	4-200-40	28 23 05	96 49 59	21	17.3	7.4
San Antonio Bay	5 Nov 13	4-200-49	28 22 30	96 49 20	21.5	17.2	6.9
San Antonio Bay	12 Nov 13	4-300-151	28 14 45	96 47 15	19.4	19.5	7.2
San Antonio Bay	12 Nov 13	4-300-100	28 17 55	96 48 15	19.3	16.7	8.6
Nueces Bay	25 Apr 13	6-260-14	27 52 29	97 22 38	18.8	38.2	5.4
Nueces Bay	25 Apr 13	6-260-12	27 52 14	97 24 59	19.0	39.2	5.5
Nueces Bay	18 Jun 13	6-260-20	27 51 37	97 28 43	28.1	39.0	5.7
Nueces Bay	18 Jun 13	6-260-6	27 52 35	97 30 25	28.0	40.0	4.0
Nueces Bay	30 Oct 13	6-260-7	27 52 19	97 29 06	25.2	24.5	6.1
Nueces Bay	30 Oct 13	2-260-19	27 51 52	97 29 08	25.2	24.9	6
Nueces Bay	6 Nov 13	6-260-20	27 51 36	97 38 32	22.4	22.7	6
Nueces Bay	6 Nov 13	6-260-21	27 51 58	97 27 59	22.6	22.6	6.1
Nueces Bay	12 Nov 13	6-260-4	27 53 01	97 20 44	19.4	37.4	6.4

Appendix 1.2. Dates, locations, depths, and physicochemical data for the prey and sediment collections.

Bay	Date	Site	Latitude	Longitude	Depth (m)	Water Temperature (°C)	Salinity (psu)	Dissolved Oxygen (mg/L)
Lavaca Bay	1 Jul 13	A	NA	NA	~0.25	29.11	30.62	7
Lavaca Bay	1 Jul 13	E	NA	NA	~0.25	nd	nd	nd
Lavaca Bay	1 Jul 13	E	NA	NA	~2.0	nd	nd	nd
Lavaca Bay	1 Jul 13	F	NA	NA	~0.25	nd	nd	nd
Lavaca Bay	1 Jul 13	G	28 40 22.0	96 38 12.1	~0.25	27.53	31.3	6.44
Lavaca Bay	19 Nov 13	D	28 36 50.9	96 37 10.7	~0.25	19.53	28.11	8.68
Lavaca Bay	19 Nov 13	C	28 38 26.5	96 30 31.7	~0.25	19.18	30.2	6.93
Lavaca Bay	19 Nov 13	B2	28 36 11.4	96 31 42.8	~0.25	18.96	29.91	7.66
Lavaca Bay	19 Nov 13	B2	28 36 11.4	96 31 42.8	~2	18.96	29.88	7.63
Lavaca Bay	19 Nov 13	I	28 40 04	96 34 29	~0.25	19.09	29.26	8.02
San Antonio Bay	16 Jul 13	H	28 26 19.7	96 45 21.9	~0.25	29.14	12.51	5.76
San Antonio Bay	16 Jul 13	E	28 22 02.0	96 44 41.2	~0.25	28.72	nd	nd
San Antonio Bay	16 Jul 13	E	28 22 02.0	96 44 41.2	~2.0	nd	nd	nd
San Antonio Bay	16 Jul 13	D	NA	NA	~0.25	28.29	16.16	6.26
San Antonio Bay	16 Jul 13	C	28 22.02.9	94 42 04.1	~0.25	28.08	26.31	5.56
San Antonio Bay	17 Dec 13	1	28 24 38.3	96 47 56.5	~0.25	11.97	24.2	13.1
San Antonio Bay	17 Dec 13	2	28 24 09.6	96 44 40.4	~0.25	12.58	22.59	8.68
San Antonio Bay	17 Dec 13	3	28 18 55.7	96 43 57.4	~0.25	11.6	23.33	16.81
San Antonio Bay	17 Dec 13	3	28 18 55.7	96 43 57.4	1.6	11.59	26.89	11.85
San Antonio Bay	17 Dec 13	4	28 16 29.6	96 47 51.9	~0.25	14	21.19	13.7
Nueces Bay	11 Jun 13	NA	NA	NA		NA	NA	NA
Nueces Bay	11 Jun 13	D	NA	NA	~0.25	29.7	38.95	7.1
Nueces Bay	11 Jun 13	C	27 52 2438	97 23 26.4	~0.25	27.31	37.44	5.99
Nueces Bay	11 Jun 13	F	27 52 16.0	97 26 1.0	~0.25	27.97	37.34	5.64
Nueces Bay	11 Jun 13	H	27 52 14.6	97 30 00.2	~1.6	28.61	38.38	5.9
Nueces Bay	11 Jun 13	E	NA	NA	~1.6	NA	NA	NA
Nueces Bay	20 Feb 14	A	27 50 8.9	97 24 1.3	~0.25	20.09	35.22	8.87
Nueces Bay	20 Feb 14	B	27 51 23	97 24 19.1	~0.25	20.81	35.66	7.81
Nueces Bay	20 Feb 14	B	27 51 23	97 24 19.1	1.6	20.77	35.68	7.74
Nueces Bay	20 Feb 14	G	27 51 7.4	97 30 30	~0.25	20.62	32.09	7.66
Nueces Bay	20 Feb 14	I	27 52 59.5	97 20 49.7	~0.25	20.45	35.57	7.65

Appendix 1.3. Dates, locations and physicochemical data for the phytoplankton and zooplankton sample collections.

Bay	Date	Site	Latitude	Longitude	Water Temperature (°C)	Salinity (psu)	Dissolved Oxygen (mg/L)
Lavaca Bay	8 Aug 13	A	28 34 09.5	96 33 11.4	30.33	34.29	6.74
Lavaca Bay	8 Aug 13	E	28 37 59.0	96 34 56.2	30.56	33.81	7.09
San Antonio Bay	8 Aug 13	C	28 22 01.5	96 42 03.7	28.97	26.25	6.15
San Antonio Bay	8 Aug 13	D	28 21 51.7	96 47 33.7	29.55	29.82	5.92
San Antonio Bay	8 Aug 13	E	28 21 53.5	96 44 55.7	29.24	26.71	6.45
Nueces Bay	8 Aug 13	C	27 52 25.5	97 23 31.9	28.11	44.11	5.47
Nueces Bay	8 Aug 13	D	NA	NA	28.35	44.78	5.32
Nueces Bay	8 Aug 13	E	27 50 54.0	97 27 19.9	28.53	45.53	5.44
Lavaca Bay	18 Jul 14	I			17.57	17.57	5.81
Lavaca Bay	18 Jul 14	B2			27.31	27.31	5.92
Lavaca Bay	18 Jul 14	D			24.19	24.19	5.78
San Antonio Bay	7 Apr 14	G					
San Antonio Bay	7 Apr 14	C					
Nueces Bay	23 Jul 14						
Nueces Bay	23 Jul 14						
Nueces Bay	23 Jul 14						

Appendix 2: Details of Organisms Used for Mercury Analyses

Appendix 2.1. List of specimen categories, numbers collected, size ranges and size classes identified for mercury analysis, and the number of samples analyzed for mercury for Lavaca Bay.

Specimen categories	Number collected	Size range (mm)	# Hg	Notes
Fishes (predators)				
Pogonias cromis	50	215 - 914	15	three size classes: 200-299, 300-399, 400-999
Sciaenops ocellatus	29	346 - 439	10	two size classes: 300-399, 400-599
Cynoscion nebulosus	33	399 - 722	10	two size classes: 300-399, 400-999
Fishes (prey)				
Anchoa mitchilli	69	26 - 45	2	one size class: 0-50
Brevoortia spp.	1	130 - 130	2	two size classes: 0-50, 101-150
Lagodon rhomboides	102	64 - 141	4	two size classes: 51-100, 101-150
Leiostomus xanthurus	194	80 - 164	4	two size classes: 51-100, 101-150
Micropogonias undulatus	15	19 - 145	4	two size classes: 51-100, 101-150
Mugil cephalus	1	175-175	2	one size class: 151-200
Invertebratess				
Callinectes sapidus	11	28 - 98	4	three size classes: 0-50, 51-100, 101-150
Farfantepenaeus aztecus	76	35 - 107	6	two size classes: 0-50, 51-100
Litopenaeus setiferus	217	22 - 188	6	three size classes: 0-50, 51-100, 101-150
Palaemonetes sp.	6	14 - 30	2	one size class: 0-50
Teuthida	56	22 - 78	4	two size classes: 0-50 , 51-100
Benthos				
Polychaetes			2	
Gastropods			2	
Bivalves (other than oysters)			2	
Crassostrea virginica			4	two size classes: 0-50, 51-100
Phytoplankton			2	
Zooplankton			2	
Sediment			4	
Total # of samples			93	

Appendix 2.2. List of specimen categories, numbers collected, size ranges and size classes identified for mercury analysis, and the number of samples analyzed for mercury for San Antonio Bay.

Specimen categories	Number collected	Size range (mm)	# Hg	Notes
Fishes (predators)				
Pogonias cromis	51	215 - 457	10	three size classes: 200-299, 300-399, 400-999
Sciaenops ocellatus	29	337 - 402	10	two size classes: 300-399, 400-999
Cynoscion nebulosus	33	327 - 438	10	two size classes: 300-399, 400-999
Fishes (prey)				
Anchoa mitchilli	12	19 - 71	4	two size classes: 0-50, 51-100
Brevoortia spp.	1	88	2	one size class: 51-100
Lagodon rhomboides	17	76 - 112	4	two size classes: 51-100, 101-150
Leiostomus xanthurus	6	96 - 116	2	one size class: 101-150
Micropogonias undulatus	4	135 - 146	2	one size class: 101-150
Cyprinodon variegatus	190	15 - 46	2	one size class: 0-50
Invertebrates				
Callinectes sapidus	13	47 - 116	4	two size classes: 0-50, 101-150
Farfantepenaeus aztecus	50	15 - 142	4	two size classes: 51-100, 101-150
Litopenaeus setiferus	14	11 - 144	6	three size classes: 0-50, 51-100, 101-150
Palaemonetes sp.	36	11 - 30	2	one size class: 0-50
Teuthida	1	40-40	2	one size class: 0-50
Benthos				
Polychaetes			2	
Gastropods			2	
Bivalves (other than oysters)			2	
Crassostrea virginica			4	three size classes: 0-50, 51-100
Phytoplankton			2	
Zooplankton			2	
Sediment			4	
Total # of samples			82	

Appendix 2.3. List of specimen categories, numbers collected, size ranges and size classes identified for mercury analysis, and the number of samples analyzed for mercury for Nueces Bay.

Specimen categories	Number collected	Size range (mm)	# Hg	Notes
Fishes (predators)				
Pogonias cromis	22	273 - 503	15	three size classes: 200-299, 300-399, 400-599
Sciaenops ocellatus	14	249 - 464	10	two size classes: 300-399, 400-599
Cynoscion nebulosus	41	340 - 765	10	two size classes: 300-399, 400-999
Fishes (prey)				
Anchoa mitchilli	70	18 - 57	3	0ne size classes: 0-50
Brevoortia spp.	133	26 - 39	3	one size class: 0-50
Lagodon rhomboides	3	96 - 127	3	one size class: 101-150
Leiostomus xanthurus	3	159 - 163	3	one size class: 151-200
Micropogonias undulatus	12	87 - 192	6	two size classes: 51-100, 101-150
Harengula jaguana	23	23 - 35	3	one size class: 0-50
Invertebrates				
Callinectes sapidus	1	35 - 35	2	one size class: 0-50
Farfantepenaeus aztecus	119	21 - 86	5	two size classes: 0-50, 51-100
Litopenaeus setiferus	26	26 - 93	4	two size classes: 0-50, 51-100
Palaemonetes sp.	35	21 - 34	3	one size class: 0-50
Teuthida	10	28 - 115	3	one size class: 0-50
Benthos				
Polychaetes			2	
Gastropods			2	
Bivalves (other than oysters)			2	
Crassostrea virginica			5	two size classes: 0-50, 51-100
Phytoplankton			2	
Zooplankton			2	
Sediment			4	
Total # of samples			92	

Appendix 3: Details of Organisms Used for Stable Isotope Analyses

Appendix 3.1. List of specimen categories, numbers collected, size ranges and size classes identified for stable isotope analysis, and the number of samples analyzed for stable isotopes of carbon and nitrogen for Lavaca Bay.

Specimen categories	Number collected	Size range (mm)	# SI	Notes
Fishes (predators)				
Pogonias cromis	32	215 - 914	27	three size classes: 200-299, 300-399, 400-999
Sciaenops ocellatus	12	346 - 439	18	two size classes: 300-399, 400-599
Cynoscion nebulosus	16	399 - 722	21	two size classes: 300-399, 400-999
Fishes (prey)				
Anchoa mitchilli	69	26 - 45	3	one size class: 0-50
Lagodon rhomboides	102	64 - 141	6	two size classes: 51-100, 101-150
Leiostomus xanthurus	194	80 - 164	3	one size classes: 101-150
Micropogonias undulatus	15	19 - 145	6	two size classes: 51-100, 101-150
Invertebrates				
Callinectes sapidus	11	28 - 98	6	two size classes: 0-50, 51-100, 101-150
Farfantepenaeus aztecus	76	35 - 107	9	three size classes: 0-50, 51-100
Litopenaeus setiferus	217	22 - 188	9	three size classes: 0-50, 51-100, 101-150
Palaemonetes sp.	6	14 - 30	2	one size class: 0-50
Teuthida	56	22 - 78	6	two size classes: 0-50 , 51-100
Benthos				
Polychaetes			3	
Gastropods			2	
Bivalves (other than oysters)			3	
Crassostrea virginica			9	three size classes: 0-50, 51-100, 101-150
Sediment			8	
Total # of samples			142	

Appendix 3.2. List of specimen categories, numbers collected, size ranges and size classes identified for stable isotope analysis, and the number of samples analyzed for stable isotopes of carbon and nitrogen for San Antonio Bay.

Specimen categories	Number collected	Size range (mm)	# SI	Notes
Game fishes				
Pogonias cromis	51	215 - 457	20	three size classes: 200-299, 300-399, 400-999
Sciaenops ocellatus	29	337 - 402	20	two size classes: 300-399, 400-999
Cynoscion nebulosus	33	327 - 438	20	two size classes: 300-399, 400-999
Prey fishes				
Anchoa mitchilli	12	19 - 71	6	two size classes: 0-50, 51-100
Lagodon rhomboides	17	76 - 112	6	two size classes: 51-100, 101-150
Leiostomus xanthurus	6	96 - 116	3	one size class: 101-150
Micropogonias undulatus	4	135 - 146	3	one size class: 101-150
Cyprinodon variegatus	190	15 - 46	3	one size class: 0-50
Shrimps and crabs				
Callinectes sapidus	13	47 - 116	6	two size classes: 0-50, 101-150
Farfantepenaeus aztecus	50	15 - 142	6	two size classes: 51-100, 101-150
Litopenaeus setiferus	14	11 - 144	6	three size classes: 0-50, 51-100, 101-150
Palaemonetes sp.	36	11 - 30	3	one size class: 0-50
Benthos				
Polychaetes			3	
Gastropods			2	
Bivalves (other than oysters)			3	
Crassostrea virginica			9	three size classes: 0-50, 51-100, 101-150
Sediment			8	
Total # of samples			127	

Appendix 3.3. List of specimen categories, numbers collected, size ranges and size classes identified for stable isotope analysis, and the number of samples analyzed for stable isotopes of carbon and nitrogen for Nueces Bay.

Specimen categories	Number collected	Size range (mm)	# SI	Notes
Game fishes				
Pogonias cromis	22	273 - 503	28	three size classes: 200-299, 300-399, 400-599
Sciaenops ocellatus	14	249 - 464	20	two size classes: 300-399, 400-599
Cynoscion nebulosus	41	340 - 765	20	two size classes: 300-399, 400-999
Prey fishes				
Anchoa mitchilli	70	18 - 57	3	0ne size classes: 0-50
Lagodon rhomboides	3	96 - 127	6	two size classes: 51-100, 101-150
Leiostomus xanthurus	3	159 - 163	8	two size classes: 51-100, 151-200
Micropogonias undulatus	12	87 - 192	3	one size class: 101-150
Shrimpos, crabs and squid				
Callinectes sapidus	1	35 - 35	9	three size classes: 0-50, 51-100, 101-150
Farfantepenaeus aztecus	119	21 - 86	5	two size classes: 0-50, 51-100
Litopenaeus setiferus	26	26 - 93	4	one size class: 51-100
Palaemonetes sp.	35	21 - 34	5	one size class: 0-50
Teuthida	10	28 - 115	6	two size classes: 0-50, 51-100
Benthos				
Polychaetes			3	
Gastropods			3	
Bivalves (other than oysters)			3	
Crassostrea virginica			3	one size class: 51-100
Zooplankton			2	
Sediment			8	
Total # of samples			139	

Appendix 4: Food Web Diagram Abbreviations

Appendix 4.1 List of the scientific and common name, and codes used in the food web diagram for each of the species or food groups.

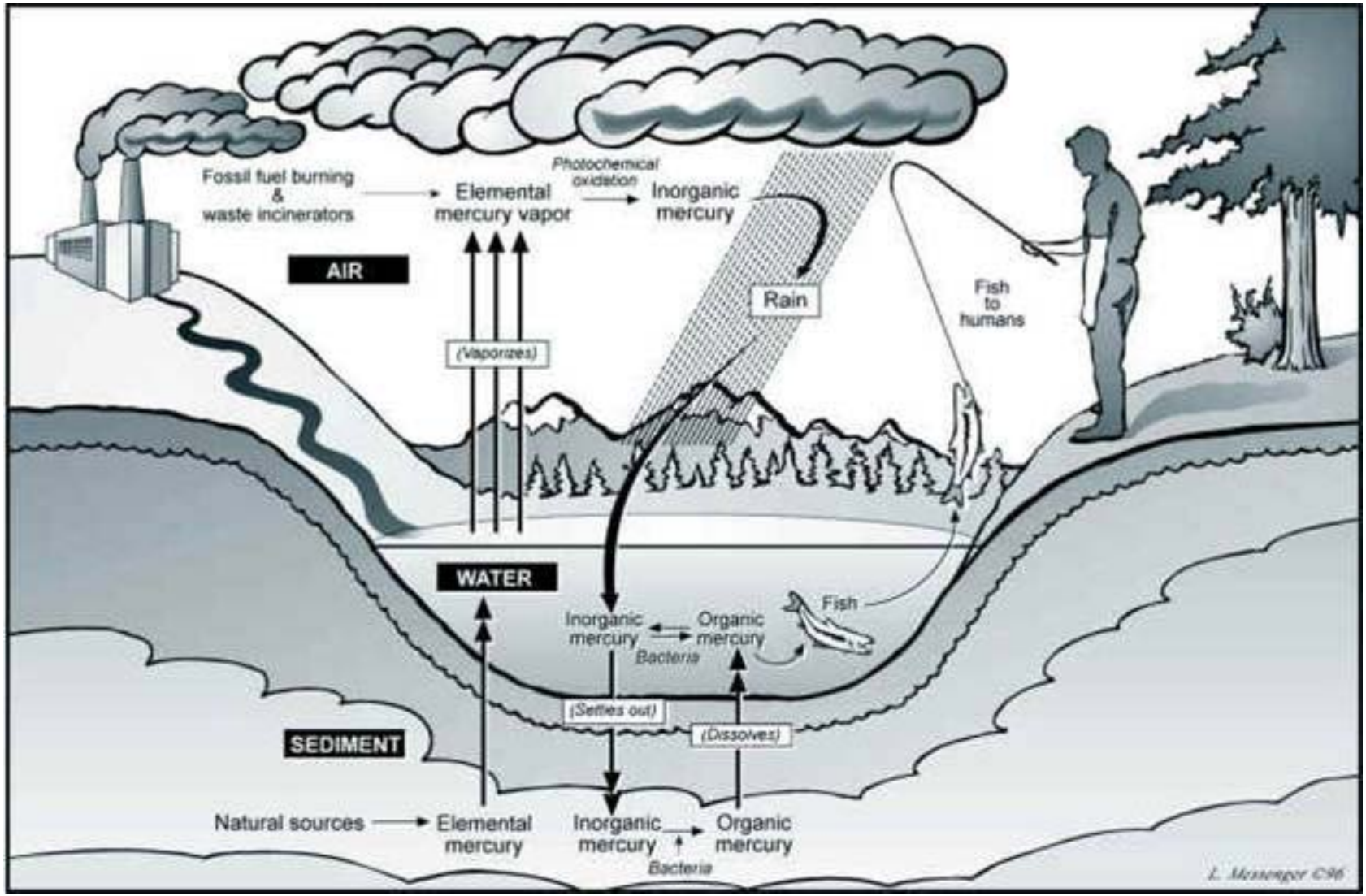
Scientific name	Common name	Code
Anchoa mitchilli	bay anchovy	Amit
Bivalves (other than oysters)	Bivalves	Biva
Callinectes sapidus	blue crab	Scap
Crassostrea virginica	Eastern oyster	Cvir
Cynoscion nebulosus	spotted seatrout	Cneb
Farfantepenaeus aztecus	brown shrimp	Fazt
Gastropoda	Gastropods	Gast
Lagodon rhomboides	pinfish	Lrho
Leiostomus xanthurus	spot	Lzan
Litopenaeus setiferus	white shrimp	Lset
Micropogonias undulatus	Atlantic croaker	Mund
Palaemonetes sp.	grass shrimp	Pala
Pogonias cromis	black drum	Pcro
Polychaetes	Polychaetes	Poly
Sciaenops ocellatus	red drum	Soce
Teuthida	Squid	Tuet
Phytoplankton	Phytoplankton	Phyt
Zooplankton	Zooplankton	Zoop
Amphipoda	Amphipods	Amph
Detritus	Detritus	Detr
Mysida	Mysids	Mysi
Ruppia maritima	widgeon grass	Rmar
Halodule wrightii	shoal grass	Hwri
Spartina alterniflora	Gulf cordgrass	Salt
Sygnathus scovelli	Gulf pipefish	Ssco
Menidia beryllina	inland silversides	Mber
Gobiosoma bosc	naked goby	Gbos
Cyprinodon variegatus	Sheephead minnow	Cvar

Appendix 5: Education and Outreach Materials

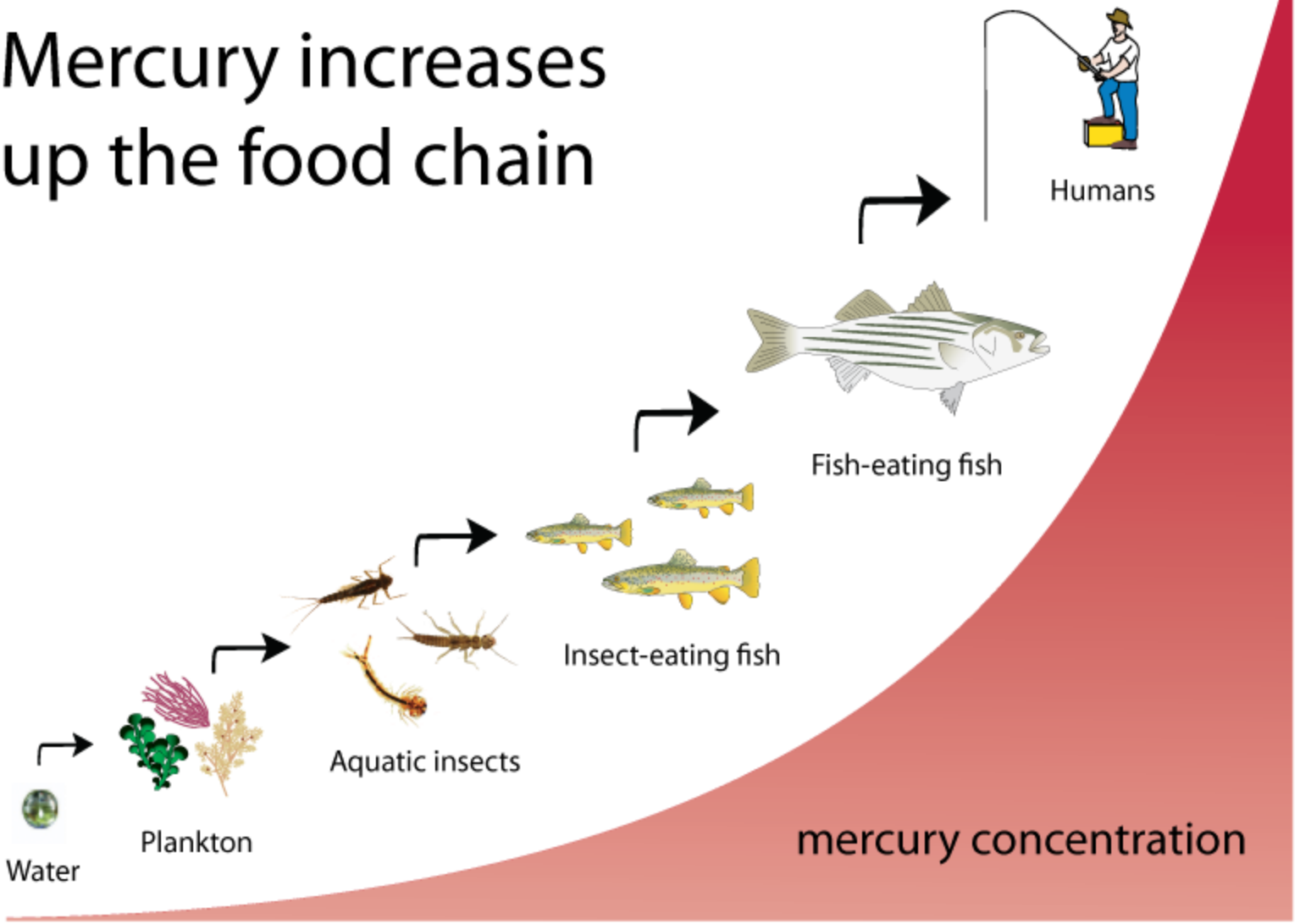
What is Mercury?

- A toxic heavy metal - Hg
  - Liquid at room temperature
  - Human exposure is mostly from eating fish

Where Does Mercury Come From?



Mercury increases up the food chain



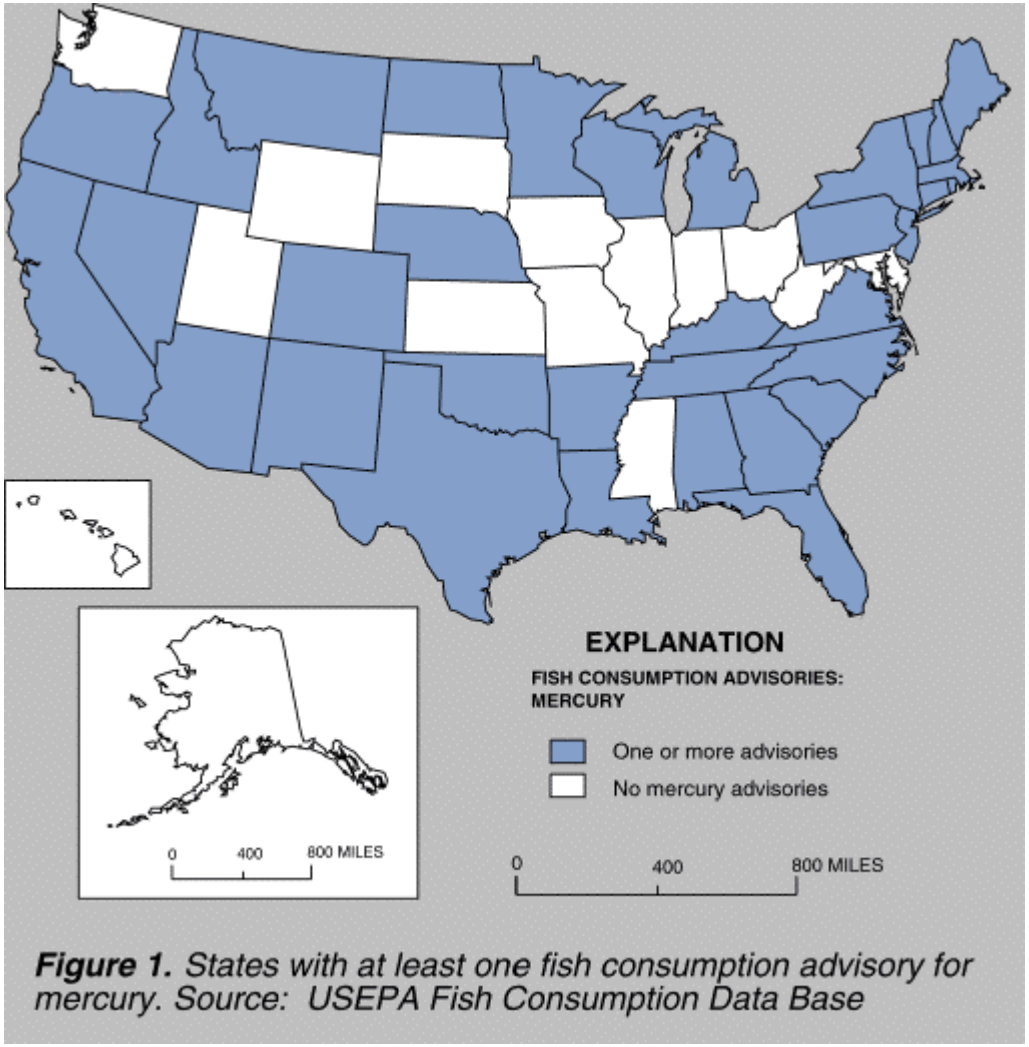
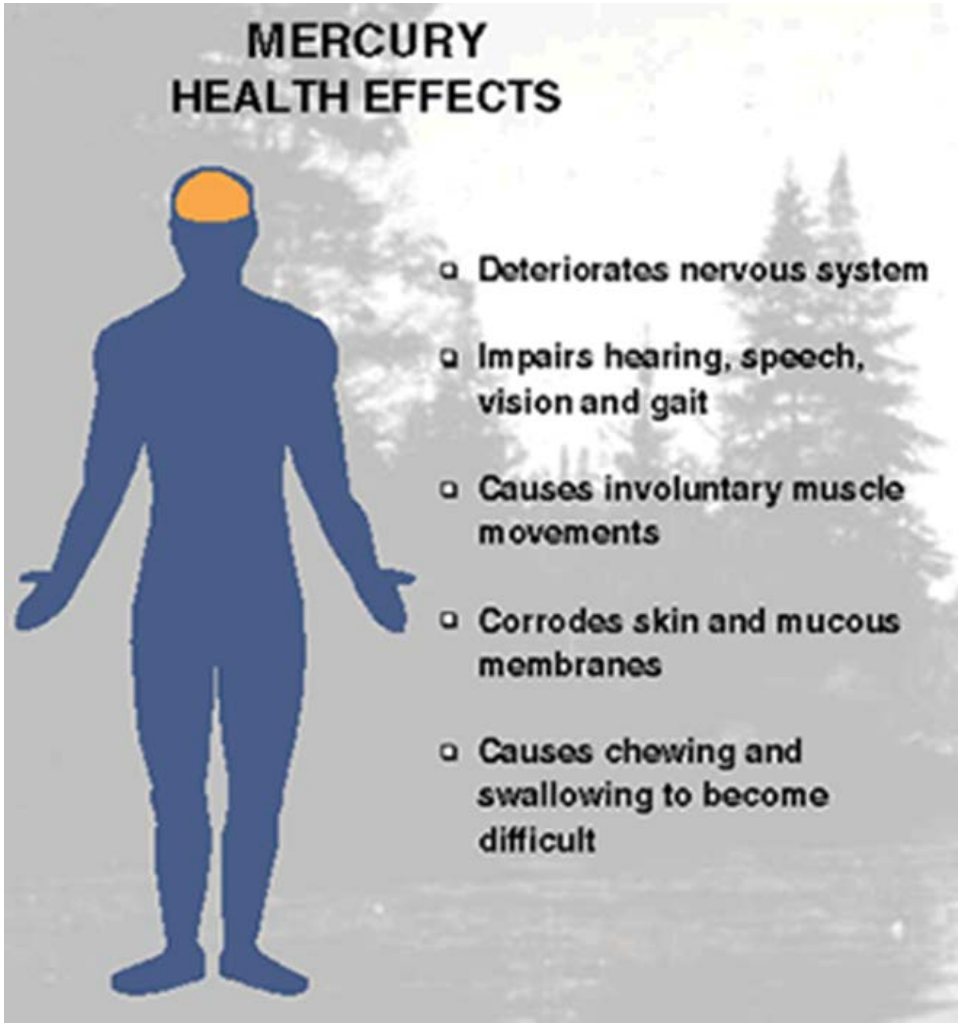
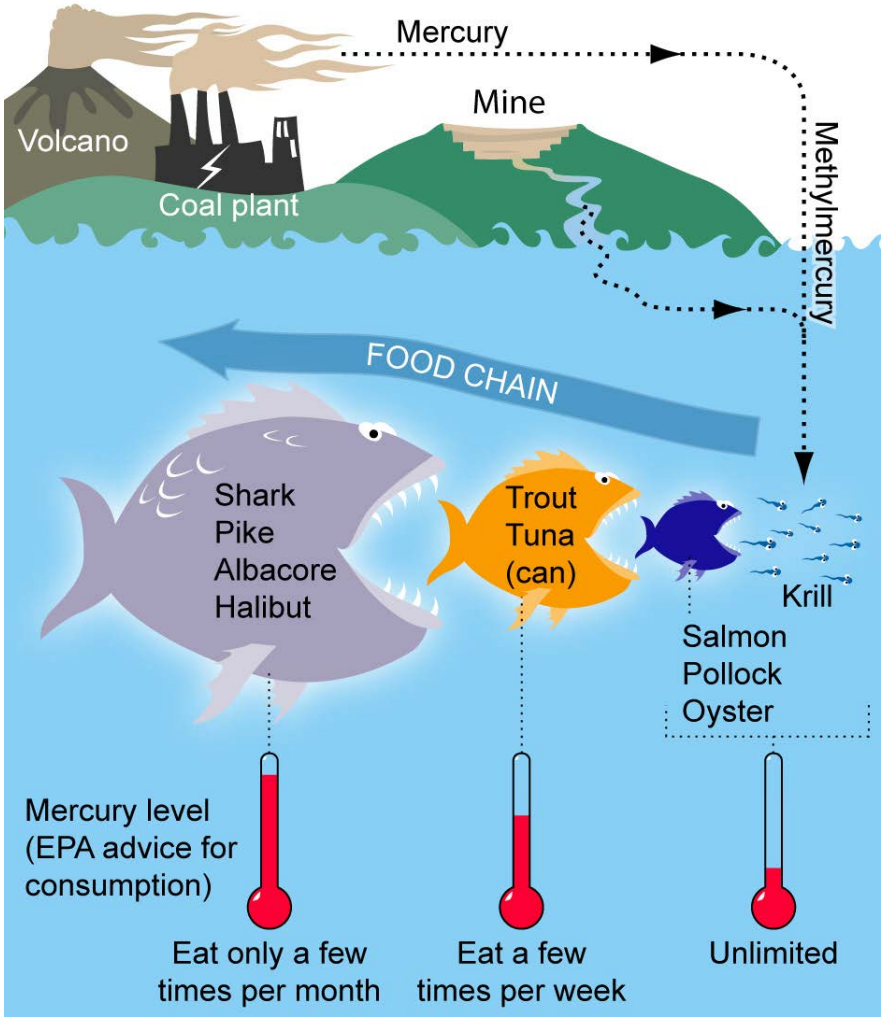


Figure 1. *States with at least one fish consumption advisory for mercury. Source: USEPA Fish Consumption Data Base*


MERCURY
HEALTH EFFECTS
Deteriorates nervous system
Impairs hearing, speech, vision and gait
Causes involuntary muscle movements
Corrodes skin and mucous membranes
Causes chewing and swallowing to become difficult


Mercury
Volcano
Mine
Coal plant
MethylImercury
FOOD CHAIN
Shark
Pike
Albacore
Halibut
Trout
Tuna
(can)
Krill
Salmon
Pollock
Oyster
Mercury level
(EPA advice for
consumption)
Eat only a few
times per month
Eat a few
times per week
Unlimited

Consumption Bans & Advisories In Texas

- All Texas Coastal Waters, Chemical of Concern: Mercury
- Blue marlin **should not be consumed**.
- For blackfin tuna, little tunny, crevalle jack, swordfish, wahoo and all species of sharks:
  - Adult men and women who are past childbearing age should limit consumption to two, 8-ounce meals per month.
  - Children under 12 and women of childbearing age should not consume these species.
- For king mackerel:
  - For specimens less than 35 inches in total length, adult men and women who are past childbearing age should limit consumption to one 8-ounce meal per week.
  - For fish more than 35 inches, adult men and women past childbearing age should limit consumption to two, 8-ounce meals per month.
  - Children under 12 and women of childbearing age should not consume any king mackerel from Texas coastal waters.
- For more information
  - https://tpwd.texas.gov/regulations/outdoor-annual/fishing/general-rules-regulations/fish-consumption-bans-and-advisories
  - http://www.dshs.state.tx.us/seafood/advisories-bans.aspx

Merging Mercury

Academic Question:

How does mercury accumulate in gamefish?

Objective:

To show how mercury travels and accumulates through food chains.

Background:

Mercury, introduced or naturally occurring, can be introduced into various food chains/webs. Because mercury is stored in tissue, it is transferred between trophic levels. At lower levels, mercury concentrations do not seem to have an effect on animal function; however, as levels rise over time, animals may begin to show adverse effects of mercury poisoning (neurological/reproductive issues). Humans are a high-level consumer and therefore, potentially at risk of mercury poisoning. Mercury poisoning in humans and occurs through a process known as **bioaccumulation.**

Bioaccumulation- refers to the accumulation of substances, such as pesticides, mercury, or other chemicals in an organism. Bioaccumulation occurs when an organism absorbs a toxic substance at a rate greater than at which the substance is lost.

Process:

This activity will use a classroom of students representing a food chain to show the bioaccumulation of mercury through several trophic levels.

Materials:

3-5 lbs. bag of pinto beans

1 ½-2 lbs. bag of red beans (try to find a similar size to the pinto beans)

Small plastic container or small shoebox to hold combined beans

1 ½ ounce plastic cups

Procedure:

First level:

Thoroughly mix together all beans in plastic container. Have each student collect a full 1 ½ ounce cup of the combined beans. At this level, the students represent a lower organism on the food chain and the beans represent their diet. (In marine systems, this level is typically made up of polychaete worms and/or zooplankton). Have the students record the number of "red" beans in their diet for the first level and return the red beans to their sample. The red beans represent mercury that the organism has eaten or absorbed from their environment.

Second level:

Have the students group together in groups of 3-4 students and combine their beans. At this level the students have moved up the food chain and now represent gastropods and bivalves that consume polychaete worms and zooplankton. Have the students record the number of "red" beans for the second level.

Third level:

Have the groups of 3-4 students join with another group of 3-4 and combine their beans. At this level the students have moved to the third level of the food chain and represent small fish (pinfish/croaker) and squid. Have the students record the number of "red" beans for the third level.

Fourth level:

Have the groups of 6-7 students join with another group of 6-7 and combine their beans. At this level the students have moved to the fourth level of the food chain and represent local sportfish (Redfish, Speckled Trout, Black Drum). Have the students record the number of "red' beans for the fourth level.

Fifth level:

Have the teacher "go fishing" and collect the beans representing the two or three "redfish" he/she caught that day. Have the students record the number of "red" beans consumed by the teacher and determine/discuss if they are susceptible to mercury poisoning.

Evaluation/Extension:

This lab can be evaluated as per district procedures.

Have students research other elements/chemicals that bioaccumulate in organisms.

Have students research local sources of mercury within their region.

Timeframe:

Typically one class period.

Grade level:

6-12

Ecopath Model for Nueces Bay

Methods - Ecopath model

Ecopath with Ecosim has four key routines, Ecopath, Ecosim, Ecospace, and Ecotracer, which are briefly described. Emphasis is placed on the underlying Ecopath mass balance equation and the Ecotracer equations that link the trophic transfer of pollutants to consumption. Ecopath provides a snap-shot of an ecosystem at a point in time and the ecosystem is defined to be at mass balance when the utilized production of each species or functional group is equal to its yield or catch plus the amount consumed by its predators or consumers. The general formula can also be extended to include immigration and emigration, and also biomass accumulation for groups that are changing abundance during the base year (Walters et al. 1997).

Once mass balance is achieved, the modeled ecosystem can be perturbed dynamically through simulations that can represent changes to the ecosystem by environmental factors (e.g., changes in primary productivity) or human factors (*e.g*., increasing mercury depositions or changes in yield) by using Ecosim (Christensen and Walters, 2004). Ecospace allows the user to apply a grid map over the underlying Ecopath model for dynamic spatial simulations and analysis (Christensen and Walters, 2004. In order to track pollutants in an ecosystem, the Ecotracer routine within EwE is used to model the flow of pollutants in an ecosystem (Christensen and Walters, 2004).

Ecotracer models the flow of mercury (Hg) through an ecosystem and estimates concentrations of Hg in the environment and each species/group. It quantifies the gains and losses of Hg for the environment and each species/group. We present Hg in units of grams. The routine is initialized so that the environment has an initial starting concentration, and a Hg inflow rate and environmental losses are represented as base volume exchange losses. Initial starting concentrations for each species/group can be specified and the gains to each species/group can result from direct uptake rates from the environment and from its diet. Losses from each species/group results from predation, metabolic processes or decay rates, and flows to detritus. Flows to detritus account for unassimilated diet fractions (*i.e*, the fraction of the consumed item that is not assimilated by the consumer) and by the amount of mortality that is not caused by trophic interactions.

Uptake of Hg from food is described by the Hg concentration in food items, the consumer's assimilation efficiency of its food, and consumer consumption rate of its food relative to its biomass. Initial concentrations and diet matrices can be estimated from those reported in the literature, and consumption to biomass ratios for each group are also estimated. Direct uptake of Hg from the environment represents the uptake per biomass per unit time and per unit environmental concentration, the biomass in each species/group, and the environmental concentration. Direct uptake rates from the environment for primary producers are estimated since this represents the main entry way for Hg. Losses from predation are quantified as the product of the Hg concentration in a species/group, and the consumption rate of a species/group by its consumers relative to the biomass in species/group. The flow of Hg to detritus is a function of the concentration in non-feeding mortalities, the unassimilated food fractions, and the

consumption rate of species/group by its consumers relative to the biomass in a species/group. Losses of Hg in each species/group can be a result of metabolic activity or decay and in Ecotracer these processes are summed. Demethylation rates of methylmercury are important to consider for marine mammals (Wagemann et al., 1998), and seabirds (Thompson and Furness, 1989).

The base Ecopath model is set in time units of per year and thus, for fishes, crustaceans, seabirds and marine mammals that are not year-round residents of Nueces Bay, biomass estimates were multiplied by the fraction of the year that they spend in Nueces Bay to derive an effective biomass on a per year basis. Similarly, diet compositions include food imports for these animals to account for the amount of food consumed outside of Nueces Bay. A simulation will be done over 100 years to look at how stable the model is and how well it predicted the measured concentrations of methylmercury in marine organisms in Nueces Bay.

Production-to-biomass ratios can be thought of in different ways, but are commonly thought of as the inverse of the average age of the population, the turnover rate of the population or the total mortality of the population. In fisheries, the total mortality is equal to the fishing mortality plus natural mortality. Allen (1971) showed that the total mortality of the population is the same as the production to biomass (P/B) ratio. Thus, for marine mammals an estimate of the average age for each population was used to estimate the P/B ratio. For seabirds, separate survival rates for adults and sub-adults were used along with the population data to compute a weighted population life expectancy.

To estimate the P/B ratio for bivalves, somatic production was used, and for fishes the total mortality rate was used. Total mortality for most fish species are, here, equivalent to estimates of natural mortality since only blue crab is reported to be targeted in a local fishery. Natural mortality rates for fish groups at the family level were approximated from species represented within Fishbase (Froese and Pauly, 2011). P/B ratios for gastropods, other benthos, annelids, squid, were based on values from literature sources. For zooplankton, the P/B ratios were constrained to be less than that for herbivorous zooplankton and also so their biomass made up approximately 50 % of the total zooplankton biomass as has been observed during summer (Buchanan and Sekerak, 1982; Longhurst et al, 1984).

Consumption-to-biomass ratios for groups are based either on: 1) estimates from the per cent body weight consumed per day multiplied by the number of days present within Nueces Bay; 2) a bioenergetics model (Innes et al., 1987; Trites et al., 1997) combining residence time, the number of animals, and daily rations. Ideally, this is applied across the different age and sex classes, but generally these data are lacking for the populations residing within the area, and therefore in most cases it is computed with an average weight for an individual of the population; or 3) values from primary literature and web sources.

Marine mammals used either the percent body weight consumed per day or the bioenergetics model. For seabirds, consumption was estimated through the use of metabolic-based equations to predict an active metabolic rate from the basal metabolic rate and assimilation efficiency (Stevick et al., 2008). Combining estimates of diet composition for the seabird groups in the Ecopath model with estimates of energy content per gram of diet component the Q/B ratio can be estimated.

Rather than estimating a Q/B ratio for bivalve groups, a production-to-biomass ratio of 0.25 was used along with biomass and corresponding P/B ratio, to have the automatic mass balance routine within EwE estimate the Q/B ratio as output. Fish groups had Q/B values estimated from Fishbase (Froese and Pauly, 2011). Gastropods, squid, other macroinvertebrates, and herbivorous zooplankton had Q/B ratios based on values reported in primary literature. The Q/B ratio for zooplankton was determined by the automatic mass balance routine by assuming a production-to-consumption ratio (P/C) of 0.25.

Results - Ecopath model for Nueces Bay

The Ecopath model construction has just begun in earnest recently. Much preliminary research was conducted to lay the groundwork for the model. Recently taxonomic experts on marine mammals, birds, and turtles have been consulted in the construction of the list of groups and species to be included in the model. Prior to that, other models were examined for their structure. The model by Booth (2012) was of particular interest because it used Ecotracer to try to predict Hg concentrations in upper trophic levels of Lancaster Sound, much as we intend to do for Nueces Bay.

The preliminary list of groups and species (see Table 1) consists of 19 groups and 43 species/taxon groups. The groups include marine mammals, sea and shore birds, sharks, turtles, fish, jellyfish, zooplankton, phytoplankton and detritus. Species/groups were selected in several ways. Many of the fish and sharks were selected based on historical data from the TPWD fisheries independent gill net and trawl surveys. Fish that were most prevalent, or keystone predators in the dataset, such as sharks, were selected from a survey of the TPWD data. It is expected that some adjustments to this list of groups/species may be made as we get further into the construction and parameterization of the model.

Construction of the diet matrix has also begun. An unpublished diet matrix for Galveston Bay is being used as a partial guide, along with advice from several modelers who have constructed Ecopath models. Diet data for several of the species has been downloaded from the GoMexSI database. In addition, reference sources to the diets of marine mammals, birds, turtles, and jellyfish have been identified and will be consulted for diet data in the coming week.

It is expected that the diet matrix construction and parameterization of the model will take another two weeks to complete. The model will then be run to balance the model. After any necessary adjustments are made and the model is balanced we will move on to simulation with EcoSim. Finally, EcoSpace and Ecotracer will be brought into play to complete the model construction.

Table 1. List of the groups and species assigned to represent those groups.

Group	Common name	Prey \ Predator
Dolphins	bottlenose dolphin	Tursiops truncatus
Sharks	blacktip shark	Carcharhinus limbatus
Sharks	bonnethead	Sphyrna tiburo
Sharks	bull shark	Carcharhinus leucas
Seabird	brown pelican	Pelecanus occidentalis
Seabird	double crested cormorant	Phalacrocorax auritus
Seabird	caspian tern	Hydroprogne caspia
Seabird	royal tern	Thalasseus maximus
Shorebird	willet	Tringa semipalmata
Shorebird	great blue heron	Ardea herodias
Shorebird	great egret	Ardea alba
Terrapin	diamond back terrapin	Malaclemys terrapin
Forage fish	bay anchovy	Anchoa mitchilli
Forage fish	pinfish	Lagodon rhomboides
Forage fish	spot	Leiostomus xanthurus
Forage fish	Atlantic croaker	Micropogonias undulatus
Forage fish	silver seatrout	Bairdiella chrysoura
Forage fish	striped mullet	Mugil cephalus
Forage fish	Gulf menhaden	Brevoortia patronus
Game fish	sptted seatrout	Cynoscion nebulosus
Game fish	black drum	Pogonias cromis
Game fish	red drum	Sciaenops ocellatus
Omnivore	hardhead catfish	Ariopsis felis
Predators	blue catfish	Ictalurus furcatus
Predators	gafftopsail catfish	Bagre marinus

Predators	sand seatrout	Cynoscion arenarius
Shrimp	brown shrimp	Farfantepenaeus aztecus
Shrimp	white shrimp	Litopenaeus setiferus
Shrimp	grass shrimp	Palaemonetes sp.
Bivalves	eastern oyster	Crassostrea virginica
Bivalves	clams and mussels	Bivalvia (other than oysters)
Crabs	blue crab	Callinectes sapidus
Snails	snails	Gastropoda
Benthic infauna	worms	Polychaeta
Squid	squid	Teuthida
Jellyfish	Moon jelly	Aurelia aurita
Jellyfish	Cannonball jelly	Stomolophus meleagris
Zooplankton	Zooplankton	Zooplankton
Primary producer	Phytoplankton	Phytoplankton
Primary producer	Benthic algae	Benthic algae
Detritus	Detritus	Detritus

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